Optimal Allocation of FACTS Devices in Power Networks Using Imperialist Competitive Algorithm (ICA)

A thesis submitted for the degree of Doctor of Philosophy

By

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ABSTRACT

Due to the high energy consumption demand and restrictions in the installation of new transmission lines, using Flexible AC Transmission System (FACTS) devices is inevitable. In power system analysis, transferring high-quality power is essential. In fact, one of the important factors that has a special role in terms of efficiency and operation is maximum power transfer capability. FACTS devices are used for controlling the voltage, stability, power flow and security of transmission lines. However, it is necessary to find the optimal location for these devices in power networks. Many optimization techniques have been deployed to find the optimal location for FACTS devices in power networks.

There are several varieties of FACTS devices with different characteristics that are used for different purposes. The imperialist competitive algorithm (ICA) is a recently developed optimization technique that is used widely in power systems. This study presents an approach to find the optimal location and size of FACTS devices in power networks using the imperialist competitive algorithm technique. This technique is based on human social evolution. ICA technique is a new heuristic algorithm for global optimization searches that is based on the concept of imperialistic competition. This algorithm is used for mathematical issues; it can be categorized on the same level as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) techniques. Also, in this study, the enhancement of voltage profile, stability and loss reduction and increasing of load-ability were investigated and carried out. In this case, to apply FACTS devices in power networks, the MATLAB program was used. Indeed, in this program all power network parameters were defined and analysed. IEEE 30-bus and IEEE 68-bus with 16 machine systems are used as a case study. All the simulation results, including voltage profile improvement and convergence characteristics, have been illustrated. The results show the advantages of the imperialist competitive algorithm technique over the conventional approaches.

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I would like to thank my lovely fiancée for all her support and love.

DECLARATION

The work described in this thesis has not been previously submitted for a degree at this or any other university and unless otherwise referenced it is the author's own work.

To my:

Dad & Mum

STATEMENT OF COPYRIGHT

LIST OF JOURNAL PUBLICATIONS

1. Mohammad Shahrazad, Ahmed Zobaa, "Optimal Allocation of FACTS Devices in Distribution Networks Using Imperialist Competitive Algorithm", *International Review of Electrical Engineering (I.R.E.E.), 2013, Vol. 8, No. 5*
2. Mohammad Shahrazad, Amirhessam Alikhanzadeh, "Application of Imperialist Competitive Optimization Algorithm in Power Industry", *International Journal of Industrial Engineering Computations, 2015, Vol. 6, No. 1*
3. Mohammad Khodapanah, Mohammad Shahrazad, "Combination of Energy Storage and Wind Turbine with Conventional Generation Using Scheduling Technique", *International Journal of Electronics and Electrical Engineering*, 2015, *Vol. 3, No. 6*
4. Yaminidhar Reddy Bhavanam, Mohammad Shahrazad, "Impact of Increased Distributed Generation on Fault Levels and the Network Equipment", *Journal of Electrical Systems, 2014, Vol. 10, No. 2*

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V_{max} Maximum voltage magnitude

V_{min} Minimum voltage magnitude

V_M Voltage Magnitude

V_A Voltage Angle (Degrees)

V_G Voltage magnitude set-point

List of Abbreviations

ATC	Available Transfer Capability
B	Shunt Susceptance (MVar injected at $V = 1.0$ p. u.)
Base_KV	Base Voltage (kv)
BFA	Bacterial Swarming Algorithm
BR_Status	Initial branch status, 1 = in-service, 0 = out-of- service
B_T	Total Line Charging Susceptance (p. u.)
Bus_Area	Area number (positive integer)
Bus_I	Bus number (positive integer)
Bus_Type	Bus Type $(1 = \text{PQ}, 2 = \text{PV}, 3 = \text{ref},)$
CBM	Capacity Benefit Margin
CDF	Cumulative Distribution Function
DE	Differential Evolution
F_Bus	‘‘from’’ Bus Number
FACTS	Flexible Alternating Current Transmission System
G	Shunt Conductance (MVar demand at $V = 1.0$ p. u.)
G/G	Generation/Generation

GA	Genetic Algorithm
Gen_Status	Machine status > 0 = machine in service ≤ 0 = machine out-of-service
ICA	Imperialist competitive Algorithm
IPFC	Interline Power Flow Controller
L/G	Load/Generation
$\mathbf{M_{base}}$	Total MVA base of machine
N	Bus number
$\mathbf{P_D}$	Real Power Demand (MW)
PDF	Probability Density Function
$\mathbf{P_G}$	Real power output (MW)
$\mathbf{P_{max}}$	Maximum real power output (MW)
$\mathbf{P_{min}}$	Minimum real power output (MW)
PSO	Particle Swarm Optimization
PTC	Power Transfer Capability
$\mathbf{Q_D}$	Reactive Power Demand (MVar)
$\mathbf{Q_G}$	Reactive power output (MVar)
$\mathbf{Q_{max}}$	Maximum reactive power output (MVar)

Q_{min}	Minimum reactive power output (MVar)
R	Resistance (p. u.)
RW	Roulette Wheel
S_E	MVA Rating C (emergency rating)
S_{LT}	MVA Rating A (long term rating)
SSSC	Static Synchronous Series Compensator
S_{ST}	MVA Rating B (short term rating)
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
T_Bus	‘‘to’’ Bus Number
Tap	Transformer off nominal turns ratio
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Capacitor
TRM	Transfer Reliability Margin
TSC	Thyristor Switched Capacitor
TSR	Thyristor Switched Reactor
TSSC	Thyristor Switched Series Capacitor

TTC	Total Transfer Capability
UPFC	Unified Power Flow Controller
X	Reactance (p. u.)
Zone	Loss zone
$\boldsymbol{\delta}$	Transformer phase shift angle (degree)

Chapter 1

Introduction

1. Introduction

1.1. Power Systems Environment

Flexible Alternating Current Transmission System (FACTS) devices are used to enhance the controllability of power systems and improve all the restricted conditions in the structure of transmission lines to create smooth power transfer between areas. This leads to improvement in power system operation and an increase in power transfer capability. Easy access to the power market depends on the competition between companies. In this case, it is desirable to consider the parameters and transfer power in different areas. Increasing demand requires extra transmission lines to deliver the necessary power. In this case, many researches have issued the challenge to introduce new technology and methods to compensate for the power with other physical components such as FACTS devices. In addition, the quality of transferred power is extremely important in the power market [1]. In the study of power systems, transmission networks have been introduced as a structure of power systems [2].

1.2. FACTS Devices

Rapid development in the FACTS area has seen the introduction of different types of this component for different purposes. These devices are flexible and help systems to improve power transfer and stability. In terms of the high competition in the power market, using FACTS devices is essential to achieve the maximum transferable power. In this case, the amount and type of FACTS devices should be computed to reach the maximum efficiency with a stable network. There are advantages to using FACTS devices in power networks, including: controlling power transfer, controlling the stability and certain capabilities of the network and preventing voltage collapse, improving power quality and power factor and voltage profile, improving dynamic stability, enhancing the load-ability of the transmission lines, and decreasing reactive power losses and as a result increasing active power transfer.

1.3. Power Networks

In recent years, power network design engineers have decided to create a large power network without having connections with other networks to minimize the difficulties and increase the efficiency, controllability and security of the systems. Due to the growing demand, these parameters are developing and every year new technology and methods are released to minimize the losses and increase the quality of the power networks. Basically, a power system can transfer the maximum capability of the power if the network can be controlled properly. So in this case there are different ways to enhance the transfer capability in power systems, which is important. One of the most important and useful components in a power system is FACTS.

1.4. Research Aim and Objectives

This study mainly focused on optimization of the power networks. The objective was stabling the level of the voltage and reducing the losses and increasing the efficiency and power quality. To achieve that point basically FACTS devices such as SVC and UPFC were used in the network. Indeed, optimal size and place of those devices were the objectives. Evolutionary algorithms have been involved during the optimization. The aim of intelligent methods is to find the optimal engineering response: for instance, how the engine is designed with maximum output or how a robot's arm works until reaching destination with the shortest route. It should be noted that all of these are optimization problems. Classic mathematical methods have got two main disadvantages [4]. Some of these methods consider local optimum as a final answer to the problem and only some of them are also used for specific problems. Allocating and estimating the type and size of FACTS devices are the most important areas of the transmission network. Indeed, with the use of certain techniques, maximum efficiency can be obtained from power networks without installing new generators

[3]. For financial reasons, it is essential to install these FACTS devices in optimal locations. For this purpose, initially a mathematical model of FACTS devices should be considered, and then, by using an optimization technique, they can be placed in the optimal places. Allocating FACTS devices is a combinatorial optimization in which the location and size of the devices should be determined in order to achieve maximum savings in power systems. In this study, the aim of the optimization is to find the best solution for the proposed problems. In this case, there are many types of methods that can help to achieve the solution.

1.5. Principle Contribution to Knowledge

This study used different objective functions with various numbers of constraints to discover the solution. Using different objective functions in the problems delivers different solutions. This is because of the behaviour of the objective functions. In many cases, same constraints were used. So it can be seen that those constraints are compulsory in the optimization, such as voltage profile and FACTS compensator size. The imperialist competitive algorithm basically proved that it is faster than other mentioned optimization techniques such as the genetic algorithm and particle swarm optimization. And this algorithm discovered the solution with fewer iterations. In this study, the IEEE-30 bus system was analysed by imperialist competitive algorithm technique and the results were compared with other optimization techniques.

1.6. Research Methodology

In this thesis, basically two case studies have been analysed with different optimization methods. All the results are discussed in terms of convergence characteristics and iterations in the results chapter. This study has focused on a new optimization method that has recently been developed. The aim of this study was to implement imperialist competitive algorithm technique, and to compare the results with other different optimization methods to find out the advantages and disadvantages in terms of speed characteristics and cost. The proposed optimization algorithm is based on human evolution.

This algorithm starts with initial selections that are called “countries”. They can be the answers to the proposed problem. These countries are the same as chromosomes in genetic algorithms and particles in particle swarm optimization. All these countries are divided into two main groups: imperialist and colony. After several steps the algorithm will converge and obtain the optimum solution to the problem. This algorithm is based on human evolution history. In this study, this algorithm was implemented in the two case studies and all related results are presented in the results chapter. This algorithm is used for different purposes in power systems. In this study, the imperialist competitive algorithm was used to allocate FACTS devices in the power network.

1.7. Thesis Outline

Chapter 1 provides general knowledge about energy demand and the importance of FACTS in power networks. Basically FACTS devices are used to enhance the quality of power transfer. The aim of optimization is discussed and the role of algorithms is briefly discussed. In this regard, the imperialist competitive algorithm is introduced and the main role of this algorithm in this study is explained.

Chapter 2 demonstrates the effect of FACTS devices in power networks. FACTS devices are used to enhance the constructability and security of the system, and in this case FACTS devices are fully discussed. There are several types of FACTS devices in the power market that are used for different purposes. The advantages and disadvantages of FACTS devices in terms of power transfer capability are also mentioned. Different types of FACTS devices are also discussed.

Chapter 3 demonstrates the importance of optimization. In this case, 52 case studies are demonstrated and analysed in terms of convergence characteristics, performance, objective functions and constraints. The advantages and disadvantages of the algorithms based on the case studies are illustrated.

Chapter 4 provides full information about the imperialist competitive algorithm, which is a recent optimization algorithm used to find optimal solutions for problems. In this case, all the algorithm steps are demonstrated and discussed. The structure of the imperialist competitive algorithm is demonstrated in terms of convergence to the problem.

Chapter 5 presents the IEEE-30 and IEEE-68 bus system networks. In this case, objective functions and constraints are illustrated.

Chapter 6 presents simulations and results in terms of convergence characteristics. In this case, ICA is compared with other optimization techniques. Static Var Compensator (SVR) and Unified Power Flow Controller (UPFC) are implemented in the IEEE test systems. Losses and level of voltage profiles are also illustrated.

Chapter 7 summarizes the principal conclusions of the research work presented in this thesis, highlighting its main achievements, contributions and potential for further developments.

Chapter 2

FACTS Devices

2. FACTS Devices

2.1. FACTS Background

In recent years, energy demand has increased. In this case, some energy issues, environment problems, exceed to the others properties land and installing new transmission lines are the main issue of the project. In response to this situation there have been a few theories with regard to increasing the power transfer capability and power quality of systems. Engineers have tried to design flexible device to make power networks function optimally.

Nowadays, in the area of power electronics, advanced component are used in power networks. The aim of these devices is to enhance the capability of the system in terms of transferring high-quality power to fulfil the demand. Flexible AC transmission system devices are based on power electronics converters. In this regard, they are able to create rapid adjustment to control the electrical components. And in this area, FACTS devices have offered many advantages to power systems.

These devices are able to connect to power systems in parallel or series or a combination of these. The benefits of using FACTS devices include: controllability, increased stability, security and efficiency of power systems. By applying FACTS devices, power transfer flow can be controlled along with the thermal limit of the transmission lines enabling them to operate to their limit. As previously mentioned, installing extra transmission lines is not always the right way to increase power transfer. In some cases, property owners do not give permission to cross their land to set up the lines.

One of the major parameters that has a special role in the operation of power systems is power transfer capability [58]. Power transfer capability can be defined as the ability of a power network to transfer power in a specific condition without disturbing the constraints and security of the power system. This condition depends on the physical constraints and financial issues of the transmission systems. With regard to physical constraints, major issues are related to the security of power systems. Power transfer constraints can be categorized as the thermal limit of transmission lines, voltage constraints at bus-bars and the stability of power systems [59]. In this case, the power transfer capability of the system is directly relevant to the economic part of the network, which needs several functions to be defined. In this part, this study is going to stress the power transfer capability in power networks by explaining some parameters.

2.2. Available transfer capability

ATC is one of the major functions of power transfer capability. Basically it can be defined as the available power that is transferred in transmission lines to achieve more profit. This parameter can be obtained by deducting the Transmission Reliability Margin (TRM), the Capacity Benefit Margin (CBM) and existing transmission commitments (including the CBM) from the Total Transfer Capability (TTC) [60]. ATC is expressed in Eq. 3.1.

$$ATC = TTC - TRM - existing\ transmission\ commitments\ (including\ CBM) \quad (2.1)$$

This section demonstrates the difference between transfer capacity and transfer capability, which have different expressions in power systems. Transfer capacity represents the loading of transmission network components such as thermal limit, which is constant and depends on the physical characteristics of the electrical components. But transfer capability covers almost the whole system. To operate safely this parameter should be calculated and it should be ensured that this value does not exceed a certain level [61]. The capability of the whole system in terms of power transfer capability between two areas that have been connected by transmission lines is greater than the power transfer ability between the same areas. This is because of the physical and electrical limitations of components in the power network. In a good scenario, power transfer capability can match the power transfer ability of electrical components between those areas. This amount is measured and defined in terms of MW. Transfer capability in contrast to transfer capacity is an oriented vector. This means the amount of power transfer capability from area A to B is not necessarily equal to the amount of power transfer capability from B to A. Transfer capability can be defined as a power transfer between one area and another with considering and remaining in constraints.

Depending on the power transfer in power networks (power injected in source and sink areas), all other parameters such as voltage magnitude and angles will be affected. Indeed, Kirchhoff's voltage and current law in power systems determines the coefficient of power transfer capability based on power transfer between two bus-bars [62]. In the case of power transfer between two areas, usually some constraints such as thermal limit, voltage at bus-bars and stability of the system are recognized as restricting power transfer.

It can be seen that this element depends on the input variable functions. Also, the amount of power transfer capability can be affected by the power in source and sink areas. The ability of power transfer in connected networks to deliver power will be restricted by electrical and physical characteristics. Here this study will demonstrate three common constraints in power systems: thermal limits, voltage limits and stability of the system. Current flowing through the electrical equipment creates warmth. Each piece of equipment has different characteristics in terms of thermal limit. And this can be defined as the maximum current flowing through the device in a specific period before damaging the components. So as a result, the current flowing through the equipment is limited by thermal characteristics [63]. In all situations, including normal operation and emergency situations, the voltage of the network should remain within the defined range. During the power transfer in transmission networks, the system gets active and reactive losses and the voltage will drop.

Depending on the power transfer increase, the amount of losses will increase and the network will need some reactive power to remain within the desirable voltage. Reactive power will be needed in whole route of the transmission power, especially in sink areas and also some areas with a shortage of generated power [64]. In some cases, such as emergency situations, for instance, decreasing the generated power can be achieved by eliminating one or several of the generation units in the power system. This situation will get worse if those units provide the largest amount of reactor power in the system. Voltage collapse can lead to horrible consequences.

Basically, voltage collapse starts at one point of the network and is extended to the whole system immediately. The power network should remain stable in terms of disturbances because of the transient states. A transient situation can occur between milliseconds and minutes. In the case of stability, all the generators must operate at the same frequency, but after disturbances appear they will start to oscillate and as a result the voltage will change in the system. To remain in a stable state, all the disturbances should be reduced, then the system needs to start again from a new point. If the system cannot compensate and regulate itself to become stable, this leads to some part or all of the power system becoming out of control and shutting down the entire network. It can be seen that varying the amount of constraints to reach a different ability of power transfer creates a complex situation. One of the most important concepts during the calculation of the transfer capability is the transfer reliability margin. In order to, it is such a power transfer needs to be remained in the system during operation and facing faults. Uncertainty in the power system needs to have high security operation [65].

Total transfer capability is very important in transfer capability and is a fundamental part of it. Because transfer capability is related to total transfer capability. The amount of delivering power between two areas can also be defined with a high level of certainty. In this situation, the system should be able to eliminate the oscillation of the power against the disturbances after knocking down one of the system components such as a transmission line or generator and remain stable. To achieve total transfer capability, some points should be considered. Reducing the load from the overloaded transmission lines leads to an increase in power transfer capability and this can be done by using FACTS devices.

In this case, it is important to find out the impact of FACTS devices on the market when assessing total transfer capability. To obtain total transfer capability, first of all the initial condition of the power system, such as estimating the load, distributing the load between the generators, the transfer schedule and the operating point of the system, should be identified. Also, in terms of variation it supposes to compute again. When assessing the total transfer capability unforeseen situations should be appeared for such as the breakdown of generation and transmission components, and the worst failure situation must be considered when assessing the total transfer capability. Due to the continuous fluctuation of the network, the effect of failure should be calculated for different operating states. Total transfer capability is determined according to thermal, voltage and stability constraints. These constraints can be changed according to different situations such as changing system situations and the breakdown of components.

2.3. Importance of FACTS

Power transfer capability is the potential of the network between the bus-bars and areas according to the constraints of the network. To assess the power transfer capability basically the power transfer will be increased until it reaches the minimum value for security, in order to by increasing the amount of the power, power system might be collapsed. In this case, the role of the constraints is sensitive, such as thermal limit, voltage limit and stability of the system. Based on this, FACTS devices are used to compensate for all power system weaknesses [66]. Optimal allocation of FACTS devices has recently been challenged by many researchers and all have introduced different methods and techniques to allocate these devices in power networks.

The genetic algorithm (GA) and particle swarm optimization (PSO) are the most common algorithms used in this area to find the optimal location for FACTS devices [67]. In this study, the imperialist competitive algorithm has been introduced and this algorithm is implemented in the case studies. In this study, two case studies have been analysed and the IEEE-30 bus case study analysis is compared with other optimization techniques and all the related results are shown in the results chapter.

Nowadays, reactive power compensators as a part of FACTS devices are essential in power systems. And these devices have special roles in increasing the dynamic stability and voltage regulation in power networks. Reactive power compensators are divided into two groups: active and inactive (passive).

- Inactive (passive) reactive compensators: including inductors and capacitors that are connected in series and parallel, which cannot be changed continuously. In spite of cut on and off they are out of control.
- Active reactive compensators: including synchronous compensators and static compensators. These types are controlled rapidly and continuously.

Basically, FACTS devices are not able to prevent faults in the system but they are able to reduce the inconvenient conditions that occur due to faults in the system. For example, cutting off one load from the system causes an increase in the line voltage. In this case, FACTS compensators eliminate the extra voltage from the lines and make them stable. Long transmission lines, several networks connected to each other, the effect of varying loads and transmission line faults make the network unstable. This leads to a decrease in the efficiency of transmission lines and even to them breaking down. But using FACTS devices in transmission lines decreases the risk of these phenomena in the network.

Modern industry needs high-quality power in order to operate, including stable voltage, fixed frequency and continuous injected power. Applying various voltages and frequencies to operate the system causes delay in some parts of the generation process and leads to huge losses. Using FACTS devices reduces these losses and creates high-quality power for customers. FACTS are compatible with the environment and do not create pollution. FACTS devices increase the efficiency of suppliers and reduce the number of extra transmission lines.

2.4. FACTS Device Investment

The cost of FACTS devices can be divided into two parts:

- FACTS device cost
- Infrastructure cost

The cost of FACTS devices depends on their own nominal operating value and some other parameters such as system control, earthquake condition, environmental temperature and system control communication with substation. Infrastructure cost depends on the geographic condition of FACTS devices where they should be installed. This cost is included land owner and building a room for FACTS devices including control equipment and protection facilities.

A variety of FACTS devices are used in transmission lines. This study recommended SVCs and UPFCs as compensated components in transmission lines. UPFCs are used as serious and shunt compensators together and SVCs are a reactive source added at the end of transmission lines.

The optimal installation cost of FACTS devices can be defined from the following mathematical equation [68]:

$$IC = C \times s \tag{2.2}$$

where IC is the minimum installation cost in $US\$$ and C is the function of installation cost in $US\$/KVAr$. The installation cost of a TCSC, SVC and UPFC according to the data applied from Siemens is [68]:

$$C_{TCSC} = 0.0015s^2 - 0.71305s + 153.75\ (US\$/kVar) \tag{2.3}$$

$$C_{SVC} = 0.0003s^2 - 0.3051s + 127.38\ (US\$/kVar) \tag{2.4}$$

$$C_{UPFC} = 0.0003s^2 - 0.2691s + 188.22\ (US\$/kVar) \tag{2.5}$$

In the above equations, S is operating level of FACTS devices, which can be defined as:

$$S = |Q_2| - |Q_1| \tag{2.6}$$

In this study, the cost function equations will be the same as in other case studies.

In this case, Q_2 is the reactive power in the transmission line after installing FACTS devices and Q_1 is the reactive power in the transmission line before installing FACTS devices in $MVAr$. All the constraints are the same as this study has already used for optimization. However, one more constraint, transmission reactance (X_{TCSC}), needs to be added by the

TCSC in transmission lines. This constraint is also limited between minimum and maximum value:

$$-0.8X_L \leq X_{TCSC} \leq 0.2X_L \quad (2.7)$$

The algorithm objectives include only the cost function of FACTS devices. This function shows the installation cost only. However, by analysing the case study in other area such as Power World, simply other parameters can be achieved such as annual maintenance cost and the cost of both active and reactive power. It is necessary to measure both economic and technical benefits to obtain optimal investment. So, by installing in the right place, the whole investment can be recovered after a decade. Fig. 2.1 illustrates the cost function graph for SVC, TCSC and UPFC devices. In this case, the UPFC has more load-ability characteristics and the SVC has a lower installation cost.

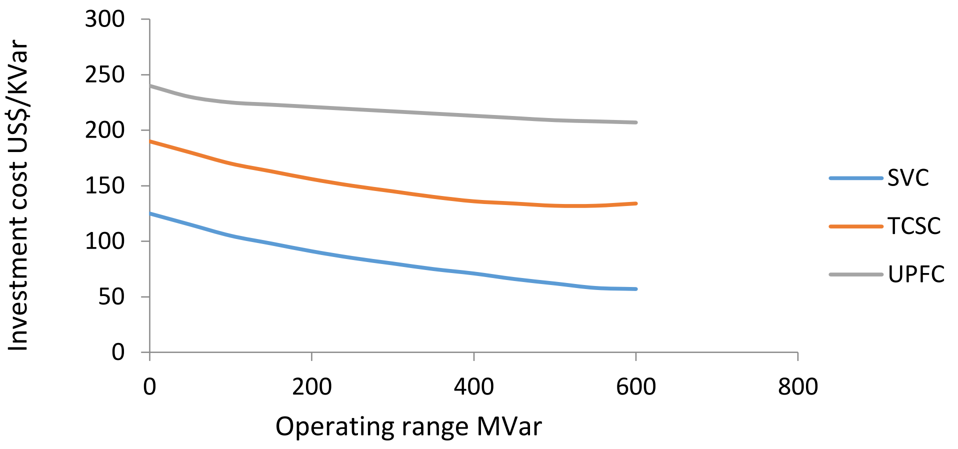

Figure 2. 1 Investment cost curves

2.5. Category and Types of FACTS

In general, FACTS can be divided into four groups and this study will discuss most common devices in this chapter:

- Parallel devices
- Series devices
- Series-Series devices
- Series-Parallel devices

2.5.1. Parallel Device Compensator

This component can be variable impedance or variable source or a combination of these. This component in general, injects a current into the contact point. A parallel FACTS compensator is mostly used to compensate reactive power. Basically, reactive power causes some problems in power networks such as:

- Increasing power transfer price per KW
- Increasing flowing current through the transmission line
- Increasing losses and costs
- Decreasing the power transfer capability of the systems
- Decreasing the load-ability of the generators (decreasing system efficiency)

These issues affect the system in different ways and as a result decrease the power quality. Good management can eliminate all these issues and achieve the following targets:

- Increasing the transient stability limit
- Converging the power oscillation
- Holding the voltage in limited range
- Improving the power factor
- Balancing the unbalanced three-phase load

2.5.1.1. Static Var Compensator

SVCs were initially used in power systems in 1978. According to one estimation, in 1990, there were 195 cases of an SVC being used in power systems. This device is static, which means it does not have rotating and mobile components, and this enables SVCs to provide a fast response to the network. In addition, less maintenance of the components is required because there are no rotating parts. There are some advantages to using an SVC in the network, including: rapid response, more flexibility, good certainty, balancing phases, eliminating extra voltage, fast operation, low maintenance cost, simple control, increasing transient stability, prevention of voltage collapse, improving power factor, improving power quality and eliminating harmonics. An SVC is an electrical component used in high-voltage transmission networks. SVC is a parallel compensator that can be used as a capacitor and variable inductor according to its capacity in power networks. Basically, an SVC is a component that can control the voltage. So, an SVC is a kind of generator with zero active power that compensates the voltage at the connected bus-bar. Fig 2.2 illustrates the current injected model by SVC.

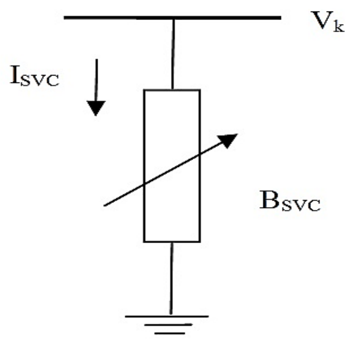

Figure 2. 2 Injected current schematic by SVC

Reactive power injected into the *k* bas-bar follows the equation below and this element can also be defined between maximum and minimum value as already mentioned:

$$Q_{SVC} = B_{SVC} * V_k^2 \qquad (2.8)$$

Fig 2.3 illustrates the schematic of the ideal static compensator. An ideal compensator is able to regulate reactive power itself continuously. One of the most important characteristics of this component is adjusting the reactive power with constant voltage in its terminal [69].

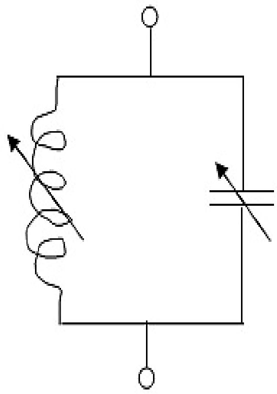

Figure 2. 3 Ideal static reactive compensator

Another important characteristic of this component is rapid response. A reactive power compensator should be changed immediately with small portion of changes. Static var compensator is categorized for several models which this study addresses briefly below.

2.5.1.1.1. Thyristor Controlled Reactor

A TCR is a reactor controlled with a thyristor that is allocated in parallel with the network. The amount of reactance can be controlled continuously by triggering. The amount of current flow from the inductor can change between zero and maximum value by triggering. Fig 2.4 shows the schematic of a TCR [70].

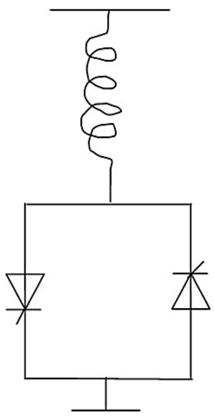

Figure 2. 4 Schematic diagram of TCR

There are two thyristors in this component as switchers. Whenever voltage is more if the thyristor is turned on, current will flow through the inductor. A thyristor controlled reactor has rapid response characteristics. After receiving a time signal, to change the reactive power in a TCR, there is a $1/2f$ delay in the circuit. But the delay in the measurement system and control circuit and impedance circuit lead to a decrease in the speed in the control system of up to 10 cycles of source frequency.

In a three-phase system the maximum delay is $1/2f$. A thyristor controlled reactor has simple structure and control characteristics, and control of the phases can be carried out directly. Due to this feature this component is used to achieve phase balance. But there is a disadvantage in that a thyristor does not have a sinusoidal current, so it will generate harmonics that should be filtered.

A thyristor controlled reactor can only absorb reactive power from the system. To generate continuous reactive power, three capacitors are connected in parallel permanently with the TCR. In this case, by adding one inductor with a capacitor in series the harmonics generated by the TCR can be removed.

2.5.1.1.2. Thyristor switched Reactor

A thyristor switched reactor is similar to a thyristor controlled reactor. The difference is that in this component there is no continuous control of the angle and it is only operated at 90 and 180 degrees. That means thyristors are either completely connected or disconnected. So reactive current injected will be a function of the voltage network. Fig 2.5 shows the schematic of a TSR [71].

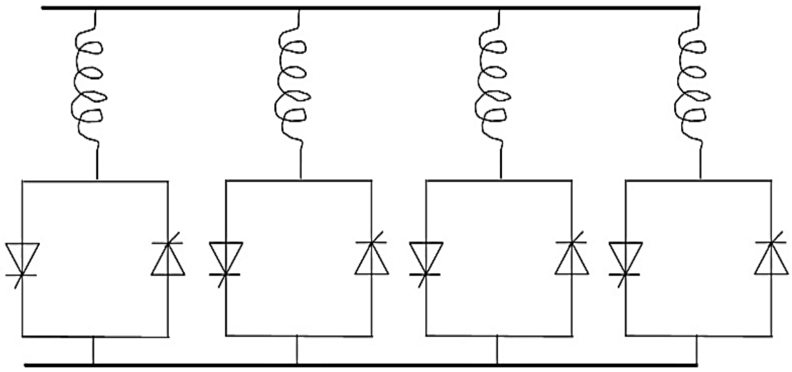

Figure 2. 5 Schematic diagram of TSR

2.5.1.1.3. Thyristor Switched Capacitor

A thyristor switched capacitor is a capacitor that is parallel with one thyristor. By applying on and off mode on the thyristor (without having control of the angle) the reactance value can be controlled step by step. Fig. 2.6 shows the schematic of a TSC.

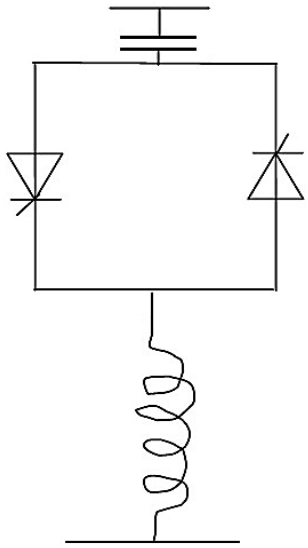

Figure 2. 6 Schematic diagram of TSC

The purpose of the inductor in the component is to limit the transient effect of switches and also to converge the current and create a filter to eliminate the harmonics. Harmonics generation in a TSC is very low. In order to current is almost sinusoidal shape.

Whenever the thyristor switch is on, the capacitor will be in the circuit and generate reactive power until the signal reaches the thyristor gate.

A TSC has got a simple structure and control and it is also less expensive. Phase control can be achieved simply and this component will not generate harmonics. This component has less loss than other SVC models. The dynamic response of a TSC is very fast and is about 0.5 to 1 cycle.

2.5.1.2. Static Synchronous Compensator

In recent years, FACTS components have been developed rapidly and new components have replaced the old ones such as the TSC and TCR. A static synchronous compensator is a parallel reactive compensator that is able to generate or absorb reactive power. The output of this component is changed in terms of controlling the power system parameters.

This component is able to control the three-phase voltage profile with high response. It can compensate reactive power without requiring voltage from the AC system. The main part of this component includes one transformer with a reactance and voltage source converter based on IGBT and one DC capacitor.

Basically, the voltage difference in the reactance causes a reactive power transaction between STATCOM and power systems. As a result it can adjust the voltage in the bus-bar and improve the level. Fig. 2.7 shows the schematic of STATCOM [72].

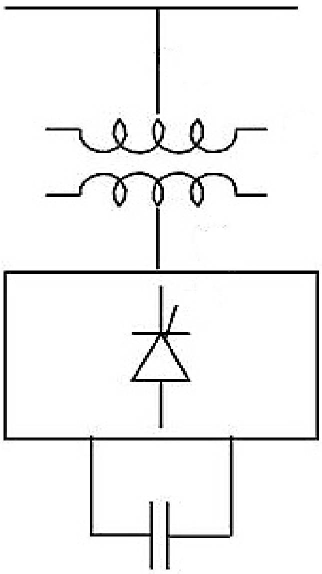

Figure 2. 7 Schematic diagram of STATCOM

There are some advantages to using STATCOM:

- ✓ Dynamic control of the voltage
- ✓ Improvement of transient stability
- ✓ Elimination of power fluctuation in power networks
- ✓ Active and reactive power control

STATCOM is used as a synchronous voltage source and this feature creates better operation and flexibility than SVC. STATCOM will operate better than an SVC for providing voltage under the huge amount of disturbances in the power systems. The ability of STATCOM when protecting the output current of the capacitor during a low voltage situation makes this component operate better than an SVC in relation to transient stability of the system.

STATCOM is one of the most common FACTS devices that is connected to the system in parallel. One of the most important features of this device is improving the quality of the power. The operation of STATCOM in most cases is similar to that of an inverter, which changes DC voltage to AC. Whenever the voltage of the system decreases due to extra demand, STATCOM will act as an active power generator and inject some of the required active power into the network.

The generated reactive power of STATCOM depends on the connected bus-bar voltage level and this makes it more complicated. But the maximum reactive power generated by STATCOM is independent of voltage level so in a critical situation it can rescue the system from voltage collapse.

2.5.2. Series Device Compensator

2.5.2.1. Thyristor Switched Series Capacitor

The main part of this component is a capacitor with a bypass switch. In this case, the capacitor can be involved in the transmission lines when the switch is in off mode. A TSSC is a collection of capacitors and each of them is parallel with a bypass switcher. In this method of compensation, there is no control of the angle. So line reactance will not change continuously and this is the main disadvantage of the component. Fig. 2.8 shows the schematic of a TSSC.

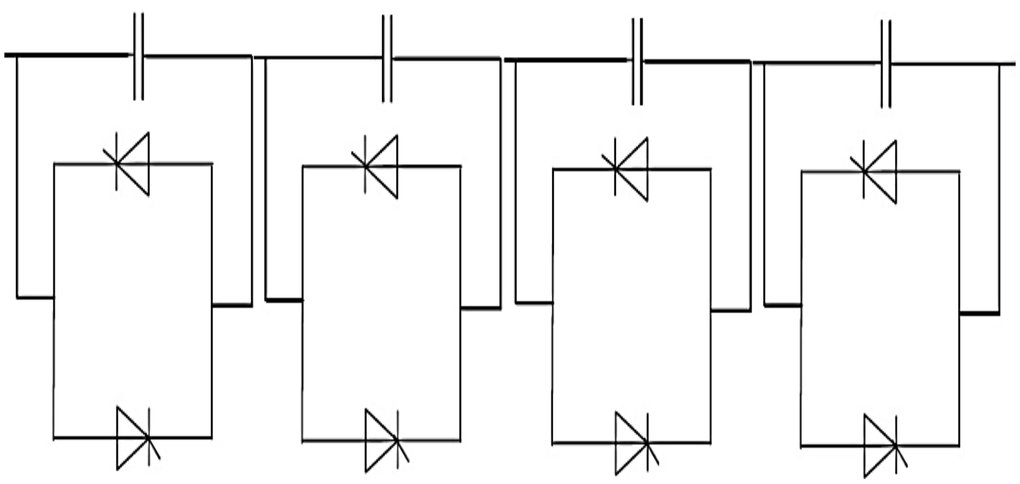

Figure 2. 8 Schematic diagram of TSSC

2.5.2.2. Thyristor Controlled Series Capacitor

A thyristor controlled series capacitor includes a series capacitor that is parallel with a TCR. This component can make various currents with a series capacitor and TCR and control voltage injected into the system. This component is also able to work in both capacitance and inductance areas. In the inductance, area the angle of the thyristor changes within 180 degrees up to the maximum value of δ_L and in the capacitance area the angle changes between zero and δ_C and in this case $\delta_L < \delta_C$. Fig. 2.9 shows the schematic of a TCSC [73].

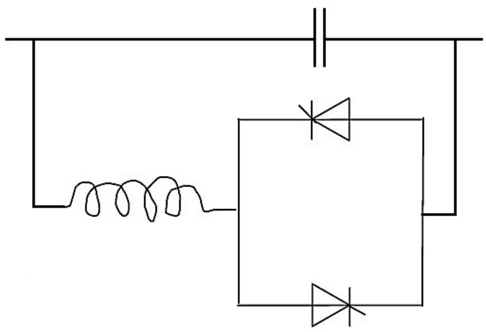

Figure 2. 9 Schematic diagram of TCSC

A TCSC is a series compensator component that is used as a capacitor and inductor element in transmission lines. This device increases the dynamic stability of power transmission lines and improves the load sharing between transmission lines. The amount of the compensator is calculated with the percentage of reactance of the transmission line that is connected, and based on this connection the admittance matrix of the network is improved. The reactance injected by the TCSC can be calculated by using the following equation:

$$x_{TCSC} = Kx_{Line} \tag{2.9}$$

In this case, K is the compensation range, and also, to avoid extra compensation, this range should be limited and should follow the equation (5.5). Fig. 2.10 illustrates the current injected by the TCSC.

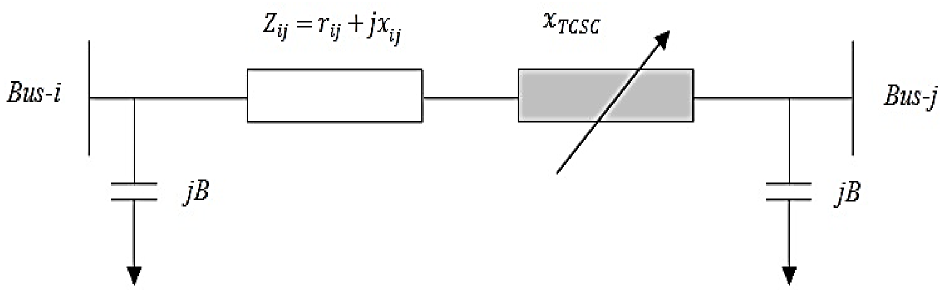

Figure 2. 10 Injected current schematic by TCSC

According to the electrical circuit rules, all equations regarding injected active and reactive power into transmission lines between buses by installing TCSC can be defined as:

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos \delta_{ij} + \Delta B_{ij} \sin \delta_{ij}] \tag{2.10}$$

$$P_{jc} = V_j^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos \delta_{ij} - \Delta B_{ij} \sin \delta_{ij}] \tag{2.11}$$

$$Q_{ic} = - V_i^2 \Delta B_{ij} - V_i V_j [\Delta G_{ij} \sin \delta_{ij} - \Delta B_{ij} \cos \delta_{ij}] \tag{2.12}$$

$$Q_{jc} = - V_j^2 \Delta B_{ij} + V_i V_j [\Delta G_{ij} \sin \delta_{ij} + \Delta B_{ij} \cos \delta_{ij}] \tag{2.13}$$

In the above equations, ΔB_{ij} and ΔG_{ij} can be defined as:

$$\Delta B_{ij} = \frac{x_{ij}(-k^2 x_{ij}^2 - k x_{ij}^2 + k r_{ij})}{\left(r_{ij}^2 + x_{ij}^2\right)\left(r_{ij}^2 + \left(x_{ij} + k x_{ij}\right)^2\right)} \tag{2.14}$$

$$\Delta G_{ij} = \frac{k r_{ij} x_{ij}^2 (2+k)}{\left(r_{ij}^2 + x_{ij}^2\right)\left(r_{ij}^2 + \left(x_{ij} + k x_{ij}\right)^2\right)} \tag{2.15}$$

FACTS technology is one of the most important facilities used in emergency situations without losing the security of the system. A TCSC is one of the most important FACTS devices and changes the impedance of the transmission line whether power flows from appointed routes. This controlled impedance is programmed so that in emergency conditions it increases the security of the power system. Refer to mentioned feature operating system in huge amount of power is possible. Although using mechanical switches can obtain this benefit, the speed and certainty of the thyristors causes an increase in the efficiency and total transfer capability.

A TCSC in a power system is used to adjust the load between the parallel transmission lines so as to achieve the maximum transfer capability. Whenever two transmission lines are allocated in parallel, transferable power will be divided according to their impedance. If both transmission lines have a different structure they will have different thermal limits. If the first transmission line (L_1), which has a lower thermal limit, does not become overloaded, the second transmission line (L_2) will not reach the maximum level. In this case, by allocating the TCSC to the one that has a higher thermal limit and with proper compensation, both of the lines operate up to the maximum thermal limit.

The availability and certainty of the TCSC depend on its own component characteristics. The initial understanding of certainty of the system depends on the utilization of the system. Basically, a TCSC is able to change its own reactance slowly or fast according to transmission line impedance. Indeed, a TCSC is able to change power flow through the transmission lines. With proper adjusting, the preferred power can be reached through the lines. There are two ways to control this device: manual and automatic.

Usually a TCSC is installed to split the load in emergency conditions. Many characteristics are involved to obtain high-quality capability. For instance, the situation of the system gets worse if faults appear in the TCSC. Optimal allocation of a TCSC can have different effects in terms of load separation in transmission lines. In the case of an ideal TCSC in power system study case, it can be seen that it will work without fault permanently and results will be reasonable. Generally, a TCSC is able to operate in three situations:

- Thyristor blocked: in this case the trigger will not work and the whole system will operate like a simple capacitor
- Bypass thyristor: in this case the whole system will operate like a small inductor where the thyristor conducts completely
- Normal operation: in this case the whole system is in a situation between those conditions above and its characteristics change between those of a capacitor and an inductor.

2.5.2.3. GTO Controlled Series Capacitor

According to Fig. 3.11, a GCSC includes a series capacitor with two GTOs in parallel. The advantage of this component is that it is able to switch off at specific points. The aim of a GCSC is to control the AC voltage in the capacitor while the current is flowing. To achieve this, the angle of the GTO is controlled between 90 and 180 degrees. As a result, the AC voltage in the capacitor is controlled so that in line with the specific line value the amount of injected impedance is controlled continuously. Fig. 2.11 illustrates the schematic of a GCSC.

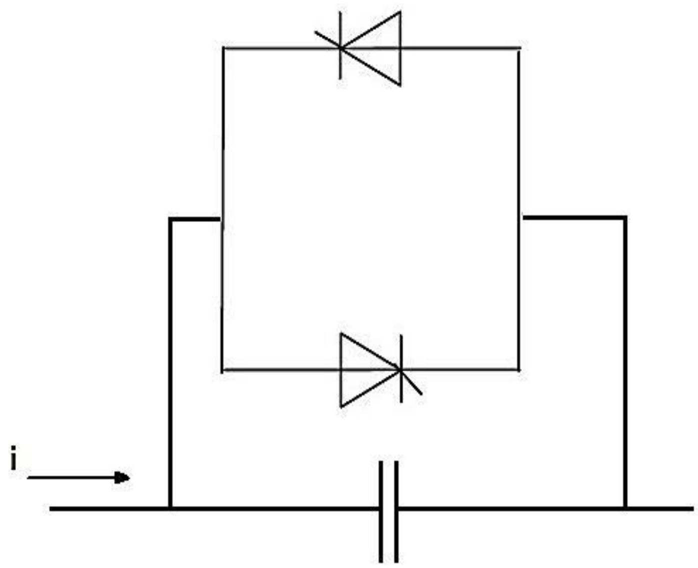

Figure 2. 11 Schematic diagram of GCSC

2.5.2.4. Static Synchronous Series Compensator

This component, by using an inverter as a main part of the component, is able to control the power in transmission lines. This device features quick response, smaller size, lighter weight, reasonable price, balancing, and continuous and accurate control. Poor control of the reactive power in power networks causes a reduction in the quality of power. This component has an inverter with a source that is connected in series to the network by one transformer. The SSSC can inject pre-controlled voltage in the network and also the network is secure against disturbances. Fig. 2.12 shows the schematic of an SSSC [74].

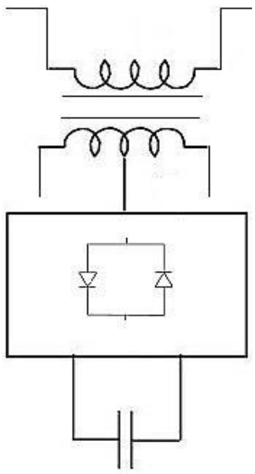

Figure 2. 12 Schematic diagram of SSSC

2.5.3. Series-Series Device Compensators

2.5.3.1. Inter Line Power Flow Controller

This component is a combination of two or more other series compensators that are connected in the AC terminal with a DC link. Injected voltage magnitude and angle using this component are controlled in transmission lines. This device increases the reactive power transfer. This device does not have control on reactive power and as a result is not able to share load between transmission lines.

This device can reduce the load from overloaded transmission lines and increase the stability in terms of dynamic disturbances. Fig. 2.13 shows the schematic of an IPFC [75].

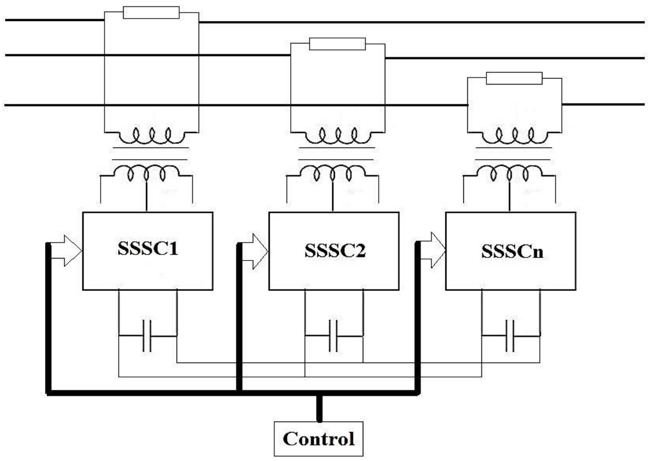

Figure 2. 13 Schematic diagram of IPFC

2.5.4. Series-Parallel Device Compensators

2.5.4.1. Unified Power Flow Controller

A UPFC is one of the most useful FACTS devices and is used to control power transfer. In general, a UPFC is able to control voltage, impedance and angle at the same time. One of the other important features of this component is its control of active and reactive power in transmission lines at the same time. In this device, an SVC is one of the parts of this device that makes active and reactive power transactions. Using a UPFC for controlling power transfer is better than increasing system transfer capability. Basically, a UPFC is used to adjust the power transfer between two transmission lines that are parallel together. This leads to maximum power transfer capability in the power system. A UPFC is one of the most frequently applied FACTS devices in power networks. This component has several benefits for static and dynamic operation of transmission lines. This feature includes STATCOM and SSSC characteristics. UPFC has a unique capability in terms of the control of active power in transmission lines and reactive power at a requested point. If two transmission lines have different characteristics they will have different thermal limits. To achieve the same power transfer through the lines, they should have the same impedance. In this case, the UPFC is connected to the system and both transmission lines will operate within their own nominal thermal limits. Generally, a UPFC has got all the other compensator features. Also, it is able to adjust the voltage, compensate the impedance of the transmission line and shift the angle [55]. This device has got dynamic characteristics, which is important in a transmission system. Basically, a UPFC is able to control voltage, impedance and phase angle at the same time. Also, it is able to control active and reactive power through the transmission lines to achieve maximum load-ability. But this device has been challenged a lot in terms of power electronics and power systems.

2.5.4.1.1. UPFC Structure

A UPFC includes two converters that are connected back to back via a DC capacitor. Each of the converters is connected to a transformer separately. The first converter is called a STATCOM, which injects a sinusoidal current with variable magnitude where it is connected. The second converter is called an SSSC, which injects series sinusoidal voltage with variable magnitude into the transmission line.

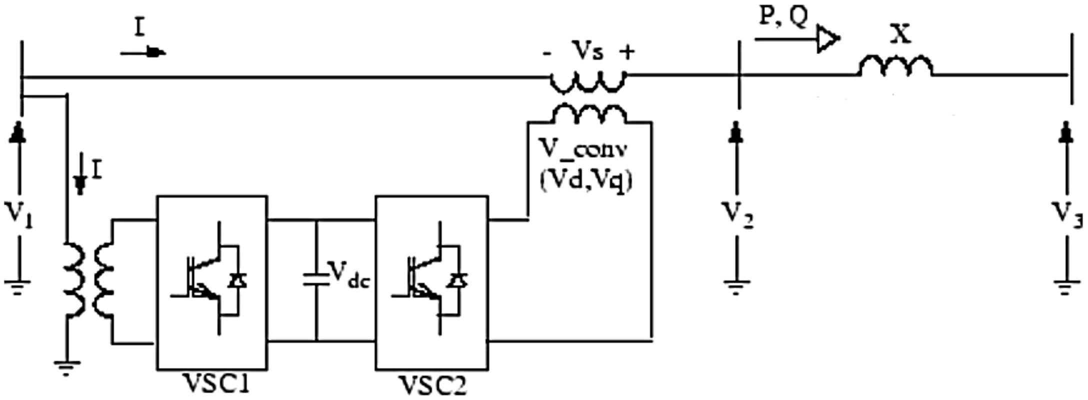

Figure 2. 14 Diagram of UPFC and its two converters

2.5.4.1.2. Operation of UPFC

Power flow though a transmission line is a function of the impedance of the line, the voltage of the source and loads and the angle of those voltages. Basically, power flow depends on the crossing voltage through the impedance of the line. Fig. 2.15 shows a diagram of a simple transmission line:

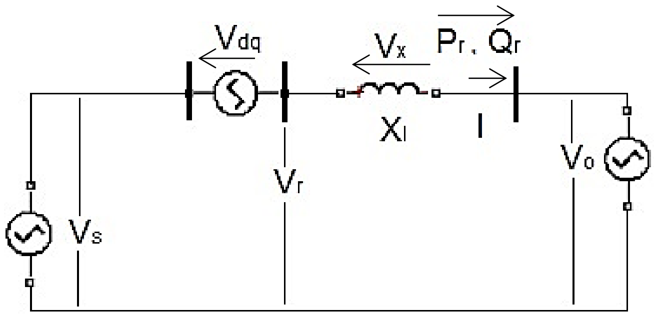

Figure 2. 15 UPFC injects voltage

In this case, X_l is the inductive reactance of the line, V_{dq} is the series-injected voltage, V_s is the voltage source in the sending area and V_r is the voltage source in the receiving area. The crossing voltage through the reactance of the line is equal to:

$$V_x = V_s - V_r - V_{dq} = IX_l \tag{2.16}$$

In this case, I is the current of the transmission line. V_x changes whenever V_{dq} is changed and as a result the current will be changed. Initially it can be assumed that $V_{dq} = 0$, then the vector below can be obtained:

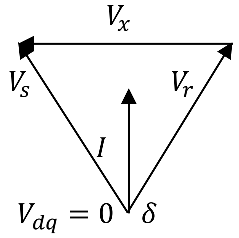

Figure 2. 16 $\boldsymbol{V_x}$ variation when $\boldsymbol{V_{dq}}$is chenged

δ is the angle between V_s and V_r. I is the transmission line current. P_r and Q_r are the active and reactive powers in the receiving area. Injecting V_{dq} as a series voltage into the lines V_o and V_r makes δ_1.

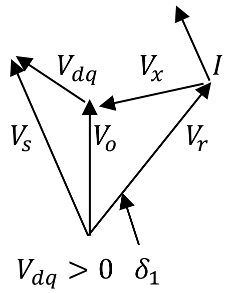

Figure 2. 17 creation of $\boldsymbol{\delta_1}$

As a result, the transmission line current will be changed. If V_{dq} increases more, V_o and V_r will make δ_2, which is lagging. At this moment the current and power are in reverse positions.

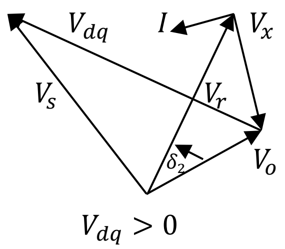

Figure 2. 18 creation of $\boldsymbol{\delta_2}$.

2.5.4.1.3. Physical Operation of UPFC

According to Fig. 2.19, a UPFC includes two converters that are connected back to back by a DC link.

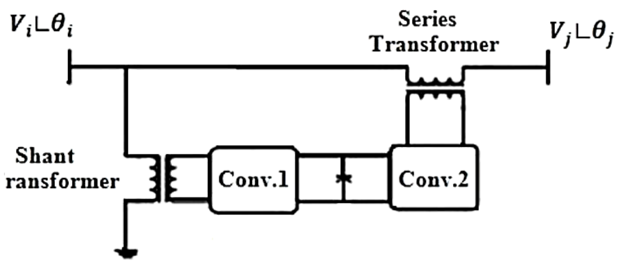

Figure 2. 19 Schematic of UPFC

The second converter, which is a series converter, injects controllable V_{dq} with magnitude (v_{dq}) and phase (ρ) using a series transformer into the transmission line. The reactive power transaction in the AC terminal is done by the converter itself. The first converter provides or absorbs the active power requested by the second converter via the DC link. This power is transferred from the second converter to the first converter via the DC link and will be changed to AC power. Then it will be transferred by shunt transformer to the network. The shunt part is able to provide the requested active power to the series transformer and also it is able to generate or absorb reactive power when required. UPFC operation is traditionally based on shunt reactive compensation, series compensation and adjust phase angle. The UPFC is able to manage all three operations.

2.5.4.1.4. UPFC Control Modes

To demonstrate these modes, the UPFC is connected to the power network as shown below:

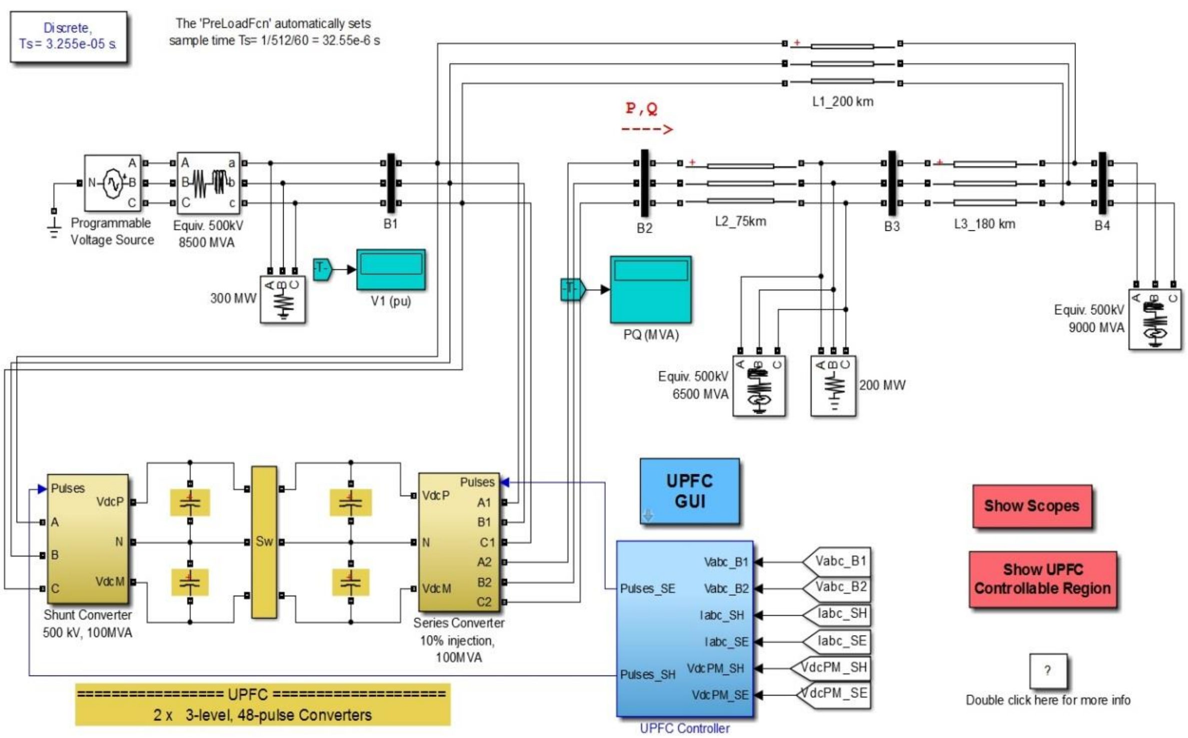

Figure 2. 20 UPFC Connection to the network

2.5.4.1.4.1. Parallel Converter

This converter absorbs controlled current from the transmission line. Some of this current is provided according to the requested active power in the series converter. Another part of this current is reactive. A parallel converter operates in two modes:

1) Var control mode

In this case, the var request is inductive or capacitive. In this control mode, the converter's gates are adjusted to generate a convenient current. This control uses current feedback signals that are sent from the transformer.

2) Automatic voltage control mode

In this case, the reactive current in the parallel converter is adjusted which sets line voltage in connected point according to source one.

2.5.4.1.4.2. Series Converter

This converter controls the voltage and phase angle that are injected into the transmission line in series. This injected voltage wants to have an impact on the power flow in the transmission line. This voltage can be provided in different ways:

1) Injecting direct voltage mode

A series converter simply generates voltage magnitude with angle, which is requested by the source.

2) Emulation mode (phase shift)

The series converter injects voltage whose V_2 phase angle is shifted towards the V_1 phase angle with an angle specified by the source point.

3) Emulation mode (line impedance)

Proportional injected voltage with line current is controlled if we look at series transformer from line side, it will be assumed such impedance. Generally, in this case, creating negative resistance or capacitive inductance should be avoided, otherwise it will create instability in the power network.

4) Automatic power flow control mode

In this case, the injected series voltage is determined, in terms of automatic and continuous modes by system control. In this situation, P and Q are held constant.

2.5.4.1.5. UPFC Constraints

A UPFC has got many characteristics in terms of parameter control and it also has quick response in terms of off and on mode. It can control the system in transient and dynamic modes and it can be used to improve transient stability and eliminate the disturbances in the power system. According to UPFC characteristics, it is able to compensate (shunt and series) and change the phase angle. A UPFC is able to control active power through a transmission line independently. The aim of using a UPFC in the power system is to increase the load-ability of the system near its thermal limit. But during the application of a UPFC in a power network there are some constraints that should be considered.

A UPFC, as with other power electronic facilities, has got some limitations in power networks. Some of these constraints are listed below:

1) Injected series voltage magnitude
2) Series converter current flow

3) Active power transaction between series and parallel converters
4) Maximum and minimum UPFC voltage where connected
5) Parallel converter current flow

The application of FACTS devices in power networks will have more effect in the future. But during the application of these devices, there are some problems that should be challenged. By increasing the series voltage magnitude, the power flow range gets bigger (and vice versa). But series voltage can increase in a limited range because series transformers and converters are designed for specified voltages and will not allow the use of high voltage. As a result, the series-injected voltage is between zero and V_{imax}. But the voltage angle has no limitations and can be any value between zero and 2 pi:

$$0 \leq V_i \leq V_{i\,max} \tag{2.17}$$

$$0 \leq \theta \leq 2\pi \tag{2.18}$$

By applying I = 4.15 p.u, only $0 \leq \theta_i \leq 66$ and $115 \leq \theta_i \leq 360$ are able to transfer power. When considering line voltage limitation, the voltage angle range will be $87 \leq \theta_i \leq 133$ and $247 \leq \theta_i \leq 293$. The limitation of flow current from the parallel converter in some cases has an effect on the power flow and makes it smaller, but generally it has no effect on maximum power transfer. Whenever $V_E = 1\, p.u$, there is no limitation on the power transfer area. In summary, when considering all the constraints, the phase angle range will be $115 \leq \theta_i \leq 133$ and $247 \leq \theta_i \leq 293$. In this case, maximum power transfer takes place when $\theta_i = 115°$.

2.5.4.2. Thyristor Controlled Phase Shifting Transformer

A TCPST is a transformer phase-shifting component. This component applies a thyristor to adjust the phase quickly. This is a series-parallel compensator component and this device is used to adjust the difference in voltage between the first point and last point of the transmission lines. Usually the phase adjustment limitation in a TCPST is between -5 and +5 degrees. Fig. 2.21 shows the schematic of a TCPST.

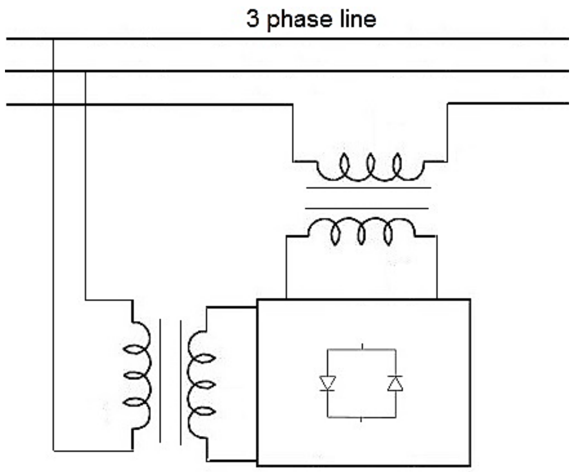

Figure 2. 21 Schematic diagram of TCPST

2.5.5. Advantages of SVC and UPFC in Power Networks

Basically, an SVC is a static component for delivering rapid acting reactive power compensation in power networks. This device supplies automated impedance balancing to the system. Indeed, an SVC uses reactors to balance the impedance reactively. It is able to supply adjustable reactive power to the power network. This component is used at the end of the receiving point of the transmission line. Basically, this device has advantages over other banks of shunt capacitors. For example, this device has tighter control of the voltage compensation at the end of the receiving point of the transmission line, so it will increase line stability when the load varies. This component is used for dynamic reactive power compensation with a large number of reactive power demands. It also reduces the power plant operating cost.

An SVC is a parallel device that can control specific parameters of the power networks. An SVC is a static component, which means this device does not have a rotation part. This characteristic leads to it having a fast response to system variations and disturbances. An SVC has several advantages over most FACTS components. This device has a fast response, more flexible ability and high certainty, balances the phases and eliminates extra voltages, has no rotating inertia, fast installation and lower maintenance and installation cost and is less complicated to control, converges disturbances and enhances transient stability. An SVC is used in both transmission and distribution areas.

The advantages of SVCs in terms of distribution should be mentioned: adjusting and preventing of voltage collapse, improving the power factor, balancing the load and eliminating the harmonics. With regard to the transmission system, it is able to improve voltage before voltage collapse and increase transient stability.

UPFCs are one of the strongest FACTS devices and were introduced to the power system in 1991. The structure of a UPFC includes two voltage convertors with a GTO switch connection. These two convertors are connected to each other by a DC capacitor. The parallel and series parts of the component can absorb and generate reactive power independently. This characteristic enables power flow in both directions.

From a control point of view, this device can be assumed to have two different parts. The parallel part includes a parallel transformer, voltage convertor and DC capacitor, which act as STATCOM. The series part includes a series transformer, voltage convertor and DC capacitor, which act as an SSSC. Indeed, this component is a combination of STATCOM and an SSSC. A UPFC improves transient characteristics in power systems.

In this study, SVC and UPFC were used as compensators in the case study system. An SVC is used widely in power networks because it has good characteristics in terms of loss reduction and voltage regulation. Also, because of lower installation and maintenance costs, it is recommended for use in power networks. The UPFC is the best compensator device and has many advantages over other compensators.

This device has the highest feature in terms of load-ability. The main disadvantage of this component is the installation cost, which is higher than for other compensators. This disadvantage can be analysed by a power network team to see whether this component is suitable for the system. A UPFC can reduce losses more than other FACTS devices and brings high stability to power networks. UPFCs are also used as fault detectors.

Table 2.1 shows the characteristics of various types of FACTS devices in power system.

Table 2. 1 Advantages and features of various FACTS devices

FACTS Type	Power flow control	Voltage control	Dynamic stability	Transient stability
SVC	*	***	***	**
STATCOM	*	**	**	**
TCSC	**	***	**	**
UPFC	***	***	**	**

Note: number of the star represents importance of the characteristics

2.6. Summary of the Chapter

In this chapter, basically energy demand has been explained and the impact of FACTS devices on power systems discussed. A brief history of FACTS devices has been provided and the usage of these components discussed along with the effect they have on stability and power transfer capability. In this case, maximum power transfer capability is one of the issues that researchers challenge themselves to optimize. Available transfer capability (ATC) and total power transfer capability (TTC) have been explained. The restriction of power networks during the delivery of power has also been briefly discussed. The principle of flexible AC transmission system devices, one of the most important components in the distribution and transmission in power networks, has been explained. The types of FACTS devices and their operation have been shown. In this case, several FACTS devices have been demonstrated and briefly discussed in terms of connection and capability. The UPFC is one of the most efficient devices and has more features than other FACTS devices.

Chapter 3

Literature Review

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3. Literature Review

In this chapter, this study is going to present several case studies to show the effect of algorithms on the optimal allocation of FACTS devices. In this case, many techniques have been implemented in the placement of FACTS devices. The GA, PSO and the bees algorithm (BA) are the most common algorithms that have been used in this area. In these case studies, power systems are discussed briefly in terms of objective function and constraints. Different numbers of objective functions and constraints are implemented in the case studies.

It can be seen that by using a greater number of objective functions, a high solution accuracy can be attained and systems can be analysed. At the end of this chapter, the advantages and disadvantages of the algorithms are discussed individually in terms of convergence characteristics and speed and finance issues.

Idris et al [5] presented the bees algorithm to find the optimal choice of FACTS devices for enhancing available transfer capability. In this study, a novel bees algorithm method is proposed for allocating FACTS devices to achieve the maximum available transfer capability of power systems.

In this study, the genetic algorithm was also used to prove the validation of the process. In this case, BA was used to find FACTS location and type. Three types of FACTS devices were used in the optimization: a Thyristor Controlled Series Compensator (TCSC), a static var compensator (SVC) and a Thyristor Controlled Phase Shift Transformer (TCPST).

The IEEE-30 bus system is used to indicate the outcome of the algorithm to enhance Available Transfer Capability (ATC) in the system. This system has been divided into three areas with two generators in each area. In this case, an SVC is connected at the bus-bar and its working range is between -100 MVar and 100 MVar. Also, a TCSC, which changes the line reactance, is connected in series to the transmission lines. The working range for the TCSC is between -0.7X_{Line} and 0.2X_{Line}. A TCPST is a shunt device and its working range is between -5º and +5º. In this case, phase shifting by this device may not be too large since it can also change the voltage amplitude.

The main aim of this study is to find the optimal location for FACTS devices to maximize the available transfer capability of power subject to voltage limit, thermal limit and FACTS device limits. Basically, the calculation of the total transfer capability taking FACTS devices into consideration can be defined as follows:

$$Max\ F(x) = O_{ATC} \tag{3.1}$$

$$\text{Subject to: } F(f, g) = 0 \tag{3.2}$$

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \tag{3.3}$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \tag{3.4}$$

$$V_{min} \leq V \leq V_{max} \tag{3.5}$$

$$S_j \leq S_{jmax} \tag{3.6}$$

$$X_{TCSC}^{min} \leq X_i \leq X_{TCSC}^{max} \tag{3.7}$$

$$Q_{SVC}^{min} \leq Q_{SVC} \leq Q_{SVC}^{max} \tag{3.8}$$

$$\delta_{TCPST}^{min} \leq \delta_{TCPST} \leq \delta_{TCPST}^{max} \tag{3.9}$$

The results indicate that ATC increased from 211.98 MW to 233.98 MW using the bees algorithm. On the other hand, using the genetic algorithm, ATC increased up to 231.96

MW. In this case, the results show that an SVC is the better choice for FACTS devices over other compensators. In this study, the bees algorithm can allocate an SVC much faster than the genetic algorithm.

With regard to convergence characteristics, the bees algorithm converged after 25 iterations but the genetic algorithm took 100 iterations to become converged. The results proved that a TCPST can increase ATC from 211.98 MW to 229.89 MW using the genetic algorithm and to 231.20 using the bees algorithm. It can be seen that the value of ATC using the bees algorithm is slightly higher than by using the genetic algorithm.

According to the results, the bees algorithm found the optimum and better solution than the genetic algorithm. After installing FACTS devices using the genetic algorithm, ATC increased from area 1 to area 2 by about 295.34 MW. The SVC needs to be installed at bus number 19 with an amount of 50.84 MVar and also at bus 12 with an amount of -97.83 MVar. The TCSC was also connected to the transmission line with 70 per cent of the reactance.

Indeed, the bees algorithm demonstrated almost same results. TCSC with a value of -69.99 per cent of the X_{Line} between bus 4 and bus 12 and two SVCs with a size of 58.54 MVar at bus 19 and -99.96 MVar at bus 12 were installed. It can be seen that the bees algorithm reached the optimal solution faster in terms of convergence characteristics and ATC was also better than the genetic algorithm. The main advantage of the bees algorithm is that this algorithm does not need extra parameters such as crossover and mutation, so it can find the solution faster than the genetic algorithm.

Idris et al [6] presented a multi-objective bees algorithm for optimum allocation of FACTS devices in power systems. The bees algorithm has not been used as much as other more common algorithms such as PSO and the GA. In this part, this study will discuss the IEEE-30 bus study case to show the effectiveness of the algorithm as an optimization tool. The genetic algorithm has also been implemented in this case study and there are two objective functions: minimizing the cost of the system in terms of FACTS investment and maximizing the total transfer capability.

Minimizing the total cost function can be divided into two functions because of multiple types of FACTS devices. All related data regarding the cost of FACTS devices has been taken from the official Siemens website [7]. The cost function, which includes generation cost and FACTS devices investment cost, can be defined as follows:

$$Minimize\ f_1(x) = fa\,(P) + fb(g) \tag{3.10}$$

$$C_{TCSC} = 0.0015s^2 - 0.71305s + 153.75 \tag{3.11}$$

$$C_{SVC} = 0.0003s^2 - 0.3051s + 127.38 \tag{3.12}$$

$$TTC = \sum_{i=1} P_{Di}\,(\lambda_{max}) - \sum_{i=1} P^0{}_{Di} \tag{3.13}$$

The second objective function is to increase the ATC of power between the source and sink area. To achieve the total transfer capability and ATC the injected P_{Gi} at the source area and P_{Di} at the sink area are enhanced in function of λ which are:

$$P_{Gi} = P_{Gi} + (1 + \lambda k_{Gi}) \tag{3.14}$$

$$P_{Di} = P_{Di} + (1 + \lambda k_{Di}) \tag{3.15}$$

$$Q_{Di} = Q_{Di} + (1 + \lambda k_{Qi}) \tag{3.16}$$

$$V_{min} \leq V \leq V_{max} \tag{3.17}$$

$$S_j \leq S_{jmax} \tag{3.18}$$

In this case, two constraints were determined: thermal limit and bus voltage limit. In this study, different types of FACTS devices have been considered. Static var compensator, thyristor controlled series compensator and thyristor controlled phase shift transformer are involved in this study case. Basically, the TCSC changes the line reactance, the SVC is used to control the reactive compensation and the TCPST changes the phase angle between the two terminal voltages.

The TCSC is a series compensator device. It is connected to transmission lines to modify the reactance of the line. It can be inductive or capacitive to enhance or decrease the reactance of the transmission lines. The working range of the TCSC in this case was between $-0.8X_{Line}$ and $0.2X_{Line}$. The SVC is a shunt static device to generate or absorb power. This device can be used in a power system to control the reactive compensation of the system at a nominal voltage of 1 per unit. The working area for this device has been set between -100 MVar and 100 MVar. In this study case, the TCPST is used as a shunt device that is connected to the system. The TCPST can regulate the voltage angle between sending and receiving at the end of the transmission lines. The working area for this device has been set between -5º and +5º.

Two analyses have been done. In the first scenario, only one type of FACTS is involved. The results show that the bees algorithm increased the total transfer capability more than the GA, but on the other hand, the cost is more than that of the GA. Both algorithms approached the same two bus-bars (29 and 18) as the optimal place. In this case, the available transfer capability and total transfer capability cost without installing any FACTS devices were 156.48 MW and 573.94 $/hr, respectively. After installing only one type of FACTS devices it can be seen that the transfer capability of transmission lines increased. And the SVC was selected as the best component of this analysis.

In the second scenario, multiple types of FACTS devices are involved. Both algorithms reached the same bas-bars (29, 19 and 24) at the same time. This time the bees algorithm was also slightly better than the GA in terms of total transfer capability. The results also showed that the SVC is better than the TCSC for enhancing power transfer. This is because the overall cost of the system using the SVC is cheaper than using the TCSC and the TCPST.

Shaheen et al [8] presented the optimal location for a unified power flow controller based on evolutionary optimization techniques. In this study, the IEEE-14 bus case study was analysed. In this case, two optimization methods, the GA and PSO, were implemented in the system. A unified power flow controller (UPFC) is one of the most important and useful FACTS devices for controlling the power flow in the system. In this study, two evolutionary optimization techniques are selected to find the optimal location for a UPFC in order to minimize the active power losses in the power system and then both results are compared. For this purpose, only one objective function, minimizing the active power loss of the power system, was considered. This can be shown as follows:

$$minmize\ F = \sum_{k=1}^{ntl} P_{Ltl} \tag{3.19}$$

$$V_{min} \leq V \leq V_{max} \tag{3.20}$$

$$\delta_{min} \leq \delta \leq \delta_{max} \tag{3.21}$$

$$Q_{min} \leq Q \leq Q_{max} \tag{3.22}$$

In this analysis, bus voltage magnitude and angle and reactive power were considered to be constraints with a definition of minimum and maximum value. After replacing the FACTS device in the system, both algorithms reached the same place. The results achieved from both techniques in the case study indicated that both algorithms are able to find the optimum solution for the problem of allocating the UPFC in a way that minimizes the active power losses in the power network by keeping all voltages and thermal limits within their working range area. In this regard, three places were found.

According to the simulation results, it can be seen that the GA was slightly better than PSO in this case. With regard to numerical results, it can be seen that minimum and average loss value and calculation time using the genetic algorithm were 0.1198, 0.12352 p.u. and 76.9 s, respectively. But using PSO technique, minimum and average and calculation time were 0.1198, 0.125708 p.u. and 39.4 s, respectively.

In this study, these techniques were also implemented in the 3 bus and 5 bus study case and the obtained results show the advantage of the genetic algorithm in terms of loss value and the advantage of PSO technique in terms of convergence characteristics.

In this case, the genetic algorithm minimum and average and calculation values for the 3 bus and 5 bus study case were 0.2478, 0.25817, 24.9, 0.0271, 0.03471 and 58.4, respectively. On the other hand, in reference to PSO technique, these values were 0.2478, 0.24801, 14.3, 0.02708, 0.03074 and 27.4, respectively.

In summary, optimal allocation of FACTS devices in power networks has a special role in achieving the better functionality of these devices. The GA was able to improve the voltage magnitude more than the PSO algorithm. Both techniques can easily and successfully find the optimal location of FACTS devices within their constraints. The PSO algorithm was faster than the GA in terms of convergence because this technique does not have extra calculation procedures such as crossover and mutation.

Sheeba et al [9] presented the optimal location of an SVC using artificial intelligence techniques. In this study, a static var compensator was used. This device, because of the lower cost and high system enhancement, has been used widely in power networks. This device also supports the voltage, and if installed in the optimum place it can reduce power losses. In this case, the size of the compensator indicates the amount of reactive power connected to the bus-bar with a voltage of 1 p.u. A positive value indicates that the SVC generates reactive power and injects into the network and a negative value shows that the SVC absorbs reactive power from the network.

In this study, the IEEE-14 bus case study involves both the GA and PSO algorithms to find the optimum place to allocate a FACTS device. To allocate this device, voltage deviation is defined as the objective function:

$$minimize\ L = \sum |1 - V_m(i)| \tag{3.23}$$

$$0.95 \le V \le 1.1 \tag{3.24}$$

$$Q_{min} \le Q \le Q_{max} \tag{3.25}$$

The main aim of this study is to improve the voltage profile. In this study, non-optimal location also was considered whether there are no FACTS devices in the power system. In this equation, the network voltage deviation for a given network is defined as the sum of the deviations of the voltage magnitude. It is essential that voltage magnitude is within standard operating voltage. So in this work, two constraints, voltage magnitude and reactive power, are considered with their maximum and minimum limit. Both GA and PSO algorithms discovered the same place.

Bus numbers 7 and 13 were the optimal places. In reference to the results, without the SVC network voltage deviation was 0.5662 p.u. With optimal location of the SVC this value was changed to 0.28 p.u.

In this case, the accuracy of the GA is higher than that of PSO, but the speed of the convergence was slightly higher than that of the GA. In a large number of power systems it can be seen that one SVC will have a greater effect on the system and a power system requires a greater number of compensators. After installing FACTS a big improvement in the voltage over a wide range of operating conditions and for various types of disturbance in power networks can be seen.

Mondal et al [10] presented PSO-based location and parameter setting of advance SVC controller in comparison to the genetic algorithm. In this part, the IEEE-14 bus case study is analysed with only one objective function. The optimization problem mentioned here is to search for the optimal location and the optimal set of FACTS parameters using the PSO and GA algorithms. It can be said that the FACTS controller is designed to minimize small signal oscillations in the power system after a disturbance, thereby leading to improved stability. This result in terms of minimization of the Critical Damping Index (CDI) is given by:

$$minimize\ \mathrm{CDI} = \mathrm{J} = (1 - |\zeta_i|) \tag{3.26}$$

The problem constraints are the bounds on the possible locations and parameters of the FACTS devices. Both the PSO and the GA algorithms separately create the best set of parameters as well as the best location related to the FACTS device by minimizing the amount of objective function J. In this regard, PSO has been implemented for optimal parameter setting and identification of the optimal site for the FACTS device in a standard multi-machine power system in order to mitigate the small signal oscillation problem.

The ability and performance of the PSO- and GA-based FACTS devices have been compared in relation to power system disturbances: for instance, changing the load and transmission line power outage. The characteristics of the critical eigenvalue and time response analysis reveal that PSO-based FACTS devices are faster than GA-based FACTS devices even during critical loading.

The discussed method, called “PSO-based optimization technique”, seems to have a high accuracy and convergence rate and this technique is basically free from computational complexity unlike the GA technique.

Bhowmik et al [11] presented the optimal location of a UPFC based on the PSO algorithm bearing in mind the minimization of active power losses. In this part, the IEEE-14 bus study case is investigated. A UPFC was used in this study to compensate for the power. In this case, PSO and GA techniques have been used for minimizing active power loss through optimal placing of FACTS devices in power systems. In this case, two objective functions are implemented as indices of the system performance: identification of suitable buses using a line loss sensitivity index and minimization of active power losses by employing the PSO and GA techniques.

In this regard, two objective functions can be illustrated follows;

$$u_1(x) = P_L \qquad (3.27)$$

$$u_2(x) = \left|\begin{matrix}\Delta P \\ \Delta Q\end{matrix}\right|_2 + P_L \qquad (3.28)$$

In this case, the voltage magnitude and angle and size of the FACTS device were pointed constraints and they were limited.

$$V_{min} \leq V \leq V_{max} \tag{3.29}$$

$$\delta_{min} \leq \delta \leq \delta_{max} \tag{3.30}$$

$$X_{Lmin} \leq X_{FACTC} \leq X_{Lmax} \tag{3.31}$$

According to the results, the total loss reduction with the genetic algorithm was 0.8589 with a simulation time of 297 s. But with PSO technique the total loss reduction was 0.5682 with a simulation time of 254 s. A UPFC was located in three places: lines 4-9, 13-6 and 4-3. The total loss reductions with the UPFC using the same lines are 0.5201, 0.55353 and 0.5732, respectively, and without the UPFC using these lines they are 0.8429, 0.8229 and 0.8432, respectively. It can be seen that by allocating a compensator to line 4-9 maximum loss reduction can be achieved.

With regard to the study case system, both GA and PSO techniques can find the optimal location for the FACTS device, but the PSO technique is better in terms of minimizing the active power loss problem. Basically, in this case PSO takes less simulation time than the GA. Also, PSO is an easier-to-use, more robust and faster optimization technique than the GA.

Rekha et al [12] presented a comparative analysis on reactive power optimization using various techniques in a deregulated power system. In this part, the IEEE-30 bus study case will be analysed. In this example, real power is maximized and reactive power should be minimized as well. In addition, sufficient reactive power should be provided locally in the system to keep the bus voltages within nominal ranges in order to satisfy customers' equipment voltage ratings.

In this regard, the mathematical model of reactive power optimization and its algorithm was modified. In this case, FACTS devices are used to enhance the voltage profile. In this regard, PSO and the GA are used and the MATLAB program is deployed.

In this study, two objective functions are used: minimizing reactive power and voltage deviation. As usual there are a few constraints in the problem.

$$Q_i = -i\{V_i * [V_i Y_{ii} + \sum_{j=1}^{n} V_{ij} V_j]\} \quad (3.32)$$

$$V(i) = \sum_{i=1}^{n}(1 - V_i) \quad (3.33)$$

$$V_{min} \leq V \leq V_{max} \quad (3.34)$$

$$Q_{min} \leq Q \leq Q_{max} \quad (3.35)$$

$$T_{i-min} \leq T_i \leq T_{i-max} \quad (3.36)$$

After analysing using the GA and PSO algorithm, it can be seen that reactive power has a reduction of 4.9% after optimization using the GA and a reduction of 7.1% after optimization using PSO for the base case. The GA and PSO are implemented to reduce the reactive power. The reactive power obtained after optimization using the genetic algorithm is 23.641 MVar. The opportunity cost value is $7.0320. The bus voltages of the 26^{th} and 30^{th} buses are improved to 1.062 and 1.053 p.u. The reactive cost of compensator 1345 was obtained $4.8417. The total cost of reactive power was obtained $11.8737.

The reactive power obtained after optimization using the PSO is 23.106 MVar. The opportunity cost is calculated as $7.05063. The bus voltages of the 26^{th} and 30^{th} buses are improved to 1.069 and 1.055 p.u. The reactive cost of the compensator is $4.646. The total cost of reactive power is given as $11.6966. Comparing the two methods, the PSO technique has more optimized values than the genetic algorithm.

Rashed et al [13] presented the optimal location and parameter setting of multiple TCSCs for increasing power system load-ability based on the GA and PSO techniques. In this study, the IEEE-6 and IEEE-14 bus study case will be analysed. In this case, one objective function has been defined. Indeed, the location of FACTS devices in power systems has a special role in achieving the problem goal.

This study used a TCSC to obtain a maximum system load-ability in the power network with minimum cost of installing this component. In this case, two algorithms, the GA and the PSO algorithm, are deployed to analyse the system in MATLAB. FACTS are used to increase the load-ability of the system. In this objective function there are two parameters.

The first part is related to the cost of a FACTS device and the second part is the sum of two parts, which are thermal and bus voltage limit factors.

The objective function can be defined as follows:

$$minimize\ F = 1000 \times C_{FACTS} \times S \times \lambda_1 \times VL \tag{3.37}$$

$$C_{FACTS} = 0.0015S^2 - 0.7130S + 153.75 \tag{3.38}$$

$$V_{min} \leq V \leq V_{max} \tag{3.39}$$

$$X_{L\,min} \leq X_{FACTC} \leq X_{Lmax} \tag{3.40}$$

$$\mathrm{X_{L\,min} \leq X_{FACTC} \leq X_{Lmax}} \tag{3.41}$$

Both GA and PSO techniques increased the load-ability by 15%1. But in terms of installation cost, using the GA to find out the installation cost is less expensive than using the PSO technique. In terms of compensation, PSO is higher than the GA. They both found three places to allocate FACTS devices. In this case, by increasing the number of FACTS, it can be seen that the installation cost was increased significantly.

In this study, two scenarios have been considered. In the first scenario, three places were allocated for FACTS devices and both the genetic algorithm and the PSO technique were implemented to achieve the solution. After running the program, the genetic algorithm found lines 3, 4 and 5 to place the FACTS devices. The percentages of compensation were 11%, 34% and 16%, respectively, and the minimum installation cost was 0.23661*106. After running the case using PSO technique lines 3, 4 and 8 were found and the percentages of compensation were 22%, 41% and 95%, respectively. The minimum installation cost was 0.29683*106. It can be seen that the installation cost value using PSO was higher than with the genetic algorithm.

By using five optimal places to allocate FACTS devices it can be seen that the system load-ability increased by 22%. The PSO algorithm discovered lines 5, 6, 7, 11 and 13, while the genetic algorithm lines 2, 3, 6, 13 and 20. According to the compensation percentages, line 6 in the genetic algorithm and line 7 in the PSO technique were at the top. The PSO algorithm’s compensation characteristics are higher than those of the GA, but the installation cost using the PSO is higher than that of the GA. Based on convergence characteristics, the PSO algorithm is faster than the GA at the beginning of the optimization; this is because the GA includes steps such as selection, crossover and mutation, while PSO does not have these features. But after a couple of generations it can be seen that the performance of the GA is higher than that of PSO.

In this study, maximizing the system load-ability and minimizing the investment cost of FACTS devices that are installed in the power system were considered. The results achieved from the implementation of the two techniques have high-quality features such as quality solution and convergence characteristics. It can be seen that the efficiency of the system was increased using both optimization techniques.

Lu et al [14] presented the optimal location for FACTS devices with a bacterial swarming algorithm for reactive power planning. In this part, the IEEE-30 and IEEE-118 bus study cases will be analysed. In this case, the bacterial swarming algorithm (BSA) has been deployed in the systems. The results of the simulation show that the performance and power quality of the system were increased. In this case, three algorithms, the BSA, the GA and the PSO technique, were used and compared. The goal of the optimization is to minimize the real power losses and improve the voltage profile.

$$f(x) = F_L + K_V F_V + K_Q F_Q \tag{3.42}$$

There are a few constraints:

$$V_{min} \leq V \leq V_{max} \tag{3.43}$$

$$Q_{min} \leq Q \leq Q_{max} \tag{3.44}$$

$$\delta_{min} \leq \delta \leq \delta_{max} \tag{3.45}$$

$$X_{L\,min} \leq X_{FACTC} \leq X_{Lmax} \tag{3.46}$$

$$T_{i-min} \leq T_i \leq T_{i-max} \tag{3.47}$$

With regard to the IEEE-118 bus study case, the final solution for the power loss in the GA was 320.1823 MW, while in PSO it was 359.6403 MW and in the BSA it was 297.6209 MW. So it can be seen that the BSA was better than both the other techniques.

With regard to the IEEE-30 bus study case, the final solution for the power loss in the GA was 12.0739 MW, while in PSO it was 8.2172 MW and in the BSA it was 6.4989 MW. So it can be seen that the BSA was better than both the other techniques.

In this study case, multiple types of FACTS devices were considered. The best BSA results for the IEEE-30 bus system in terms of allocating different types of FACTS devices were: the TCSC at branch 2-5, the TCPST in branch 4-12, the TCVR in branch 3-4 and the SVC at bus 22. With regard to the IEEE-118 study case, the best BSA solutions in terms of finding the optimal place for different types of FACTS devices were: the TCSC in branch 64-61, the TCPST in branch 9-10, the TCVR in branch 89-92 and the SVC at bus 38. Optimal location, using all three methods, was analysed and it can be seen that the behaviour of the BSA was better than the other techniques. Basically, the BSA is most suitable for discovering multiple types of FACTS devices in large-scale power systems.

Mohammadi et al [15] presented a hybrid particle swarm optimization algorithm for optimal location of an SVC device in power system planning. In this example, the IEEE-68 bus study case is considered for the simulation. In this case, two techniques, the GA and the PSO technique, are deployed to find the optimal place for the FACTS devices.

In this study, one objective function is used that includes two parameters. The first part is related to the voltage profile at the bus-bar and the second part is related to the operation and installation cost. By applying the PSO and the GA technique, the optimal location for FACTS devices was found. By replacing FACTS devices in the system it can be seen that losses decreased.

$$F(x) = w_1 \times V_K + w_2 \times CO \tag{3.48}$$

There are two constraints in this problem:

$$V_{min} \leq V \leq V_{max} \tag{3.49}$$

$$Q_{min} \leq Q \leq Q_{max} \tag{3.50}$$

The goal of the optimization is to find a perfect place to allocate FACTS devices in power networks. After analysing using PSO and the GA it can be seen that both techniques found one place to allocate a FACTS device. In terms of total loss reduction, PSO was higher than the GA.

According to the results, the genetic algorithm found bus 34 to replace the compensator. After allocating FACTS device the total power loss reduction was 0.3559 p.u. The PSO algorithm was run on the system and the algorithm discovered bus 31 to place the FACTS device. After replacing it, it can be seen that the total power loss reduction was 0.4608 p.u. In some cases, researchers combine some algorithms and basically use some of their characteristics and mix these with other techniques.

In this case, a new algorithm was proposed: the PSO-GA algorithm. This combined algorithm was also implemented in the case study and bus 50 was found to allocate the FACTS device. After running the system, the total power loss reduction was 0.8823p.u. By applying this algorithm in the case study the total loss reduction was higher than with the other two techniques. In this case, a different place was found to allocate the FACTS device. This is because of the behaviour of the algorithm while dealing with the optimization problems.

Rashed et al [16] presented evolutionary optimization techniques for optimal location and parameter setting of the TCSC. In this study, the IEEE-14 and IEEE-6 bus study case was considered. In this regard, two evolutionary techniques, the GA and the PSO algorithm, are implemented to find the optimal allocation for FACTS devices in power networks. In this case, both the GA and PSO algorithms found a suitable place to allocate the FACTS devices. In this example, the main objective function was defined in terms of optimal location of FACTS to eliminate and minimize voltage deviation under critical circumstances. The following equations show the objective function and constraints:

$$minimize\ F_t \qquad (3.51)$$

$$V_{min} \leq V \leq V_{max} \qquad (3.52)$$

$$Q_{min} \leq Q \leq Q_{max} \qquad (3.53)$$

$$\delta_{min} \leq \delta \leq \delta_{max} \qquad (3.54)$$

$$-0.5X_L \leq X_{FACTC} \leq 0.5X_L \qquad (3.55)$$

Simulation has been carried out on the IEEE-6 bus and IEEE-14 bus systems. The results achieved show that FACTS can improve sharply the security of a power system by minimizing the overloading of transmission lines and voltage deviation. Both algorithms found the same place to allocate the FACTS devices. The PSO algorithm is much faster than the GA technique and this is because in the GA there are features such as selection, mutation and crossover and the PSO does not have these features.

This study chose the TCSC component because of its flexible control over the impedance of transmission lines so that, it can change its own current reactance according to the power system requirements. Also, this device is faster in terms of response than other switched series compensators. Both the GA and PSO successfully optimized the system with virtually the same quality and performance. These methods have stable characteristics and a high quality of convergence.

Valle et al [17] presented the enhanced particle swarm optimizer for power system application. In this example, the study case is part of the Brazilian power network with 45 bus-bars and 10 machines. The case study has been optimized with the PSO technique and the related results are compared with other techniques such as the BFA and the GA. The results proved that the PSO technique is able to find reasonable and optimal places to allocate FACTS devices with a high speed of convergence.

In this case, there are two objective functions to be considered. The first is to minimize the voltage deviation and the second is to minimize the possible FACTS size. They can be defined as follows:

$$J_1 = \sqrt{\sum_1^N (V_k - 1)^2} \tag{3.56}$$

$$J_2 = 100{,}000 \times \sum_1^M \eta_p \tag{3.57}$$

$$J = w_1 \times J_1 + w_2 \times J_2 \tag{3.58}$$

$$V_{min} \leq V_k \leq V_{max} \tag{3.59}$$

$$0.95 \leq V_k \leq 1.05 \ , \ k: 1 \rightarrow N \tag{3.60}$$

$$Q_{min} \leq Q \leq Q_{max} \tag{3.61}$$

According to the results, the minimum, maximum and average function values and standard deviation value were 0.51745, 0.68390, 0.58791 and 0.04167 using the PSO technique, respectively. On the other hand, the minimum, maximum and average function values and standard deviation value were 0.52441, 0.96422, 0.74765 and 0.09654 using the

BFA, respectively. Overall, the PSO performance after analysing was better than the BFA and GA techniques.

In terms of success ratio, both algorithms achieved a feasible and suitable solution. In the case of global optimality, PSO was able to reach and find a global solution while the BFA was able to find a near optimal solution. In terms of global optimality, PSO was in forward and had a smaller value of the objective function and a much higher accuracy than the BFA.

Sharifzadeh et al [18] demonstrated the optimal reactive power dispatch based on particle swarm optimization considering FACTS devices. In this example, the IEEE-30 bus study case is considered. In this case, the PSO algorithm has been deployed in the system and related results are compared with other techniques such as the GA and differential evolution (DE). Simulation results illustrate the capability of PSO for finding the solution to the problem. In addition, comparing the results from these algorithms proved the greater robustness of the PSO technique over the GA and differential evolution algorithms.

In this case study, there is just one objective function to minimize the real power loss in transmission lines and it can be shown as follows:

$$f = \sum_{k \in N} P_{k_{loss}} \quad (3.62)$$

$$V_{min} \leq V_k \leq V_{max} \quad (3.63)$$

$$Q_{min} \leq Q \leq Q_{max} \quad (3.64)$$

$$X_{L\,min} \leq X_{FACTC} \leq X_{Lmax} \quad (3.65)$$

$$-0.8\, X_L \leq X_{TCSC} \leq 0.2\, X_L \quad (3.66)$$

$$-0.5 \leq X_{SVC} \leq 0.5 \tag{3.67}$$

$$\delta_{min} \leq \delta \leq \delta_{max} \tag{3.68}$$

$$T_{i-min} \leq T_i \leq T_{i-max} \tag{3.69}$$

In this regard, two types of FACTS devices were considered and two different amounts were considered in terms of constraints. In this study, there were no stop condition criteria and the algorithm was run for several times. In this case, after running each algorithm 30 times, it can be seen that the average power loss result from the PSO algorithm is less than from the genetic algorithm and differential evolution technique.

According to the results, the best active power losses using the genetic algorithm, differential evolution and PSO technique were 0.16384, 0.16399 and 0.16364, respectively. With regard to convergence characteristics, PSO performs higher than the other two techniques. It can be seen that using the PSO technique in the system increases the efficiency as well.

Valle et al [19] presented the multiple STATCOM allocation and sizing using particle swarm optimization. In this study, the 45 bus system, which is part of the Brazilian power network, has been considered as a case study. In this case, the PSO technique is implemented in the case study along with considering different power system load conditions. The impact of STATCOM is investigated in terms of size and location.

In this study, there are two objective functions:

$$\mathrm{J_1} = \sqrt{\textstyle\sum_1^{45} (\mathrm{V_i} - 1)^2} \tag{3.70}$$

J1 represents the first objective function, which is voltage deviation.

$$J_2 = \eta_1 + \eta_2 \tag{3.71}$$

η_1 and η_2 are the size of the first and second STATCOM in MVar. The multi-objective optimization is defined as follows:

$$J = w_1 * J_1 + w_2 * J_2 \tag{3.72}$$

A few constraints have been used in this study:

$$1 \le \lambda_1 \le 45 \tag{3.73}$$

$$1 \le \lambda_2 \le 45 \tag{3.74}$$

$$0.95 \le V_i \le 1.05 \tag{3.75}$$

$$0 \le \eta_1 \le 250 \tag{3.76}$$

$$0 \le \eta_2 \le 250 \tag{3.77}$$

Different scenarios are investigated and analysed in this study. Single and multi STATCOM are placed in the power network with different load conditions. In the first scenario, the PSO technique found two solutions, which were buses number 378 and 430 with sizes of 95 MVar and 137 MVar, respectively. Voltage deviation in this case without and with STATCOM was 0.2481 and 0.1753, respectively. Also, the convergence rate was 60%. In the second scenario, the PSO technique was implemented with a multiple number of STATCOM, and after running, the program found three solutions for the problem. Buses number 377 and 432 with sizes of 154 MVar and 144 MVar, buses 378 and 430 with sizes of 95 MVar and 137 MVar, and buses number 378 and 433 with sizes of 150 MVar and 103 MVar were found.

By applying different load conditions after replacing the STATCOM algorithm discovered different numbers. When the load was 90, 95, 100, 105 and 110 per cent, the percentage of improvement was 4.4, 16.2, 29.3, 40.0 and 52.1, respectively. The PSO technique was implemented in this case study as this case study was a medium-sized power network. In the case of a large power network this algorithm will have a strong effect on the system rather than having some complicated calculations.

Kheirizad et al [20] presented a novel algorithm for optimal location of FACTS devices in power system planning. Particle swarm optimization has been used widely in power networks. In this study, the IEEE-68 bus is used for simulation. In this case, two objective functions have been used. The PSO technique and genetic algorithm were used for the simulation process.

$$F = w_1 * V_k + w_2 * CO \qquad (3.78)$$

In this function V_k is the voltage deviation and CO is the cost of installation and operation. Two constraints were used in this study:

$$V_{min} \leq V_k \leq V_{max} \qquad (3.79)$$

$$B_{SVC,min} \leq B_{SVC} \leq B_{SVC,max} \qquad (3.80)$$

After running the genetic algorithm bus number 34 was found as an optimal place with an amount of 1.4654 p.u. The total power loss reduction was 0.3559 p.u. On the other hand, after running the PSO technique on the case study bus number 31 was found with an amount of 1.9754 p.u. The total power loss reduction was 0.4608 p.u. It can be seen that the total power loss reduction using PSO was less than with the genetic algorithm.

Kowsalya et al [21] presented voltage stability enhancement through optimal placement of a UPFC. In this study, researcher implemented in the two study cases: the WCCC-9 bus and IEEE-30 bus system. The researcher identified the new index to improve the overall stability margin of the system by allocating the best position of the UPFC. The voltage stability index for the load bus was given as:

$$L_j = \left|1 - \sum_{i=1}^{g} F_{ij} \frac{V_i}{V_j}\right| \quad (3.81)$$

In this case, the L-index varies between zero and 1. There are two constraint parameters. The voltage series and shunt are controlled in both their magnitude and angle through r and γ. These values follow the limits below:

$$0 \leq r \leq r_{max} \quad (3.82)$$

$$0 \leq \gamma \leq 2\pi \quad (3.83)$$

According to the load flow analysis, the model extracts the weakest bus and carries out by replacing the unified power flow controller at the identified bus-bar to obtain the L-index. In this case, the UPFC injects real and reactive powers into the system with control parameters that they both vary in their limit. The analyses on the WCCC-9 bus indicated that the optimum location of the UPFC will be between buses 9 and 6. From the analyses and results on the IEEE-30 bus system, the optimum place for the UPFC was between buses 25 and 26. Also, bus 26 was the weakest bus according to the L-index.

Jahani Rouzbeh [22] presented the optimal placement for a UPFC in power systems using the imperialist competitive algorithm. The analysis was carried out on the IEEE-14 bus system. In this study, objective function is defined as follows:

$$OF = \prod_{i=line} LF_i + \prod_{j=bus} BF_i \quad (3.84)$$

In this equation, LF is the line flow index and BF is the bus voltage index. Also, voltage level was limited between 0.95 and 1.05 as a constraint. In this study, two scenarios are carried out. The UPFC is allocated as a single component in the first scenario and in the second scenario two UPFCs are used to compensate the power. The best result for one UPFC was found between buses 9 and 4. Also, the best result for using two UPFCs in the system was found between buses 3 and 4, and buses 5 and 6. The level of the voltage was improved by using one UPFC in the network. However, the level of voltage using two UPFCs was satisfactorily flat.

Jayanti et al [23] presented the solution for multiple UPFC placements using the gravitational search algorithm. In this case, the researcher presented a heuristic method based on the gravitational search algorithm to allocate the UPFC in the optimal place bearing in mind generation cost and power system losses. The objective functions are defined below:

$$\sum_{i=1}^{N_G} C_i(P_{Gi}) = \sum_{i=1}^{N_G}(a_i + b_i P_{Gi} + c_i {P^2}_{Gi}) \tag{3.85}$$

$$P_L = \sum_t (real(yline_t)(V_{kt}^2 + V_{mt}^2)) - \left(V_{kt}V_{mt}abs(yline_t)\cos\left(\delta_{kt} - \delta_{mt} - \delta(yline_m)\right)\right) - (V_{mt}V_{kt}abs(yline_t)\cos(\delta_{mt} - \delta_{kt} - \delta(yline_m))) \tag{3.86}$$

The constraints in this study are listed below:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \tag{3.87}$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \tag{3.88}$$

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{3.89}$$

The UPFC constraints are:

$$V_{se,min} \leq V_{se} \leq V_{se,max} \tag{3.90}$$

$$V_{sh,min} \leq V_{sh} \leq V_{sh,max} \quad (3.91)$$

$$0 \leq \theta_{sh} \leq 2\pi \quad (3.92)$$

$$0 \leq \theta_{se} \leq 2\pi \quad (3.93)$$

$$P_{mk} \leq P_{mk,max} \quad (3.94)$$

Three case studies, the IEEE-14 bus, IEEE-30 bus and IEEE-57 bus, were used to demonstrate the results. In this study, cost and loss minimizations are deployed with single and three UPFCs. Regarding to IEEE-14 bus, IEEE-30 bus and IEEE-57 bus algorithm found optimal place of 10-11, 21-22, 27-28, respectively. The level of voltage was also improved. The number of iterations needed for the optimum solution were 13, 11 and 11, respectively. There was a comparison between other algorithms such as the BBO, GA, ACO and PBIL. Computational time in terms of seconds needed to allocate an optimal place was faster than with other algorithms.

Bhattacharyya et al [24] presented UPFC as a series and shunt FACTS controller for the economic operation of a power system. In this study, the genetic algorithm is applied to minimize transmission losses. The proposed technique is applied to the IEEE-30 bus system for the optimal setting of FACTS devices. Cost functions for the TCSC, SVC and UPFC are shown below:

$$CF(TCSC) = 0.0015(TCSC_{value})^2 - 0.7130(TCSC_{value}) + 153.75(\frac{US\$}{kVar}) \quad (3.95)$$

$$CF(SVC) = 0.0003(SVC_{value})^2 - 0.3051(SVC_{value}) + 127.38(\frac{US\$}{kVar}) \quad (3.96)$$

$$CF(UPFC) = 0.0003(UPFC_{value})^2 - 0.2691(UPFC_{value}) + 188.22(\frac{US\$}{kVar}) \quad (3.97)$$

So, the objective function can be described as follow:

$$C_{TotalCost} = C_{Energy} + C_{FACTS} \quad (3.98)$$

In this case, C_{Energy} is the cost due to the energy loss component and C_{FACTS} is the investment cost of the FACTS devices. There are constraints, which are shown below:

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (3.99)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad (3.100)$$

$$V_{i}^{min} \leq V_{i} \leq V_{i}^{max} \quad (3.101)$$

After running the program the algorithm allocated the TCSC between buses 28 and 20, the SVC at buses 17 and 21, and the UPFC between buses 4 and 3. Two case studies are considered for the optimal location and types of FACTS devices. In the first scenario, TCSC such a series controller and SVC such a shun controller are used with power system variables to obtain economic operation of the power system. In the second scenario, the UPFC are used with the series and shunt FACTS components to minimize active power losses and system operation cost. It can be seen that using the UPFC with a series and shunt device generated a better result than without the UPFC. Operating cost and also active power losses were reduced sharply by allocating the UPFC.

Ramesh et al [25] presented loss reduction through optimal placement of a unified power flow controller using the firefly algorithm. The aim of this study is to decrease the power losses and enhance voltage profile in power networks optimally. To demonstrate the validity of the proposed technique, analyses were carried out on the IEEE-14 and IEEE-30 bus systems. Also, simulation was implemented in normal and 150% of loading conditions. The voltage stability index is defined below:

$$L_j = \left|1 - \sum_{i=1}^{g} F_{ij} \frac{|V_i|}{|V_j|}\right| \quad (3.102)$$

Voltage and Q are limited as follows:

$$V_{min} \leq V \leq V_{max} \quad (3.103)$$

$$Q_{min} \leq Q \leq Q_{max} \quad (3.104)$$

After running the program on the IEEE-14 bus system, the algorithm detected buses 9, 10 and 14 as weak buses and then replaced the UPFC in these buses. Basically, the UPFC was replaced between buses 9 and 14 in normal loading and 150% of loading conditions. This method was also run using the genetic algorithm and the results were compared. In terms of system losses, both algorithms arrived at the same solution in terms of normal loading. The firefly algorithm was slightly better in terms of the 150% loading condition. The voltage profile level was also slightly better than with the genetic algorithm and all were almost 1.00 p.u. After running the program on the IEEE-30 bus system, the algorithm allocated the UPFC between buses 27 and 30. Again, system loss reduction using the firefly algorithm was slightly better than with the genetic algorithm. The voltage profile level after replacing the UPFC in the network was improved and the firefly algorithm was better than the genetic algorithm in this respect.

Nwohu et al [26] presented the optimal location for a unified power flow controller in the Nigerian grid system. In this study, the optimal place for a UPFC was found based on the sensitivity of the total active power loss in terms of UPFC control variable parameters. The total active power loss was as follows:

$$P_{loss}(\theta, V) = \sum_{m=1}^{n} V_m \sum_{k=1}^{n} V_k G_{mk} cos\theta_{mk} \quad (3.105)$$

To allocate the UPFC in the optimal place, active power loss sensitivity analysis must be performed. This index is calculated for each line and the highest loss sensitivity index is selected to allocate the UPFC device. In this case, the UPFC was allocated between buses 13 and 14. The active and reactive power in the network became stable after replacing the UPFC device.

Sreerama et al [27] presented the optimal placement for a unified power flow controller to minimize power transmission line losses. In this study, the genetic algorithm was used to discover the solution and the 5-bus standard test system was chosen as a case study. Load flow analysis with the connection of the UPFC model was used to calculate the fitness function of each individual in the first population. In this case, the fitness function was defined as follows:

$$F_n = 1.0/(1 + P_{Loss}) \qquad (3.106)$$

and P_{Loss} is the total transmission line losses and can be defined as:

$$P_{Loss} = \sum_{M=1}^{NB} G_{KM}\{V_K^2 + V_M^2 - 2V_K V_M Cos(\partial_{KM}) \quad for\ K = 1,2,\dots,NB \qquad (3.107)$$

After running the program, the algorithm allocated UPFC between buses 5 and 4. It can be seen that line losses after replacing the UPFC decreased.

Verma et al [28] presented the location of a unified power flow controller for congestion management. In this study, two objective functions have been considered and the results are compared after analysing the problem. The two objective functions that are used in this study are: total system loss sensitivity indices and real power flow performance index sensitivity indices:

$$P_{LT} = P'_{LT} - \left(P_{is} + P_{js}\right) \qquad (3.108)$$

$$PI = \sum_{m=1}^{Nl} \frac{w_m}{2n} (\frac{P_{lm}}{P_{lm}^{max}})^{2n} \quad (3.109)$$

Three case studies, the 5-bus system, the IEEE-14 bus system and the 75-bus Indian system, are considered. With regard to the 5-bus system, the results show that the placement of the UPFC is at line 2. In terms of the IEEE-14 bus system, the results show that the UPFC is suitable between lines 1 and 8. With regard to the Indian 75-bus system, results show that the UPFC is suitable between lines 31 and 32.

Arabkhaburi et al [29] presented the optimal placement of a UPFC in power systems using the genetic algorithm. The IEEE-14 bus system was used to demonstrate the results. The results showed that power efficiency can be enhanced by optimal location and parameters of the UPFC. The objective function was defined as follows:

$$Objective\ Function = \prod_{i=line} LF_i + \prod_{j=bus} BF_j \quad (3.110)$$

$$0.95 \leq V \leq 1.05 \quad (3.111)$$

LF is the line flow index and BF is the voltage index. In this study, five cases were considered in terms of different circumstances. In case 1, load was increased at some buses on the network. After running the program and analysing the network, the genetic algorithm proposed that it is essential to place one UPFC at line 9. In case 2, active load was increased at all buses. The genetic algorithm proposed two UPFCs at lines 9 and 16 as one UPFC is not able to restore the system to a secure condition. In case 3, reactive load was increased at all the buses. In this case, only voltage was dropped at bus-bars and transmission lines were not overloaded. In this case, an SVC and STATCOM were proposed instead of using the UPFC. Finally, the genetic algorithm proposed a UPFC for reactive power flow controlling. So, two UPFCs were used at lines 3 and 8. In case 4, active and reactive loads were increased. The genetic algorithm proposed two UPFCs at lines 6 and 8. In case 5, active and reactive and load generation were increased at the same time. In this case, using two UPFCs cannot restore system stability and another UPFC needs to be used at line 14. But using three UPFCs is not economical in this small network and it is better to use one SVC or STATCOM at line 14 and two UPFCs at lines 6 and 16.

Asadzadeh et al [30] presented the allocation of a UPFC in the north-west grid of Iran to increase power system security. In this study, the allocation of a UPFC in the Azerbaijan transmission network was implemented. In this regard, the optimal placement of the UPFC was based on sensitivity analysis to enhance the load-ability of the system and improve the voltage profile that was provided. The loading and voltage security index of transmission lines in this study are indicated in the formulae below:

$$J_P = \sum_i \frac{w_i}{2n}\left(\frac{P_i}{P_i^{max}}\right)^{2n} \quad (3.112)$$

$$J_V = \sum_m b_m \left(V_m - V_m^{ref}\right)^2 \quad (3.113)$$

As the above power network was divided into three zones, each zone was allocated a UPFC in the optimal place with the proposed size. It can be seen that total power losses decreased and system security was enhanced.

Sarkar M [31] presented the effect of UPFC allocation on transmission system power loss. In this study, the IEEE-30 bus system is used. The allocation of a UPFC was performed to minimize power losses in transmission lines. Three optimal places were found. So, a UPFC was allocated between buses 6-7, 10-17 and 29-30. It can be seen that the voltage profile level was improved and the transmission loss decreased.

Beykverdi et al [32] presented the optimal location and parameter setting for a UPFC device in the transmission system based on the imperialist competitive algorithm. In this study, the IEEE-14 bus system was deployed to show the validity of the method. In this case, the fitness function was based on indices such as optimizing with overloaded lines and bus voltage violation.

$$F_t(X,U) = \sum_{i=1}^{No.of\ Lines} L(OL) + \sum_{j=1}^{No.of\ Buses} V(BV) \tag{3.114}$$

$$S \leq S_{max} \tag{3.115}$$

$$0.95 \leq V_i \leq 1.05 \tag{3.116}$$

After running the program, the algorithm allocated the UPFC between buses 7 and 9. After replacing the FACTS device, the level of voltage was improved. The active and reactive power flows were improved in transmission lines.

Othman et al [33] presented real-world optimal UPFC placement and its impact on reliability. The UPFC is able to control active and reactive power and voltage profile at its terminals. In this study, a real-world 110 KV sub-transmission network was proposed as a case study. The genetic algorithm was deployed to show the validity of the work. Fitness function was defined as follows:

$$F_t(X,U) = \sum_{i=1}^{No.of\ Lines} L(OL) + \sum_{j=1}^{No.of\ Buses} V(BV) \tag{3.117}$$

$$0.95 \leq V_i \leq 1.05 \tag{3.118}$$

$$S \leq S_{max} \tag{3.119}$$

In this study, the load for each bus at the same time increased by 115% and 118%. The optimal locations for the UPFC were lines 6-4 and 11-3, respectively. It can be seen that after allocating the UPFC, no overloading and no voltage violation occurred and also the load-ability of the network increased.

Laifa et al [34] presented the optimal placement and parameter setting for a UPFC device using a perturbed particle swarm optimization. In this study, line overload and bus voltage limit violations as a performance index are considered. The IEEE-14 bus system was used as a case study. The objective function below demonstrates the active and reactive power flow control setting with minimum overloading and voltage security level.

$$PI = \sum_{l=1}^{nl} w_l \left(\frac{S_l}{S_{l\,max}}\right)^2 + \sum_{i=1}^{nb} w_V \left(\frac{V_i - V_{iref}}{V_{iref}}\right)^2 \qquad (3.120)$$

Constraints were defined as follows:

$$0 \le V_{se} \le V_{se\,max} \qquad (3.121)$$

$$-I_{q\,min} \le I_q \le I_{q\,max} \qquad (3.122)$$

$$Q_{g\,min} \le Q_g \le Q_{g\,max} \qquad (3.123)$$

$$V_{i\,min} \le V_i \le V_{i\,max} \qquad (3.124)$$

$$S_l \le S_{l\,max} \qquad (3.125)$$

After running the program, the algorithm allocated the UPFC between lines 2 and 3. After installing the UPFC, the voltage profile was improved.

Izadpanah Tous et al [35] presented the optimal placement of the UPFC for voltage drop compensation. In this study, the UPFC was allocated based on the voltage drop sensitivity with respect to the increase in network loads. The IEEE-14 bus system was used to show the validity of the work. The voltage drop index can be defined as:

$$TVDI_i = \sum_{j=1}^{m} VDI_{i,j} \quad i = 1, \dots, n \ \ and \ j = 1, \dots, m \qquad (3.126)$$

After running the program, the algorithm allocated the UPFC between buses 9 and 10. The voltage profile level was improved.

Kumar et al [36] presented the improvement in the voltage profile in power system networks with the SVC and UPFC by using the optimal genetic algorithm. The IEEE-30 bus system was used to demonstrate the results. In this case, the voltage stability index was defined as follows:

$$L_i = \left|1 - \sum_{i=1}^{g} \frac{V_i}{V_j} F\, Fij\right| \quad (3.127)$$

After running the program, the algorithm allocated the SVC and UPFC at buses 18 and 3-4, respectively. After allocating the devices, the voltage profile was improved in the system.

Rezaee et al [37] presented the optimal location for the UPFC in the Esfahan-Khuzestan network using APSO to increase the stability. In this study, during the allocation of the UPFC, voltage limitation, load-ability, losses and installation cost were considered. DIgSILENT was used to demonstrate the simulation as well. In this case, objective function was defined as follows:

$$Min\ \rho_1 \sum_{i=1}^{n} \left(\frac{|V_i - V_{ispes}|}{V_{imax}}\right)^2 + \rho_2 \sum_l loss_l + \rho_3 \sum_l \left(\frac{S_l - S_{lspec}}{S_{lmax}}\right)^2 + \rho_4 cost_{upfc} \quad (3.128)$$

After running the program, the UPFC was allocated between buses 15 and 57. The voltage profile was improved significantly. It will protect power systems from disturbances and overloading and will increase the security of the system.

Singh et al [38] presented the location of the UPFC to enhance power system load-ability. The IEEE-14 bus system was used to show the validity of the work. In this study, the maximum load-ability was gained by solving the equation below:

$$Max\ \lambda \tag{3.129}$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \tag{3.130}$$

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{3.131}$$

$$\delta_i^{min} \leq \delta_i \leq \delta_i^{max} \tag{3.132}$$

$$0 \leq V_T \leq V_{T,max} \tag{3.133}$$

$$0 \leq \emptyset_T \leq 2\pi \tag{3.134}$$

$$I_q^{min} \leq I_q \leq I_q^{max} \tag{3.135}$$

After running the program, the algorithm allocated the UPFC between buses 8 and 9. In this case, the system load-ability was increased and the voltage profile was enhanced.

Reddy et al [39] presented an approach for optimal placement of the UPFC to enhance the voltage stability margin under contingencies. In this study, the 75-bus Indian network was used to show the validity of the work. To discover the solution, the sensitivity factor is used from the reactive power flow balance equation. After running the program, the UPFC was allocated between buses 29 and 38. In this case, the maximum enhancement was achieved in terms of the voltage stability margin.

Singh et al [40] presented the enhancement of power system security through optimal placement of a TCSC and UPFC. To allocate a UPFC in the optimal place, sensitivity indices were used such as sensitivity of the transmission lines taking into consideration the FACTS device parameters. In this study, the IEEE-30 bus system and Indian-246 bus system were used to demonstrate the validity of the work. Objective function and constraints were defined as follows:

$$PI = \sum_{m=1}^{Nl} \frac{w_m}{2n} (\frac{P_{lm}}{P_{lm}^{max}})^{2n} \tag{3.136}$$

$$X_{min} \leq X_{comp} \leq X_{max} \tag{3.137}$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \tag{3.138}$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \tag{3.139}$$

$$V_{i}^{min} \leq V_{i} \leq V_{i}^{max} \tag{3.140}$$

$$\delta_{i}^{min} \leq \delta_{i} \leq \delta_{i}^{max} \tag{3.141}$$

The PI sensitivity factors were obtained with respect to UPFC parameters. After optimal allocation of the TCSC and UPFC, system security was enhanced in case of line outage. The voltage profile level was improved.

Kumar et al [41] presented transmission loss allocation and loss minimization by incorporating a UPFC in LFA. In this study, the UPFC was implemented in the 5-bus, IEEE-14 bus and IEEE-30 bus systems. The bus loss allocation method follows the equation below:

$$P_{loss} = \sum_{k=1}^{n} L_k \tag{3.142}$$

$$L_k = R\left[L_k^*\left(\sum_{j=1}^{nb} R_{kj}.I_j\right)\right] \tag{3.143}$$

In this study, the UPFC was allocated in three places in all case studies. After allocating this device, total power losses were decreased and the voltage profile level was improved.

Kumar et al [42] presented a comparative analysis of the UPFC as a power flow controller with applications. In this case, different aspects were discussed and then the advantages of the UPFC over other compensators were demonstrated. Those aspects included dynamic voltage control, load-ability and financial cost and benefits.

Bhowmik et al [43] presented implementation of a UPFC for power quality improvement in the IEEE-14 bus system. In this study, active and reactive power flow has been analysed with and without using a UPFC in the network. After running the program, the UPFC was located between buses 1-2 and 4-7. After allocating the UPFC, active and reactive power flow improved in the network and the load-ability of the system was enhanced.

Chandrakar et al [44] presented the improving power quality in transmission systems using a UPFC. In this study, a UPFC was allocated on transmission lines to demonstrate the effectiveness of the active and reactive power through the lines. It can be found that the UPFC has got advantages such as reducing maintenance and the ability to control real and reactive power at the same time.

Gopinath et al [45] presented the UPFC for dynamic stability in power systems using modern control techniques. To show the validity of the work, simulation was carried out on five bus test systems. After running the program, both active and reactive power flows through each bus were analysed and active and reactive power were improved.

Bindal R.K [46] presented a review of the benefits of FACTS devices in power systems. In this study, different FACTS devices are reviewed in terms of voltage and active and reactive control in power networks. It can be found from the study that the UPFC has more characteristics and usage in terms of load flow and voltage control and transient and dynamic stability. Various FACTS devices are used depending on their installation and condition in power systems.

Bhowmik et al [47] discussed placement of a UPFC for minimizing active power loss and total cost function using the PSO algorithm. In this study, three objective functions were used and implemented in the IEEE-14 bus system. Objective functions are shown below:

$$Minimize\ U(x) \tag{3.144}$$

$$Minimize\ C(t) = C_1(f) + C_2(P_g) \tag{3.145}$$

$$X_{UPFC\,min} \leq X_{UPFC} \leq X_{UPFC\,max} \tag{3.146}$$

$$\delta_i^{min} \leq \delta_i \leq \delta_i^{max} \tag{3.147}$$

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{3.148}$$

After running the program, the algorithm allocated the UPFC in three places between buses 4-9, 13-6 and 4-3. In this case, system losses were reduced and the voltage profile in the bus bars was improved.

Kalyani et al [48] presented the optimal placement and control of UPFC devices using evolutionary computing and sequential quadratic programming. The simulation was carried out on the IEEE-118 bus system to demonstrate the validity of the work. The algorithm placed the UPFC in three places: buses 5-8, 26-30 and 23-32. After placement it can be seen that the load-ability of the system and the voltage profile were enhanced.

Jafarzadeh et al [49] presented the optimal placement of FACTS devices based on network security. The IEEE-30 bus system was used in this study. Objective function is shown below:

$$VI_{sys} = VI_{bus} + VI_{line} + VI_{gen} \tag{3.149}$$

Three types of FACTS devices were used in this case. After running the program, the TCSC was placed between line 7 and 6, the UPFC was placed between line 22 and 21 and the SVC was placed at bus 5. In this case, the system load-ability and voltage profile were improved and losses were reduced.

Singh et al [50] presented the enhancement of power system security through optimal placement of the TCSC and UPFC. The IEEE-30 bus system was used to demonstrate the validity of the work. In this study, the sensitivity index was used to find the solution. The real power flow performance index is shown below:

$$PI = \sum_{m=1}^{Nl} \frac{w_m}{2n} (\frac{P_{lm}}{P_{lm}^{max}})^{2n} \tag{3.150}$$

After running the program, the algorithm allocated the UPFC between lines 1 and 2. It can be seen from the results that the voltage profile was improved and losses were decreased.

Shaheen et al [51] presented the optimal location and parameter setting for a UPFC based on the GA and PSO to enhance power system security under single contingencies. In this study, the IEEE-6 and 14-bus systems were used. The objective function that was used in this study is shown below:

$$F_t = \sum_{l=1}^{ntl} w_l \left(\frac{S_l}{S_{l\,max}}\right)^{2q} + \sum_{m=1}^{nb} w_m \left(\frac{V_{m\,ref} - V_m}{V_{m\,ref}}\right)^{2r} \tag{3.151}$$

After running the program, the GA and PSO found three places to allocate a UPFC in the networks. After allocation of the UPFCs, the voltage profile was improved. The load-ability of the system also improved.

Wartana et al [52] presented the optimal placement for a UPFC to minimize system load-ability and active power losses in system stability margins by NSGA-II. In this study, simulation was implemented in the IEEE-30 bus system. In this study, a fast voltage stability index and line stability factor were used. Objective function was defined as follows:

$$F(x,u) = [F_1(x,u), F_2(x,u)] \tag{3.152}$$

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \tag{3.153}$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \tag{3.154}$$

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{3.155}$$

$$-0.9 \leq \delta_i \leq 0.9 \tag{3.156}$$

$$v_S^{min} \leq v_S \leq v_S^{max} \tag{3.157}$$

$$i_{SH}^{min} \leq i_{SH} \leq i_{SH}^{max} \tag{3.158}$$

$$1 \leq \lambda_f \leq \lambda_f^{max} \tag{3.159}$$

After running the program, the algorithm found line 6 and 4 to allocate the UPFC. The voltage profile and load-ability of the network were improved and total losses were decreased.

Ghahremani et al [53] presented the optimal placement of multiple types of FACTS devices to maximise power system load-ability using a generic graphical user interface. In this study, the IEEE-300 bus system was used as a case study to demonstrate the simulation and validity of the work. Objective function was defined as follows:

$$J = Max\{\lambda\} \tag{3.160}$$

$$|\Delta V_{bi}| \leq 0.05 \tag{3.161}$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \tag{3.162}$$

After running the program and analysing single and multiple types of FACTS devices it was found that the load-ability of the system had increased and there was no overloaded transmission line in the network.

Gupta et al [54] presented the optimal placement of FACTS devices for voltage stability using line indicators. In this study, the IEEE-14 bus system was used as a case study. In this case, the solution was found by calculating voltage and stability indices. After running the program, three places were found for allocating the FACTS devices. It was found that the load-ability of the system was enhanced. The voltage profile level was improved at the bus-bars.

Gupta et al [55] presented static and transient power system stability by optimally placing a UPFC. The IEEE-14 bus system was used in this study to demonstrate the simulation and validity of the work. In this study, the line stability index was defined as follows:

$$L = 4\left[Vi^2\left(P_{(i+1)}r_i + Q_{(i+1)}x_i\right) + \left(P_{(i+1)}x_i + Q_{(i+1)}r_i\right)^2\right]/Vi^4 \qquad (3.163)$$

After running the programme, UPFC was allocated between buses 13 and 14, 11 and 10, 6 and12. In this case, the load-ability of the system was increased and the voltage profile was improved.

Christa et al [56] presented the application of particle swarm optimization for optimal placement of the UPFC in electrical systems with line outages. The aim of this study is to increase the load-ability of the system and improve the voltage profile. The IEEE-30 bus system was used in this case to demonstrate the simulation and validity of the work. The objective function is given below:

$$Minimize\ f = \prod_{line} Ovl_{line} + \prod_{bus} Vt_{bus} \qquad (3.164)$$

$$0.9 \leq V_b \leq 1.1 \tag{3.165}$$

In this study, two case studies were considered. Outage of line between buses 14 and 15 and also buses 10 and 21 were analysed. In both cases, a UPFC was allocated in the optimal place and compensated the power and enhanced the load-ability in the network.

Sadek et al [57] presented the effect of load presentation on the performance and optimal placement of a UPFC. This study carried out an estimation of the UPFC control variables to obtain the optimal operation condition and load flow where the UPFC was connected. In this case, total losses were decreased. In this case also, after allocation the voltage profile was improved.

In this chapter, 52 case studies have been investigated and different types of objective function with constraints applied to the systems. All the algorithms have different characteristics and features in terms of fitness and convergence characteristics. Some of them are usually used in power systems and some of the techniques are rarely used in terms of optimization.

However, nowadays it can be seen that some researchers combine the techniques and create a new algorithm with a combination of some other algorithm features to minimize the solution. After analysing those case studies it can be seen that there are advantages and disadvantages in the algorithms in terms of convergence, performance, solution and computation of the problems. The advantages and disadvantages of the algorithms that are used in the case studies are outlined below.

3.1. Genetic Algorithm

The genetic algorithm is the most widely known algorithm and is used in many areas including power systems. This algorithm is able to solve any optimization problems based on chromosomes encoding. The genetic algorithm improves the efficiency of the distribution networks, optimizes reactive power and evaluates system losses. This algorithm gives a high quality of convergence value. It is also able to solve problems with multiple solutions. It is user-friendly and easy to understand.

On the other hand, computational time of the process is more than differential evolution techniques. It has got high cost function. Also, it does not have good characteristics in terms of searching globally for solutions. In some cases, cost function value is more than PSO technique.

3.2. Particle Swarm Optimization

This algorithm uses fewer functions. It is a common technique that is used in power systems as load flow optimization. It has better characteristics in terms of convergence than other techniques. It is convenient to use in power networks for load balancing and economic dispatch. It has got good behaviour in multi-objective functions. Also, total loss calculation value is mostly less than other techniques. On the other hand, it is weak in terms of local search ability. Also, after convergence it is not able to enhance the accuracy of the answer.

3.3. Bees Algorithm

In some cases, cost function is better than other techniques. It is good in terms of solving combinatorial optimization. In the case of complex problems it has high performance characteristics than other techniques. It outperforms than GA in terms of objective function. Its high speed of convergence is one of the advantages of this algorithm. Also, it does not have required to have global search in the problem. This algorithm uses less iteration than the GA. On the other hand, cost function is higher than with other techniques. Also, it has got less accuracy in case of discovering optimal value.

3.4. Imperialist Competitive Algorithm

This algorithm enhances the efficiency in power networks and reduces the losses. It has high quality solutions and fewer functions than the GA. It has got higher speed of convergence than other techniques. Its optimal ability in comparison with other optimization methods in terms of solving problems is another feature. Also, it is a new optimization algorithm and there is a chance that it could be improved in the future to give better answers.

On the other hand, it does not have good characteristics in terms of searching globally for solutions. Sometimes the algorithm freezes; this is because of changing colonies and empires in a closed loop. Quick convergence in some cases is one of the other disadvantages of this algorithm.

Chapter 4

Imperialist Competitive Algorithm

4. Imperialist Competitive Algorithm

4.1. Optimization Overview

Optimization is extremely important in engineering and science branches. For instance, physicists, chemists and engineers are interested in applying optimum processes in planning while reducing cost and maximizing efficiency. Also, researchers and economists use optimization for optimum placing of sources in society and industries. Basically, the aim of optimization is to improve progress. During optimization, initial condition is processed with different methods and extracted data is used for improving the plan or idea. Optimization is a mathematical tool for finding a solution for many of the problems. Indeed, an optimization algorithm looks for a better solution. Obtaining the best answer and solution depends on the definition of the parameters and percentage of tolerance in the problem. So, the manner of formulation is directly relevant to finding the best answer. Some problems have obvious answers, such as: the best athlete, the longest day of the year, etc., which can be assumed to be simple equations. On the other hand, in some problems there are maximum and minimum answers, which known as optimum or extremum. The best portrait, music and view are examples of this. In optimization, changing the inputs and characteristics of a process is done by mathematical or experimental tools to obtain the best output or answer [76]. Fig 4.1 illustrates this process;

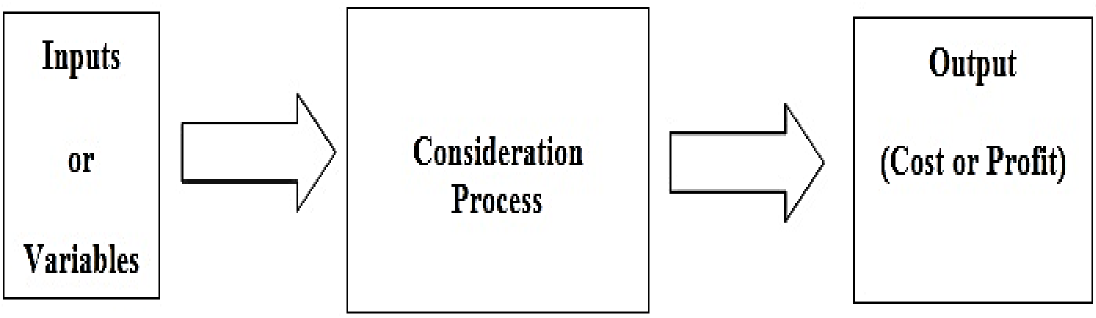


Figure 4. 1 Optimization process

Inputs or process variables are a function of a problem that is known: objective function, cost function, fitness function and performance function. And output is defined as profit or cost. It can be seen that optimization problems can be defined as minimization problems. Sometimes an optimization problem is called mathematical programming. An optimization problem in terms of mathematical programming can be defined as follows:

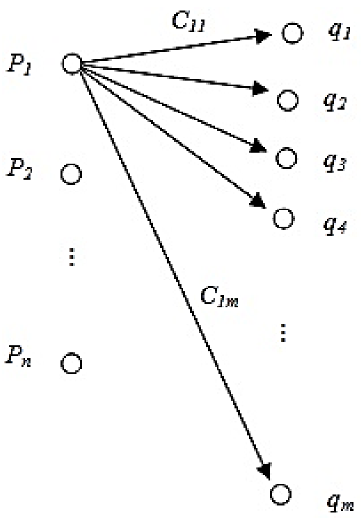
$$minimize\ f\ (x) \tag{4.1}$$

$$subject\ to\ g_i(x) \leq b_i\ , i = 1, 2, \dots, m$$

where in the above equation $x = (x_1, x_2, \dots, x_n) \in \mathbb{R}^n$ is the main variable of the problem. Objective function can be defined as $f : \mathbb{R}^n \to \mathbb{R}$ and it is a real amount. Some functions are defined such as $g_i : \mathbb{R}^n \to \mathbb{R}$ in which constraints are expressed. The right part of Equation (4.1), $(b_i\ )$ is the limitations.

There are many methods for solving linear optimization problems, which are used mostly in sciences. One of the most famous ones in the case of linear optimization is the transportation problem. In this problem there are *n* units of generation such as P_1, P_2, …, P_n. and *n* units of consumption such as q_1, q_2, …, q_n for which all the required data should be provided. In this case, it is assumed that the cost of transportation of goods from unit *i* to unit *j* is equal to C_{ij}. In this case, *i* and *j* represent generation and consumption, respectively.

To achieve the minimum cost of transportation, how much should each of the generators provide of the consumption requirements? Fig. 4.2 indicates the transportation problem [76].



$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \cdots & C_{1m} \\ C_{21} & C_{22} & C_{23} & C_{24} \cdots & C_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_{n1} & C_{n2} & C_{n3} & C_{n4} \cdots & C_{nm} \end{bmatrix}_{n \times m}$$

Figure 4. 2 Transportation problem

4.2. Types of Optimization Problems

From a different view, optimization problems can be divided into different categories. Some of the characteristics of optimization are expressed below.

4.2.1. Trial and Error Optimization

Trial and error is the phenomenon whereby input variables are changed and specific data regarding the effect of each variable parameter on output are not available. For instance, adjusting a TV antenna is a kind of optimization using trial and error, and even a professional engineer is not able to estimate the movement of an antenna in different directions.

Most human innovations and discoveries are the result of trial and error optimization: for instance, the discovery of penicillin as an antibiotic [77]. However, there are other types of optimization where the parameters are clear that can be implemented using a mathematical method.

4.2.2. Single- and Multiple-Dimension Optimizations

If there is only one variable in a problem it is called single-dimension optimization, but if there is more than one variable in a problem it is called multiple-dimension optimization [78].

4.2.3. Dynamic and Static Optimizations

If one problem which optimisation is processed on it, be function of time and change during the passing time which is called dynamic optimisation. On the other hand, if the problem is independent of the time during the optimization it is called static optimization.

For instance, finding the best route to drive in a city to reach the destination is an example of static optimization. In this case, this can be done by using a map to find the best route. But this is not easy in practice and other parameters should be considered. Traffic varies between day and night time, and the best route can change at different times [79].

4.2.4. Discrete and Continuous Optimization

If the concept of an optimization problem is continuous, it is called continuous. On the other hand, if the selected parameters of a problem variable are limited it is called discrete. One of the most important problems in discrete optimization is permutation problems.

The aim of solving this kind of problem is to select a parameter from among of group of selections [80].

4.2.5. Constrained and Unconstrained Optimization

In some optimizations, variables cannot have any values and they should be matched with a group of restrictions until they generate the preferred output. This condition is called restriction and restricted problems are called constraints. If there are no limitations in the problem, it is called unconstrained.

4.2.6. Minimum-Seeking and Random Optimization

Some of the methods start with a specific point in the search area and are based on mathematical formula, which is in algebra and geometry, they generate better results. These algorithms are very quick in terms of convergence. But they stop at minimum and maximum local answers. In these methods, next generated answers based on the present answers have direct process. On the other hand, random methods use probability algorithms to achieve better solutions so in this case operating the algorithm is not easy. The speed of convergence in these algorithms is less than in others. But they have an advantage in that they can search globally. So, they will have a better chance of converging to the optimum answer [81].

4.2.7. Optimization Outline

Optimization methods are generally divided into two categories: local optimization and global optimization. In the case of global optimization, an evolutionary method is used. These algorithms include the genetic algorithm (GA), particle swarm optimization (PSO) etc. The genetic algorithm is the most common algorithm and has got a special place in optimization and systems. Some of this algorithm has been taken from nature and the simulation is based on computer computation. However, in recent years an algorithm has been implemented in human social evolution.

Basically, many optimization algorithms are based on natural processes. But the social and historical evolution of humans, which is one of the most successful, has not been considered. This process can be defined as an algorithm that can be faster than other optimization algorithms.

This type of algorithm takes into consideration some aspects of human social-politics, and by converting this process into a mathematical equation can optimize different problems. This algorithm is also used for designing controllers for industrial systems, designing intelligent systems, and finding solutions for management problems and power systems and networks.

4.3. Imperialist Competitive Algorithm Background

Imperialism means politics in the sense of the power and influence of one country outside of its authority. This can be done in indirect ways, such as through the control of goods, language and culture. Imperialism has existed in history for ages and initially it was a sort of political-military because of its grabbing nature and human sources. In some cases, it was because of opponents. In any case, imperialists faced hard competition to grab colonies.

This can be done by implementing culture and language in those counties. For example, the UK and France have many colonies and in these countries the English and French languages are used instead of the countries' own language. Imperialist always try to grab countries in different ways.

4.3.1. Imperialist Competitive Algorithm

In this part, this study is going to explain the steps and approaches of the imperialist competitive algorithm. Basically, this algorithm starts with several countries that can provide answers problems. These countries are the same as chromosomes in the genetic algorithm and particles in particle swarm optimization. All these countries are divided into two groups: imperialist and colony.

The basis of this algorithm includes assimilation, imperialistic competition and revolution [82]. This algorithm initially starts with an initial random answer, which in this case is called *country*.

Some of these countries are selected in terms of lower cost function and other mainly positive parameters. This group is called imperialist and the remaining countries are called colonies. Imperialists will grab colonies according to their power. The total power of imperialists depends on two factors: imperialist as a core and the number of its colonies.

After initialization, the imperialist competition will begin. In this case, if one imperialist cannot succeed in the competition or increase its own power, it will be eliminated automatically from the competition. So in this situation each empire will not collapse unless it grabs more colonies.

So in this process, some empires will grow and become stronger and some will collapse and be eliminated from the competition. Empires will also be developed and increase the number of colonies.

After a time only one empire will remain and all other colonies will join the last empire, and in this case it can be seen that there is a kind of convergence. Fig. 4.3 presents a flow chart of the imperialist competitive algorithm.

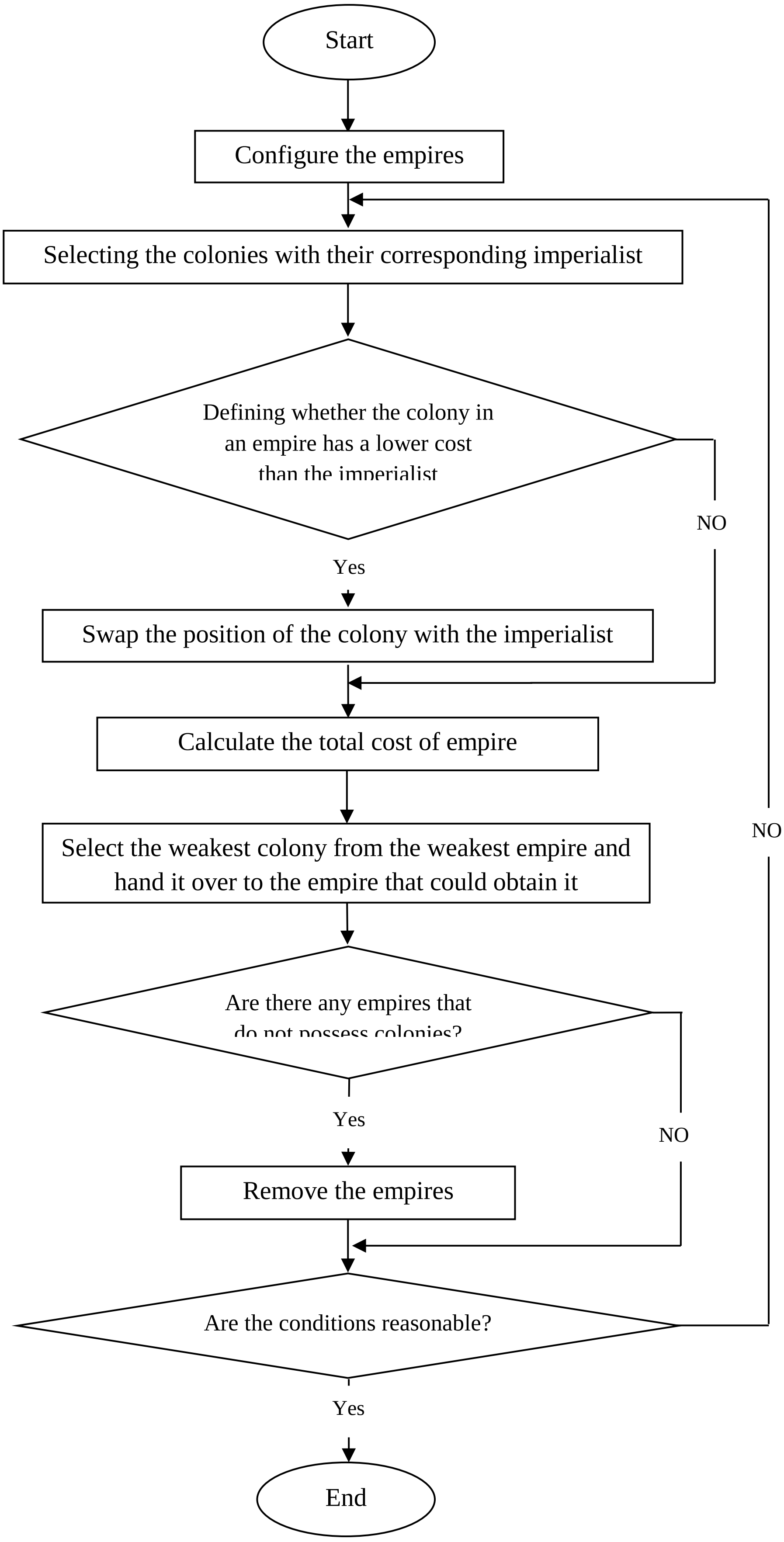


Figure 4. 3 Flowchart of the imperialist competitive algorithm

4.3.2. Performing Initial Empires

The goal of the optimization is to find the optimum solution in terms of variables. In this case, the algorithm creates an array to apply optimization. In the genetic algorithm, this array is called chromosomes, and in this algorithm it is called country. In the imperialist competitive algorithm this can be define as follows [83]:

$$Country = [p_1, p_2, p_3 \dots p_N] \quad (4.2)$$

In socio-political terms, this can be culture, language, economic structure and other features. Fig. 4.4 illustrates this performance clearly.

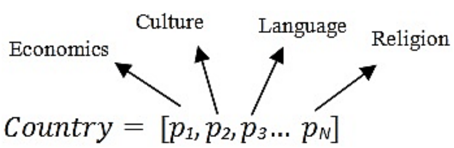


Figure 4. 4 Characteristics of function variables during the optimisation

In fact, during the optimization problem, the algorithm looks for the best country (with the best features). To find the country, the algorithm needs to find the country with the lowest cost function. The cost of these countries is defined as follows:

$$Cost = f\ (country) = f\ (p_1, p_2, p_3 \dots p_N) \quad (4.3)$$

Basically, this algorithm looks for the best country and then through assimilation and imperialistic competition tries to grab the colonies. Initially, $N_{country}$ is created and N_{imp} from the best countries which have less cost function an imperialist is selected. The Rest of the N_{col} are the number of colonies distributed between the empires. Sharing the colonies is based on the empires' power. For this purpose with having all empires, normal cost can be defined as follows:

$$C_n = c_n - max\ \{c_i\} \quad (4.4)$$

where c_n is the cost function of the n_{th} imperialist and max $\{c_i\}$ is the maximum cost between the imperialists and C_n is the normalized cost for the imperialist. So the empire has more cost, which means it is a weak empire and will have less normalized cost. Having a normalized cost, the normalized power of each empire is defined as follows:

$$p_n = \left| \frac{c_n}{\sum_{i=1}^{Nimp} c_i} \right| \tag{4.5}$$

On the other hand, the power of one empire depends on the colonies that it has in its authority. So the initial number of colonies of the empire will be:

$$N.C._n = round\,\{p_n, N_{col}\} \tag{4.6}$$

where $N.C.n$ is the initial colonies of one empire and N_{col} is the total colonies that exist and $round$ is the function that gives integer value in the case of the decimal value. Taking into account the initial position of all empires, the imperialist competitive algorithm starts to run. The process is in a loop and won't terminate unless the algorithm condition is satisfied.

Fig 4.5 shows the initial creation of the empires. It can be seen that the bigger empires own more colonies.

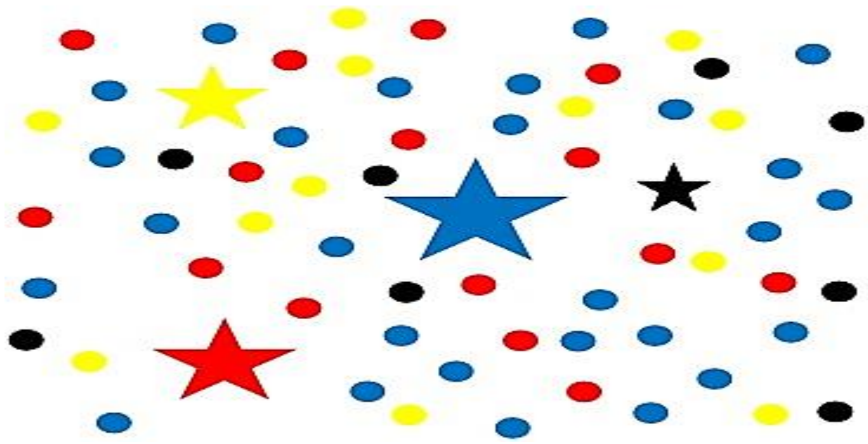


Figure 4. 5 Initial creation of the empires

4.3.3. Assimilation and Moving Colonies towards the Empires

In this level of optimization, empires try to gather all their colonies in terms of different states. Fig. 4.6 indicates this movement and provides a schematic of the empire and the colony.

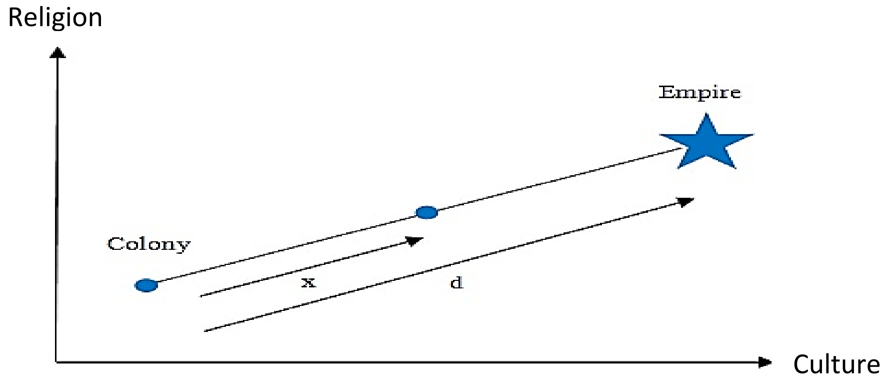


Figure 4. 6 Movement process

In Fig. 4.6, it can be seen that the colony starts to move towards the empire amount of unit *x* and reaches the new position. The total distance between empire and colony is shown by unit d. X is also a random value and follows the relation below:

$$X \sim U\ (0, \beta \times d) \qquad (4.7)$$

where β is a digit greater than 1 and close to 2. In this case, to achieve better results, the value can be assumed to be 2. By selecting $\beta > 1$ it can be seen that the colony moves towards the empire on different sides. By investigating in history it can be seen that during the assimilation between the imperialist not all the expected policies were according their preferred and sometimes there was a deviation [84].

In this algorithm, this can be defined by θ. In this regard, moving the colonies towards the empires might be done with a deviation angle. Fig. 4.7 indicates the movement of the colony towards the empire with a deviation angle.

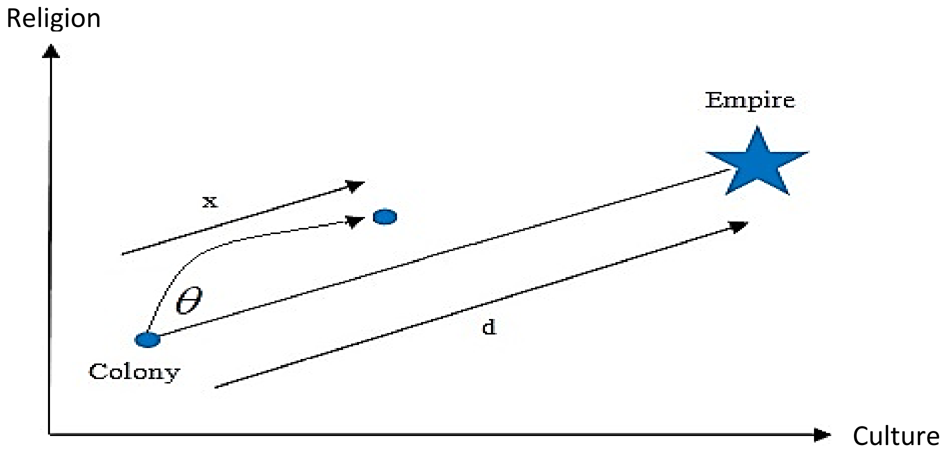


Figure 4. 7 Movement of colony towards the empire with angle

So in this case, instead of moving unit x, the colony moves towards the empire same amount with θ angle. θ is also a random value and follows the relation below:

$$\theta \sim U\,(-\gamma, \gamma) \tag{4.8}$$

In this relation, γ is an open parameter. Selecting a high value of γ creates the need to search more places around the empire and small value will make short distance to colony to reach the empire. Taking into consideration the radian for θ, $\pi/4$ has been the optimum value in most optimizations.

4.3.4. Swapping the Positions of the Colony with the Imperialist

With regard to the modelling of optimization during the movement of colonies towards empires, sometimes some colonies obtain better places than empires. That means they reach the points in the cost function that are lower than empires. In this situation, colony and empire swap places and the algorithm continues with a new empire and this time the new empire starts to perform assimilation and grab the colonies.

The swapping of colony and empire is illustrated in Fig. 4.8. In this figure the best colony is shown in a dark colour where ready to swap.

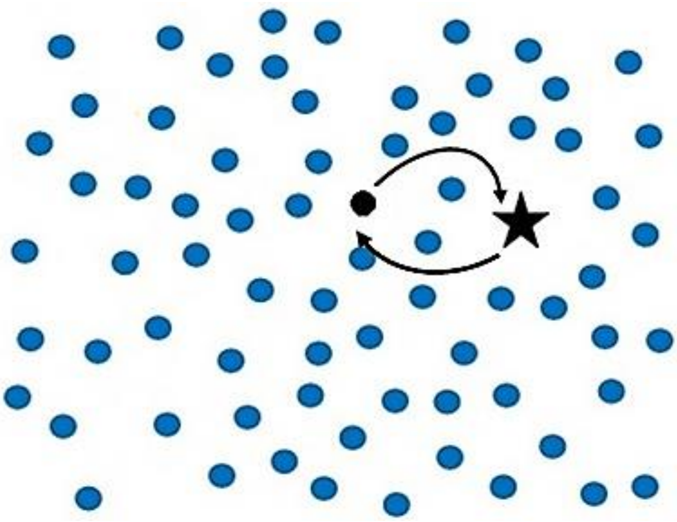


Figure 4. 8 Swapping of colony and empire

4.3.5. Total Power of Imperialist

Total power of the imperialist is equal to power of empire plus some percentage of its colony power. Total power of the imperialist is defined as:

$$T.C._n = Cost\ (imperialist_n)\ +\ \zeta\ mean\ \{Cost\ (colonies\ of\ empire_n)\} \quad (4.9)$$

In this equation $T.C._n$ total cost of n_{th} empire and ζ is a very small value between zero and 1 and this value is selected near zero. Assuming a small value of ζ causes both total cost of the imperialist and empire to become equal. However, in optimal cases it can be assumed $\zeta = 0.05$ which is a reasonable value in the process.

4.3.6. Imperialist Competition

If any empire cannot increase its power and loses the competition, it will be eliminated during the imperialist competition. This elimination will happen gradually. During the time weak empires will lose their owned colonies and strong empires will grab these colonies and increase their power.

Base on this, the algorithm assumes that one empire is about to collapse. In this case, the algorithm selects a couple of the weakest colonies and creates a competition between the empires. In this situation, the strongest one will not take all of them. The stronger empires have more probability of catching the colonies. Fig. 4.9 demonstrates this performance. In Fig. 4.9, empire number 1 is the weakest empire in the competition and one of its weakest colonies is about to be shared between other empires. Modelling of the competition between the empires to grab the colony taking into account the total cost of empires follows the equation below. First of all, based on the total cost of empires, the algorithm calculates the total normalized cost:

$$N.T.C._n = max\{T.C._i\} - T.C._n \quad (4.10)$$

where $T.C._n$ is the total cost of the n_{th} empire and $N.T.C._n$ is the normalized total cost of the same empire. So, if any empire has less $T.C._n$ then it will have more $N.T.C._n$. Basically, $T.C._n$ is equal to the total cost of one empire and $N.T.C._n$ is equal to the total power of it. The empire with a less cost function is the strongest one.

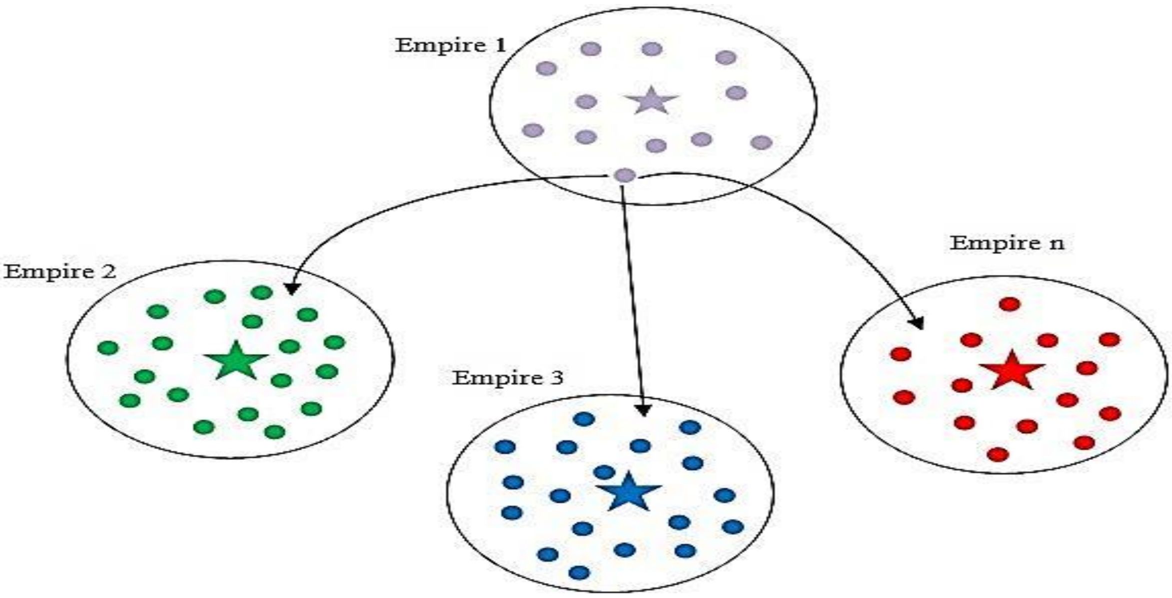


Figure 4. 9 Schematic of imperialist competition

With the total normalized cost, the probability of each empire grabbing a colony follows the equation below:

$$P_{pn} = \left|\frac{N.T.C.n}{\sum_{i=1}^{Nimp} N.T.C.i}\right| \quad (4.11)$$

With knowing probability of grabbing each empire the algorithm needs a mechanism such as a roulette wheel in the genetic algorithm that allocates the colony according to the empire's power. In this study, a new mechanism for implementing this part is introduced.

Furthermore, this mechanism has got less cost function because it eliminates the complicated computation that is required with a roulette wheel in the genetic algorithm. Indeed, it deletes the cumulative distribution function (CDF) and only needs the probability density function (PDF). With the probability of grabbing each empire algorithm distributes the related colony according to the probability of each empire. The P vector can be defined according to the above description [85].

$$P = [Pp_1, Pp_2, Pp_3, \dots , Pp_{N(imp)}] \quad (4.12)$$

This vector has a size of $1 \times N_{imp}$ and includes all the probability of the possession values of the empires. In this regard, vector R should be created to the same size. Arrays of this type of vector have a random value between 0 and 1.

$$R = [r_1, r_2, r_3, \dots , r_{N(imp)}] \ , \ r_1, r_2, r_3, \dots , r_{N(imp)} \sim U(0,1) \quad (4.13)$$

then vector D is created as below:

$$D = P - R = [D_1, D_2, D_3, \dots , D_{N(imp)}] \quad (4.14)$$

$$D = P - R = [Pp_1-r_1, Pp_2-r_2, Pp_3-r_3, \dots , Pp_{N(imp)}- r_{N(imp)}] \quad (4.15)$$

The colony is transferred to the empire, which has a high value in vector *D*. Without considering the cumulative distribution function the algorithm processes the mechanism more quickly.

This mechanism will be useful for transferring colonies to the empires and can be replaced with a roulette wheel in the genetic algorithm to increase the speed of progress. With one of the empires grabbing a colony this part of the algorithm is terminated. The next part of the algorithm is the last part, which is empires are eliminated until the algorithm keeps the last one.

4.3.7. Weak Empires Collapse

As previously mentioned, during the imperialist competition, weak empires collapse gradually and their colonies are shared between other strong empires. Different scenarios can be defined for collapsing the empires. In this case, empires are eliminated when they lose all their colonies. Fig. 4.10 illustrates this elimination.

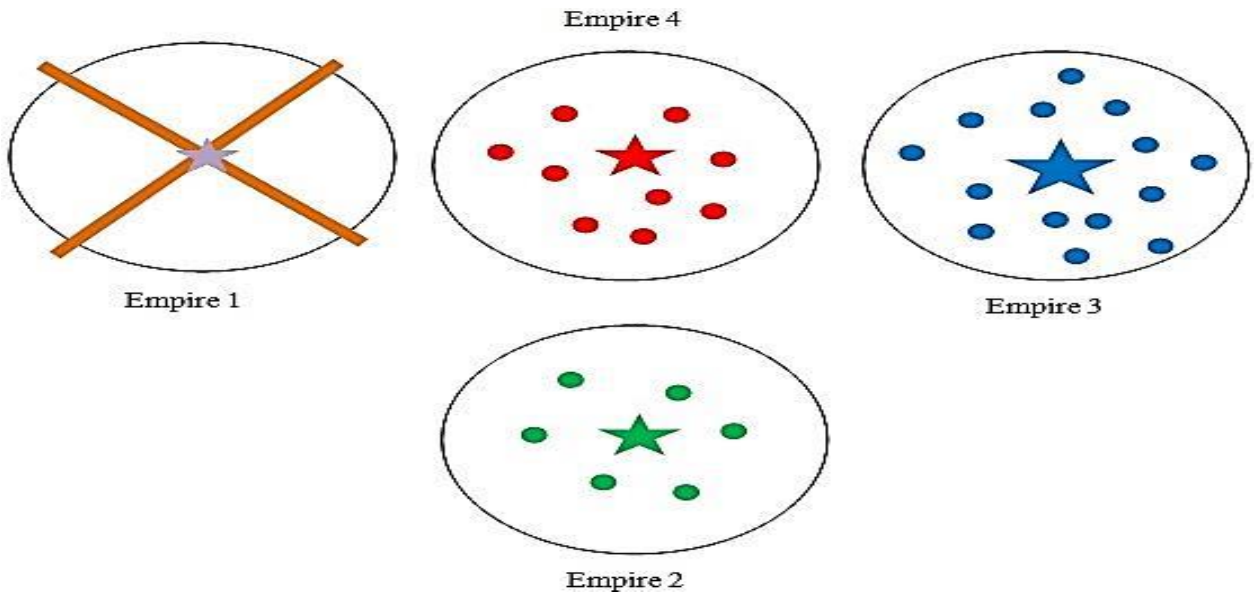


Figure 4. 10 Collapse of the weaker empires

Empire number 1, due to losing all its colonies, will be eliminated from the competition and the competition will continue between the other three empires. The algorithm will continue according to the convergence condition and until all iterations finish. After some time, all of the empires will collapse and only one empire will remain and all other colonies will be under its authority. In this situation, the algorithm will stop and show the solution. The imperialist competitive algorithm is the most recently developed optimization technique and is briefly outlined below [86].

1. Selection of random points on the function and creation of initial empires
2. Moving colonies towards the imperialists (assimilation)
3. Running the revolution operation
4. Exchange positioning of the colonies and imperialists in terms of cost function
5. Calculating the whole cost including imperialists and colonies
6. Collect the weakest colony from the weakest empire and shift to the empire that has the most opportunity to grab it
7. Eliminate the weak empire
8. If there is only one empire left, then stop, otherwise go to 2

The whole process of this algorithm is illustrated in Fig. 4.11.

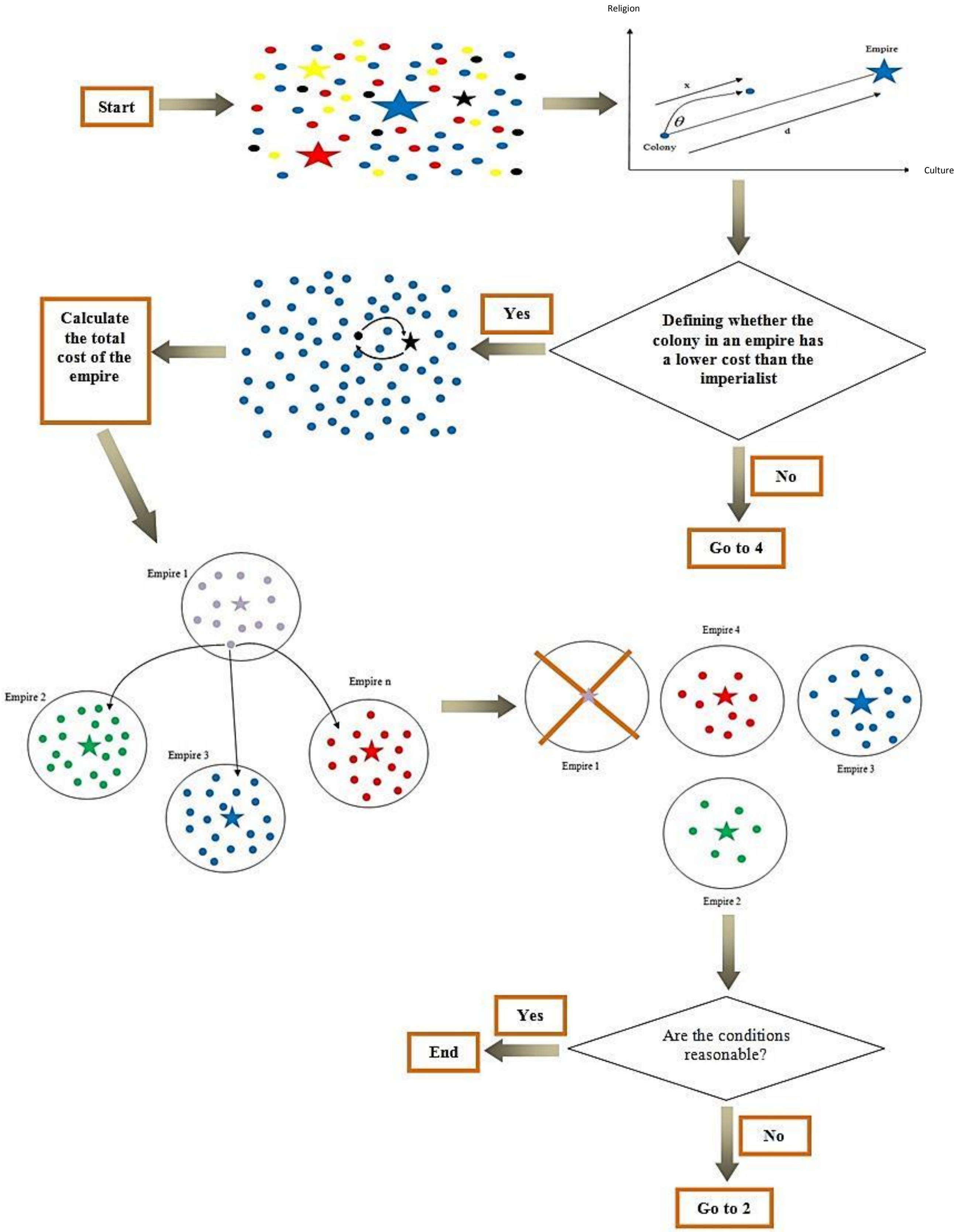


Figure 4. 11 Whole schematic diagram of the imperialist competitive algorithm

4.4. Summary of the Chapter

This chapter started with an overview of optimization in science. The aim of optimization is to improve the progress of the problem. The importance of optimization has been discussed. Some types of optimization that are used to solve problems have been shown. Constraints to optimization have been mentioned briefly. The imperialist competitive algorithm, one of the most recent optimization methods, has been discussed. This algorithm is based on human evolution. The steps of the imperialist competitive algorithm have been discussed in full. This algorithm, after processing the answer and creating competition between the empires, approaches the solution. This algorithm follows eight steps.

Chapter 5

Optimization Problem

5. Optimization problem

In this study two test systems are analysed. In this case, all simulated results, including load flow, convergence characteristics and comparison, are illustrated in the results chapter.

5.1. IEEE 30-Bus System

This case study is part of the American electric power system. In this system there are six generators and 30 bus-bars. The single diagram of the network is illustrated in Fig. 5.1 [50].

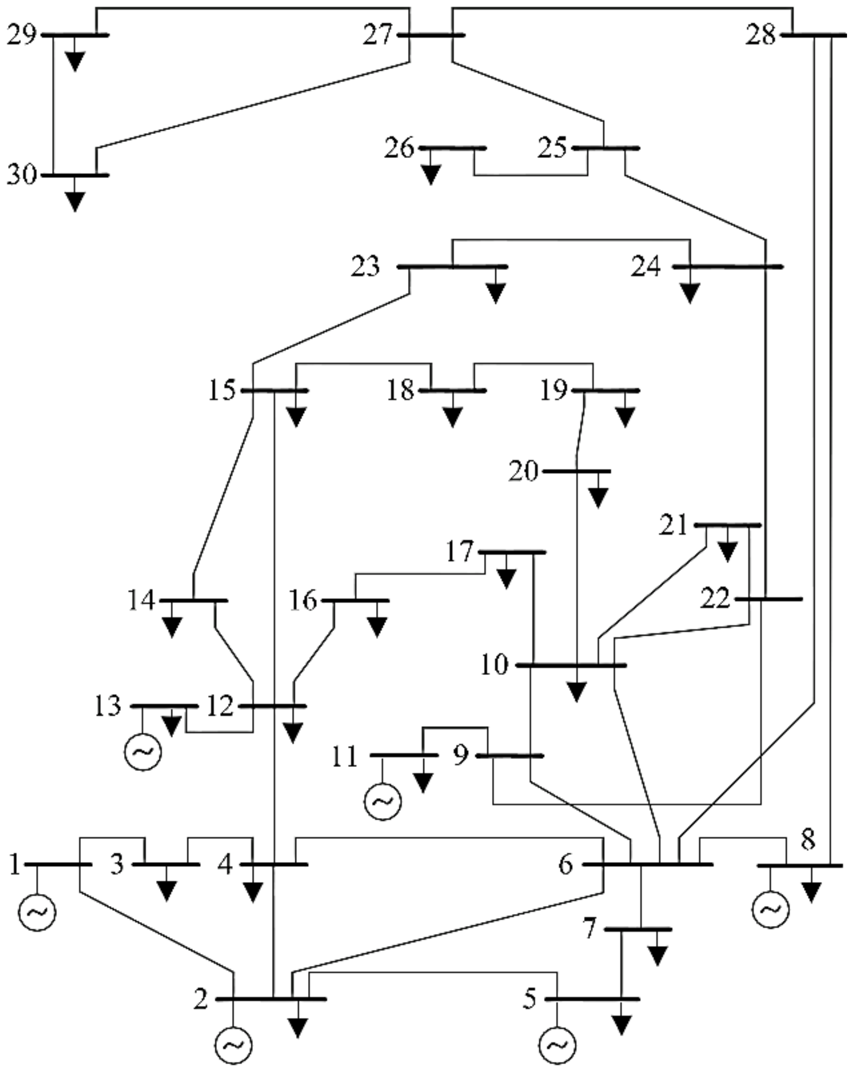


Figure 5. 1 Single diagram of IEEE 30 bus system

5.1.1. Total Transfer Capability

There are two scenarios for calculating TTC. In the first scenario, this is called LG (load/generation). Load increases at the receiving point of power so the source area will increase its generation to compensate this overload. The second scenario is called GG (generation/generation). In this scenario, the generation will be dropped in the receiving area so the source area will increase its generation to compensate this overload. In this study, LG has been considered and all the required equations can be defined as follows:

$$P_{\mathrm{Gi}} - P_{\mathrm{Di}} - \sum_{j=1}^{n} |V_{\mathrm{i}}||V_{\mathrm{j}}| \left(G_{\mathrm{ij(FACTS)}} \cos\delta_{\mathrm{ij}} + B_{\mathrm{ij(FACTS)}} \sin\delta_{\mathrm{ij}}\right) = 0 \quad (5.1)$$

$$Q_{\mathrm{Gi}} - Q_{\mathrm{Di}} - \sum_{j=1}^{n} |V_{\mathrm{i}}||V_{\mathrm{j}}| \left(G_{\mathrm{ij(FACTS)}} \sin\delta_{\mathrm{ij}} - B_{\mathrm{ij(FACTS)}} \cos\delta_{\mathrm{ij}}\right) = 0 \quad (5.2)$$

$$|V_i|_{min} \leq |V_i| \leq |V_i|_{max} \quad (5.3)$$

$$S_{ij} \leq S_{ijmax} \quad (5.4)$$

In this case, P_{Gi} and Q_{Gi} are generated real and reactive power at bus *i*, P_{Di} and Q_{Di} are the real and reactive power of the load at bus *i*, $G_{(ijFACTS)}$ is the real part of admittance (conductance) of the network including FACTS devices and $B_{(ijFACTS)}$ is the imaginary part of admittance (susceptance) of the network including FACTS devices, n is the number of buses, $|V_i|_{min}$, $|V_i|_{max}$ are the minimum and maximum voltage magnitude at bus *i*, S_{ij} is the apparent power of the line *i,j* and S_{ijmax} is the thermal limit of the line *i,j* and δ_{ij} is the difference of phase angle between buses *i and j*. $|V_i|$, $|V_j|$ are the voltage magnitude at bus *i,j*. For computing the total transfer capability some parameters are defined. The real power generations at bus *i* (P_{Gi}), which is in the source area, and real and reactive load demand at bus i (P_{Di} & Q_{Di}), which is in the sink area in the function of λ follow these equations:

$$P_{Gi} = P_{Gi} + (1 + \lambda k_{Gi}) \quad (5.5)$$

$$P_{Di} = P_{Di} + (1 + \lambda k_{Di}) \quad (5.6)$$

$$Q_{Di} = Q_{Di} + (1 + \lambda k_{Qi}) \quad (5.7)$$

k_{Gi} and k_{Di} are the constants used to show the rate of changes in loads with various λ.

The total transfer capability is defined as:

$$TTC = \sum_{i=1} P_{Di} (\lambda_{max}) - \sum_{i=1} P^{0}{}_{Di} \quad (5.8)$$

In this case, $P_{Di} (\lambda_{max})$ is the sum of the load in the sink area where $\lambda = \lambda_{max}$. On the other hand, $P^{0}{}_{Di}$ is the sum of the load where $\lambda = 0$. Basically, λ is the parameter for increasing load or generation. When $\lambda = 0$, there is no power transfer between the areas, and when $\lambda = \lambda_{max}$ it is equal to the maximum power transfer.

5.1.2. Objective Functions and Constraints

In this case, two objective functions have been involved. Firstly, minimizing the voltage deviation, and secondly, minimizing the SVC size both as variables. The two elements J_1 and J_2 are defined as [88]:

$$J_1 = V_d = \sqrt{\sum_{i=1}^{Nbus} (V_i - 1)_i - 1} \quad (5.9)$$

where J_1 is the voltage deviation and V_i is the voltage magnitude, and

$$J_2 = \sum_{j=1}^{Nunits} \eta_j \qquad (5.10)$$

where J_2 is the SVC size, η_j is the size in $MVar$ of the SVC and $Nunits$ is the number of SVCs that should be allocated.

The multi-objective function in this problem was defined as the sum of J_1 and J_2.

$$J = w_1.J_1 + w_2.J_2 \qquad (5.11)$$

In this case, $w_1$and w_2 are the weight coefficient and were considered to be 1 and 1.5, respectively.

Also, constraints can be defined as:

$$|V_i|_{min} \leq |V_i| \leq |V_i|_{max} \qquad (5.12)$$

$$S_{ij} \leq S_{ijmax}, \delta_{ij} \leq \delta_{ijmax} \qquad (5.13)$$

Maximum and minimum reactive power output of the generator was assumed to be between -999 and 999 $MVar$. Maximum and minimum voltage magnitude was assumed to be between 0.95 and 1.05 $p.u.$ and the total MVA base of the machine was considered to be 100MVA. In this case SVC was a such a reactive power source which is able to inject power into the system.

5.1.2.1. UPFC Modeling

In this part the case study will be analysed using another compensator, called a UPFC. All the basic algorithm parameters will be the same as already used. A UPFC is a sum of series and shunt components used to provide real power and also generate or absorb reactive power in the same way as STATCOM. Voltage magnitude and phase angle are added into the transmission line by series part. It can be said that a UPFC is the most powerful FACTS device. It is able to control three parameters: voltage, line impedance and phase angle. Fig. 5.2 presents the basic diagram of a UPFC.

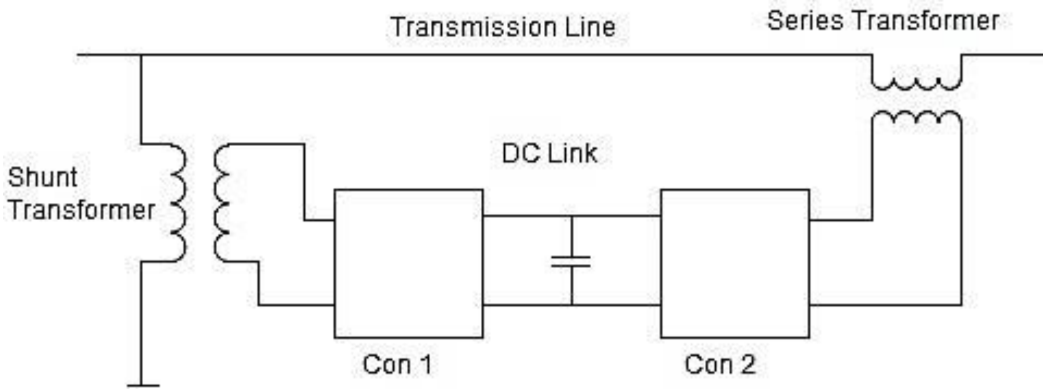


Figure 5. 2 Basic diagram of UPFC

In this study UPFC was connected as a source of current and voltages in the network. Whenever a UPFC is connected to the network between buses i & j, the injected power at bus i will be:

$$S_i = P_i + jQ_i \tag{5.14}$$

and at bus j it will be;

$$S_j = P_j + jQ_j \tag{5.15}$$

The above equations can be expressed as:

$$P_i + V_s^2 G'_{ij} + 2V_i V_s G'_{ij} \cos(\emptyset_s - \theta_i) - V_j V_s \left[G'_{ij} \cos(\emptyset_s - \theta_j) - B'_{ij} \sin(\emptyset_s - \theta_j)\right] = 0 \tag{5.16}$$

$$Q_i - V_i I_q - V_i V_s\left[G'_{ij}\sin(\emptyset_s - \theta_i) - B'_{ij}\cos(\emptyset_s - \theta_i)\right] = 0 \qquad (5.17)$$

$$P_j - V_j V_s\left[G'_{ij}\cos(\emptyset_s - \theta_j) + B'_{ij}\sin(\emptyset_s - \theta_j)\right] = 0 \qquad (5.18)$$

$$Q_j + V_j V_s\left[G'_{ij}\sin(\emptyset_s - \theta_j) - B'_{ij}\cos(\emptyset_s - \theta_j)\right] = 0 \qquad (5.19)$$

In this case, S_i & S_j are the total powers that are injected at buses i & j by the UPFC, respectively. In this part two objective functions are used to allocate the UPFC at the optimal place. The two elements, J_1 and J_2, are defined as [88]:

$$J_1 = V_d = \sqrt{\sum_{i=1}^{Nbus}(V_i - 1)_i - 1} \qquad (5.20)$$

where J_1 is the voltage deviation and V_i is the voltage magnitude.

The second objective function used in this problem is related to system losses. The power loss equation is calculated by the equation below:

$$P_L = \sum \left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] Y_{ij}\cos\varphi_{ij} \qquad (5.21)$$

where δ_i is the angle of the voltage at bus i, and Y_{ij} and φ_{ij} are the magnitude and angle of the admittance of the transmission lines at i,j. If we assume P_{lk} is the active losses in the k transmission lines, this will be calculated by the following formula:

$$P_{Lk} = P_{sending} - P_{receiving} \qquad (5.22)$$

The total power losses related to transmission lines can be calculated by the equation below:

$$P_{L_{total}} = F_{Loss} = \sum_{k=1}^{Line-number} P_{Lk} \quad (5.23)$$

$$J_2 = \sum_{k=1}^{Line-number} P_{Lk} \quad (5.24)$$

The multi-objective function in this problem is defined as the sum of J_1 and J_2:

$$minimize\ J = J_1 + J_2 \quad (5.25)$$

The objectives include the operating limits on the various power system variables and these parameters are given below:

$$P_{G_i}^{min} \le P_{G_i} \le P_{G_i}^{max} \quad (5.26)$$

$$Q_{G_i}^{min} \le Q_{G_i} \le Q_{G_i}^{max} \quad (5.27)$$

$$V_i^{min} \le V_i \le V_i^{max} \quad (5.28)$$

$$i_{sh}^{min} \le i_{sh} \le i_{sh}^{max} \quad (5.29)$$

$$V_{se}^{min} \le V_{se} \le V_{se}^{max} \quad (5.30)$$

$$0 \le \emptyset_{se} \le 2\pi \quad (5.31)$$

In this part, objective function was defined as the sum of voltage deviation and power losses. Six constraints were used in this analysis.

5.2. IEEE 68-Bus System

In the second case study, there are 16 generators and 68 buses. Briefly this system is known as the 68-bus New England test system (NETS)–New York (NYPS) interconnected system. Generators $G1 - G9$ are in New England, generators $G10 - G13$ are in New York and $G14 - G16$ are analogous generators in the neighbourhood of New York. The schematic of the network is illustrated in Fig. 5.3 [53].

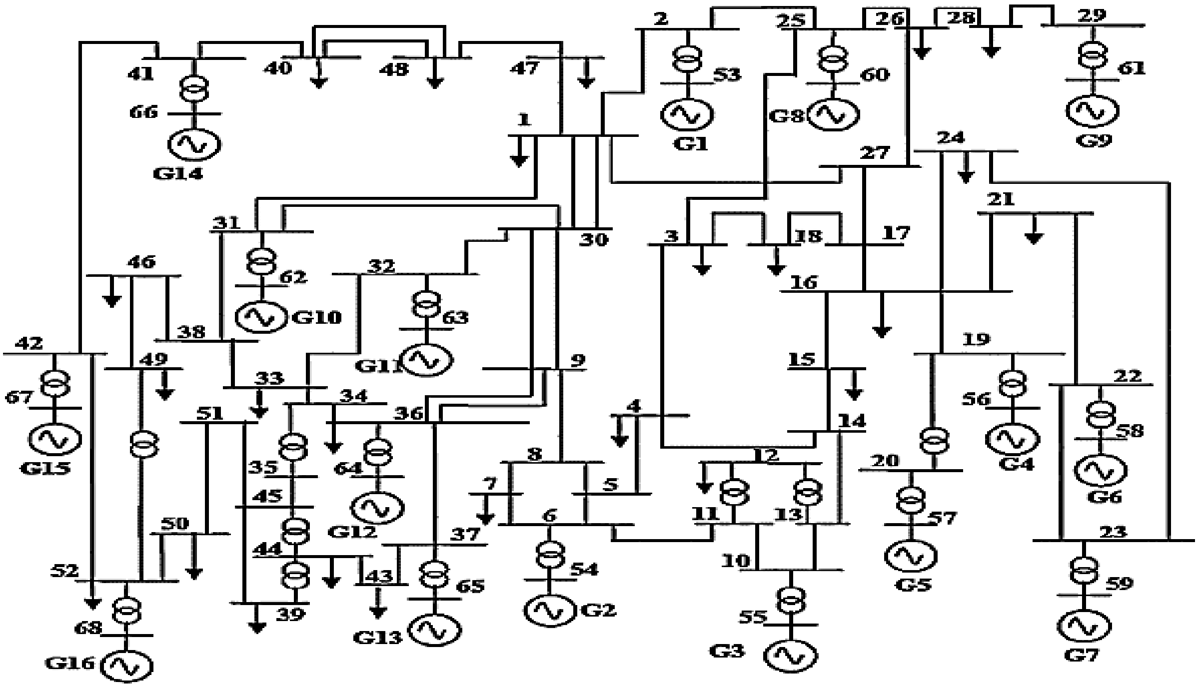


Figure 5. 3 Single diagram of IEEE 68 bus system

5.2.1. Objective Functions and Constraints

In this case, there are three objective functions: size of the SVC, voltage deviation and total system losses. Two of the objective functions and constraints are the same as used for previous case studies. Objective function will be a combination of three objectives in this part.

Three elements, J_1, J_2 and $J_{3,}$ are defined as [88]:

$$J_1 = V_d = \sqrt{\sum_{i=1}^{Nbus}(V_i - 1)_i - 1} \qquad (5.32)$$

where J_1 is the voltage deviation and V_i is the voltage magnitude, and

$$J_2 = \sum_{j=1}^{Nunits} \eta_j \qquad (5.33)$$

where J_2 is the SVC size, η_j is the size in $MVar$ of the SVC and $Nunits$ is the number of SVCs that should be allocated.

The power loss equation is calculated by the equation below:

$$P_L = \sum \left[V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j)\right] Y_{ij} \cos\varphi_{ij} \qquad (5.34)$$

where δ_i is the angle of the voltage at bus i, and Y_{ij} and φ_{ij} are the magnitude and angle of the admittance of the transmission lines at i,j. If we assume P_{lk} is the active losses in the k transmission lines, this will be calculated by the formula below:

$$P_{Lk} = P_{sending} - P_{receiving} \qquad (5.35)$$

Total power losses related to transmission lines can be calculated by the following equations:

$$P_{L_{total}} = F_{Loss} = \sum_{k=1}^{Line-number} P_{Lk} \qquad (5.36)$$

$$J_3 = \sum_{k=1}^{Line-number} P_{Lk} \qquad (5.37)$$

The multi-objective function in this problem is defined as the sum of J_1, $J_2$and J_3.

$$minimize\ J = J_1 + J_2 + J_3 \tag{5.38}$$

Also, constraints can be defined as:

$$|V_i|_{min} \leq |V_i| \leq |V_i|_{max} \tag{5.39}$$

$$S_{ij} \leq S_{ijmax}, \delta_{ij} \leq \delta_{ijmax} \tag{5.40}$$

$$Q_{min} \leq Q \leq Q_{max} \tag{5.41}$$

The maximum and minimum reactive power output of the generator was assumed to be between -999 and 999 $MVar$. The maximum and minimum voltage magnitude was assumed to be between 0.95 and 1.05 $p.u.$ and the total MVA base of the machine was considered to be 100 MVA.

All the simulated results are shown and analysed in the results chapter. It can be seen that using various numbers of objective functions can affect the results slightly and can achieve a high quality of solutions for problems.

5.3. Summary of the Chapter

In this chapter, the IEEE 30-bus and IEEE 68-bus were introduced. All objective functions and constraints that are used in case studies were demonstrated. The results and simulations are discussed in the next chapter.

Chapter 6

Results and Discussions

6. Results and Discussions

After discussing a variety of FACTS devices and their operation in power networks, this thesis investigated to find the optimal placement of the components. In this regard, objective functions with constraints were demonstrated to achieve the size and optimal place for the compensators. The test study case was implemented in the algorithm (MATLAB program) to obtain the results. In this chapter, the results will be demonstrated and all simulations will be separately shown and discussed.

This chapter includes five main parts. In the first part, the case study, which is the IEEE-30 bus system, is analysed as it is. This analysis includes the power flow and line flow of the system and the level of the voltage profile before optimization and using FACTS devices.

In the second part, this study demonstrates optimization of the IEEE-30 bus system using an SVC device with the imperialist competitive algorithm. In the third part, the IEEE-30 bus system will be optimized by the imperialist competitive algorithm using a UPFC in the network.

In the fourth part, all simulation and related results will be compared with those obtained for the same network using the GA and PSO techniques. In this thesis, two case studies were used: the IEEE-30 and IEEE-68 bus systems.

In the last part, the IEEE-68 bus system will be analysed using ICA technique. In this case, different types of objective function and constraints were used to demonstrate the simulations and results. In this case, an SVC was allocated as a parallel component to the network. On the other hand, a UPFC, which is a shunt and series compensator at the same time, was optimized and connected to the network. In both cases, the position and size were considered as variables.

6.1. IEEE-30 Bus System without FACTS

In the first part, this study demonstrates simulation of the IEEE-30 bus system without using FACTS devices in the network. In this case, the system has been analysed and all results, including load flow, line flow and convergence characteristics, will be discussed.

This case study includes a 30-bus and 6-generator. System characteristics, including bus, branch and generator data and power flow, are included in the Appendix. Power flow analysis is an important tool involving mathematical analysis applied to the power systems. Line flow has been analysed and the results are indicated in Table 6.1.

Through the load flow it can be seen that the voltage magnitude and angles at each bus, as well as real power and reactive power related to the generator and load, are computed. Furthermore, the losses in the particular line can be calculated based on the difference between the power flow in the sending and receiving areas. In this case, the system load flow was analysed by Newton-Raphson.

Newton-Raphson is one of the fastest convergence methods to the root and approximately doubles with each step. That is why this method causes the ability of the Newton-Raphson method to be more accurate to the root than other convergence techniques. Also, this method is easy to convert to multiple dimensions.

In this case, to increase the speed of convergence, it is advised that for the first couple of decades, instead of the Newton-Raphson, Fast-Decoupled is used. The reason is that Fast-Decoupled has more speed in terms of convergence because of fewer parameters in the

Jacobian matrix, but for achieving high accuracy for answers a switch to the Newton-Raphson method can be made to obtain high-quality solutions. The other reason that should be mentioned is that the computer memory should be large because of the Jacobian matrix elements and the programming logic is very complex.

On the other hand, this method has some disadvantages as well, such as: it had poor global convergence properties and sometimes it is too far from the local root and depends on the initial guess and in some cases it does not answer and maybe the loop will be infinite.

Newton-Raphson is one of the fastest convergence methods to the root; also, the method of convergence is quadratic. The major aim of the load flow in the power system is to find the voltage magnitude and angle of each bus when the power is distributed between the transmission lines. In the real power network environment, basically engineers use Fast-Decoupled for the initial couple of decades for convergence, then for enhancing the accuracy of the answers they switch to the Newton-Raphson method. Fig. 6.1 illustrates the speed of convergence.

In the Newton-Raphson method initially we need to write complex power equations as equations with real coefficients. Then the next step is resolving into real and imaginary parts. Basically, Newton-Raphson is used to determine the voltage magnitude and angle at each bus-bar in the power systems. In this case we assume that the slack bus is the first bus and then the voltage magnitude and angle at the other buses are determined correspondingly. In this method, the difficult part is determining and inverting the Jacobian matrix. After calculating the voltage angle and magnitude at each bus, the algorithm calculates other parameters such as the line flows and generator reactive power output.

Table 6. 1 Simulation of IEEE 30 bus system line flow

Line No	Line flow without FACTS						Losses without FACTS	
	Buses	P flow (p.u)	Q flow (p.u)	Buses	P flow (p.u)	Q flow (p.u)	P loss (p.u)	Q loss (p.u)
1	1-2	3.5088	-0.5427	2-1	-3.2898	1.1412	0.2190	0.5985
2	1-3	1.6881	0.3270	3-1	-1.5662	0.1309	0.1218	0.4580
3	2-4	1.0281	0.2433	4-2	-0.9681	-0.0964	0.0601	0.1469
4	3-4	1.4918	-0.1682	4-3	-1.4594	0.2535	0.0324	0.0853
5	2-5	2.0457	0.0454	5-2	-1.8607	0.6884	0.1850	0.7338
6	2-6	1.3281	0.1281	6-2	-1.2310	0.1293	0.0971	0.2574
7	4-6	1.1770	-0.5932	6-4	-1.1540	0.6651	0.0230	0.0719
8	5-7	-0.2990	0.6295	7-5	0.3217	-0.5918	0.0227	0.0377
9	6-7	1.0622	-0.1664	7-6	-1.0287	0.2538	0.0335	0.0874
10	6-8	0.0255	-1.4675	8-6	0.0025	1.5565	0.0279	0.0890
11	6-9	0.4831	0.2327	9-6	-0.4831	-0.1705	0.0000	0.0622
12	6-10	0.3792	0.3012	10-6	-0.3792	-0.1681	0.0000	0.1331
13	9-11	-0.5560	-0.6639	11-9	0.5560	0.8417	0.0000	0.1777
14	9-10	1.0392	0.8344	10-9	-1.0392	-0.6118	0.0000	0.2226
15	4-12	1.0148	0.3864	12-4	-1.0148	-0.0936	0.0000	0.2928
16	12-13	-0.5244	-0.9032	13-12	0.5244	1.0714	0.0000	0.1682
17	12-14	0.2800	0.1291	14-12	-0.2671	-0.1023	0.0129	0.0268
18	12-15	0.6498	0.4127	15-12	-0.6066	-0.3276	0.0432	0.0851
19	12-16	0.2621	0.2224	16-12	-0.2498	-0.1966	0.0123	0.0259
20	14-15	0.0749	0.0526	15-14	-0.0725	-0.0505	0.0024	0.0021
21	16-17	0.1413	0.1407	17-16	-0.1370	-0.1308	0.0042	0.0099
22	15-18	0.2081	0.1070	18-15	-0.2001	-0.0905	0.0080	0.0164
23	18-19	0.1008	0.0626	19-18	-0.0994	-0.0598	0.0014	0.0028
24	19-20	-0.1952	-0.0456	20-19	0.1974	0.0501	0.0022	0.0045
25	10-20	0.2768	0.0968	20-10	-0.2656	-0.0718	0.0112	0.0250
26	10-17	0.1431	0.0517	17-10	-0.1421	-0.0490	0.0010	0.0027
27	10-21	0.5471	0.3848	21-10	-0.5254	-0.3382	0.0217	0.0466
28	10-22	0.2715	0.1845	22-10	-0.2606	-0.1621	0.0109	0.0225
29	21-22	-0.0173	-0.0092	22-21	0.0173	0.0092	0.0000	0.0000
30	15-23	0.2166	0.1936	23-15	-0.2050	-0.1702	0.0116	0.0234
31	22-24	0.2433	0.1529	24-22	-0.2282	-0.1293	0.0151	0.0235
32	23-24	0.1058	0.1206	24-23	-0.1003	-0.1092	0.0055	0.0113
33	24-25	0.0586	0.0308	25-24	-0.0571	-0.0280	0.0016	0.0028
34	25-26	0.1204	0.0890	26-25	-0.1085	-0.0713	0.0118	0.0177
35	25-27	-0.0633	-0.0609	27-25	0.0651	0.0643	0.0018	0.0033
36	27-28	0.5704	0.6800	27-28	-0.5704	-0.3438	0.0000	0.3363
37	27-29	0.2332	0.1298	29-27	-0.2033	-0.0731	0.0300	0.0566
38	27-30	0.2721	0.1497	30-27	-0.2130	-0.0384	0.0591	0.1113
39	29-30	0.1288	0.0452	30-29	-0.1158	-0.0205	0.0131	0.0247
40	8-28	0.1526	0.4039	28-6	-0.1407	-0.3871	0.0119	0.0169
41	6-28	0.4349	0.3057	28-6	-0.4297	-0.2929	0.0052	0.0127
Total losses							**1.1207**	**4.5335**

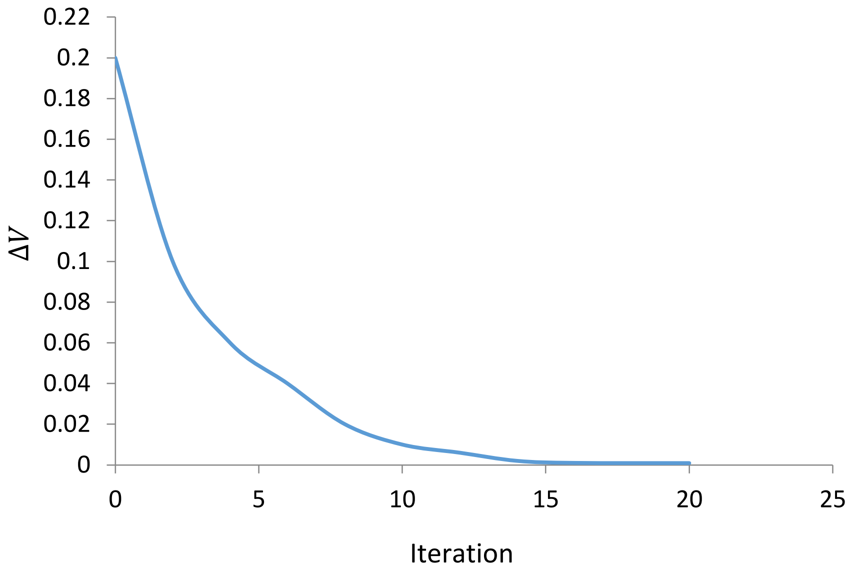


Figure 6. 1 Speed of convergence

In Fig. 6.1, it can be seen that the amount of the ΔV decreased significantly then started to decrease gradually. In this case, there is a stop criteria condition that helps the system to obtain the final results whilst being happy. In this case, the stop criteria condition is assumed to be 10^{-4}, which is acceptable. In different methods and algorithms the stop criteria condition is usually defined in the same way. The reason this study selected the same value is because a comparison was made with other optimization techniques.

Basically, voltage optimization is a kind of energy-saving method in power systems. By carrying out voltage optimization it can be seen that power losses are reduced and the level of power quality improved. In the case of additional activities, for instance balancing phase voltage and eliminating harmonics from the system, this process is called voltage power optimization. But this study did not focus on filtering the harmonics. Voltage optimization is mostly used in a large number of power network environments where it can reduce power consumption and increase the life of electrical equipment. Voltage optimization can reduce reactive power and improve the power factor in the system.

The level of the voltage before optimization is shown in Fig. 6.2. In any condition, power systems should be stable according to various operational criteria. Voltage collapse is one of the major phenomena that take place in transmission systems. In this case, the voltage decreases gradually until the system is going to shut down. Also, in the case of a small amount of overload, the voltage will decrease slightly, but in the case of massive overloaded, the voltage will drop significantly.

In Fig, 6.2, it can be seen that the voltage in buses 7, 10, 14, 15, 18-27, 29 and 30 is not stable and is under the unit value. The voltage in buses 3, 4, 6, 9, 12 and 28 dropped slightly, which can be considerable after optimization if it is still under the unit value. In power systems, to achieve a stable voltage, all disturbances need to be removed from the system. This is because of increasing load in the system or one of the electrical components in the network being broken. Voltage collapse usually happens in one area and extends and affects other areas before finally damaging the whole network.

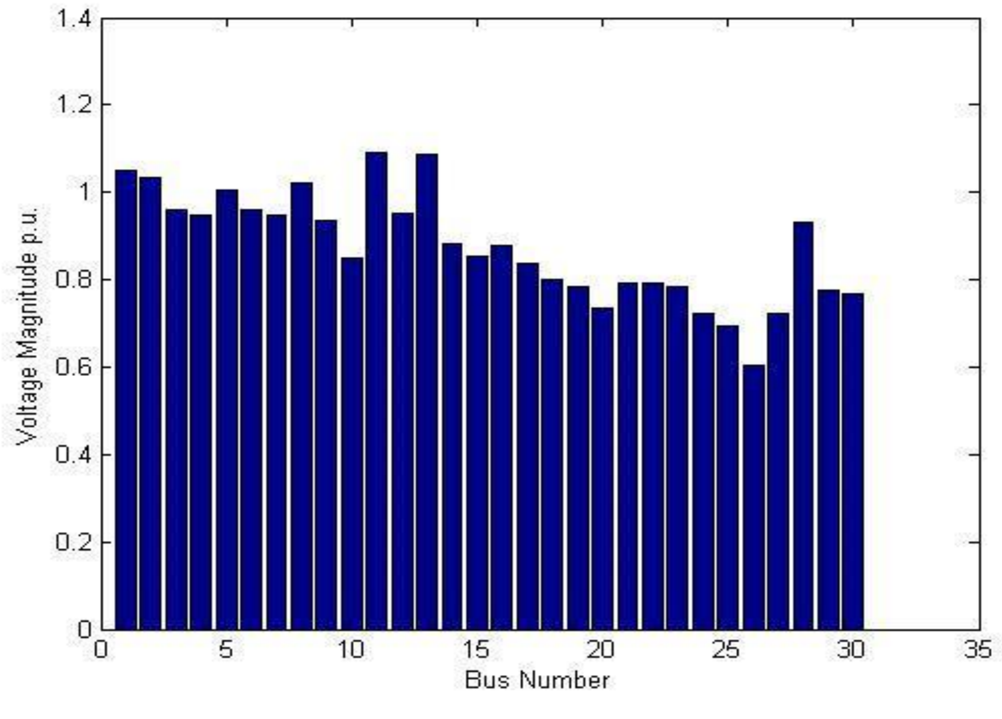


Figure 6. 2 Level of voltage before optimization

By referring to Fig. 6.2, it is essential to find out how the voltage level can be improved taking into consideration the number of FACTS devices. It can be seen that by allocating the FACTS devices in critical areas the voltage level can be improved. The key parameter that makes these components different to other facilities is flexibility. FACTS devices are able to control active power and reactive power through the transmission lines and the voltage at buses. In other mechanical components, variable parameters change step by step, but in the case of FACTS devices these parameters change continuously and quickly.

FACTS devices are used widely in power systems rather than mechanical facilities. In this case, minimizing the installation cost, which has a direct relation with the number of FACTS devices at bus-bars and transmission lines, is essential. The installation cost of FACTS devices is one of the important parameters that should be considered during network design. In some cases, installing a local generator is more economical than installing FACTS in the transmission system or bus-bars.

In this case, MATPOWER should be installed as a part of the MATLAB file and needs to be added to the MATLAB directory. MATPOWER is able to solve power flow and optimal power flow problems and this makes it easy for researchers to use and modify and simulate power system problems. The minimum MATLAB version of 6.5 is required.

This part gives the best performance possible while using the codes. This field helps after creating an M file whose return value is the mpc structure or a MAT file. Basically, in this area the base MVA field is scalar and the rest of them are matrix. In the data file generally each row represents a single bus, branch or generator and the columns are the same as the standard IEEE format. All the data that have been used to define study case characteristics are taken from the University of Washington official website [87].

There are 30 buses in the system and in the bus type section number 1 represents the load bus. In this bus, real and reactive powers are determined and voltage magnitude is computed. Both real and reactive powers in the power network assessed by polarity whether, in the case of supplying would be positive and in the case of consuming and absorbing would be negative. Number 2 indicates the generator bus. In this case, voltage magnitude is adjusted to constant value by varying the field current of the synchronous generator at the bus-bar. And finally number 3 represents the reference bus.

In the optimization area the aim of the objective functions and constraints is to find the minimum and maximum of the function, which is called the objective function. Basically, according to a mathematical process, the objective function describes the relationship between the optimization parameters. This can be done by using input parameters. Constraints are simply kinds of restrictions in a problem that are forced to the optimization engine. Constraints are defined based on optimization parameters whether the generated solution by engine should be satisfied by constraints. This study tried to define the same number of constraints as the compared one. The maximum and minimum reactive power output of the generator has been assumed to be between -999 and 999 $MVar$. The maximum and minimum voltage magnitude has been assumed to be between 0.95 and 1.05 $p.u.$ and the total MVA base of the machine has been considered to be 100 MVA.

In the IEEE study case, short-, long- and emergency-term ratios have not been considered. It can be set all those values for different approaches. The reason this thesis has not involved those values is because a comparison has been made with other techniques and this shows the advantage of the imperialist competitive algorithm. Basically, in the long term, a generator provides power to the load for an unlimited number of hours per year and in the short term this amount will decrease according to the amount of load, and in an emergency the generator runs at 70 per cent output with varying loads for short periods of time, i.e. between 50 and 200 hours per year.

6.1.1. P-V Curves

The P-V (Power-Voltage) analysis in power network transmission lines is a kind of process using a series of power flow solutions to enhance the transfer of MW taking into consideration what is happening in the voltage profile. In order to do this, the P-V curves indicate the loading of the power systems. To obtain the curves, full power flow solutions are required. To obtain P-V curves in the power system, load is increased slightly, and at each step of increasing the power, the voltage magnitude is analysed and according to the behaviour of the slope the voltage collapse point can be realised; on the other hand, voltage stability can be analysed.

To obtain the P-V curves, basically specific bus-bars should be selected for consideration and monitoring. P-V curves will be plotted for each single bus. In the curve the pick point before reversing to become zero is called critical voltage, and after that point the power flow solution fails in terms of convergence. P-V curves are illustrated in Figs. 6.3 – 6.7. Initially, by increasing the load in the system, some of the buses remain stable, but by increasing to a high rate of power those buses start to collapse.

In this case, some buses' reactions were sharp. It can be seen that buses 20, 24, 26, 29 and 30 are not stable in terms of voltage stability and collapsed earlier than other bus-bars. From the viewpoint of this analysis voltage instability is one of the major problems in power systems and it is necessary to define the exact conditions in which voltage instability can occur. It can be improved by installing FACTS devices, which is described in the next part.

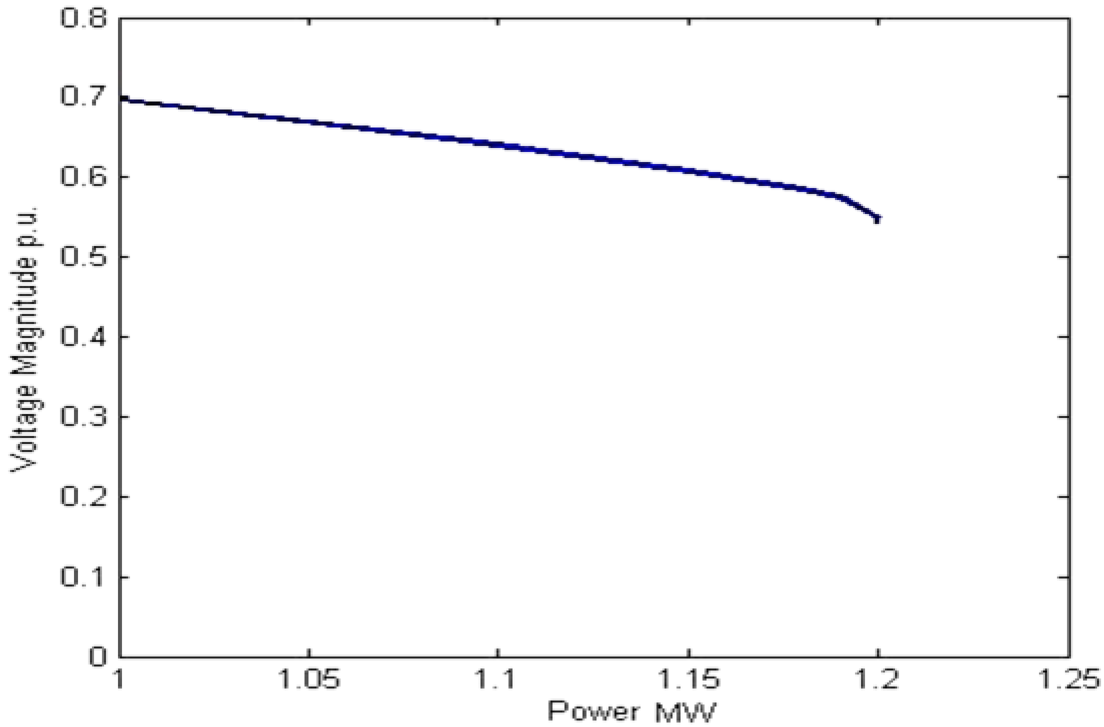


Figure 6. 3 P-V curve at bus 20

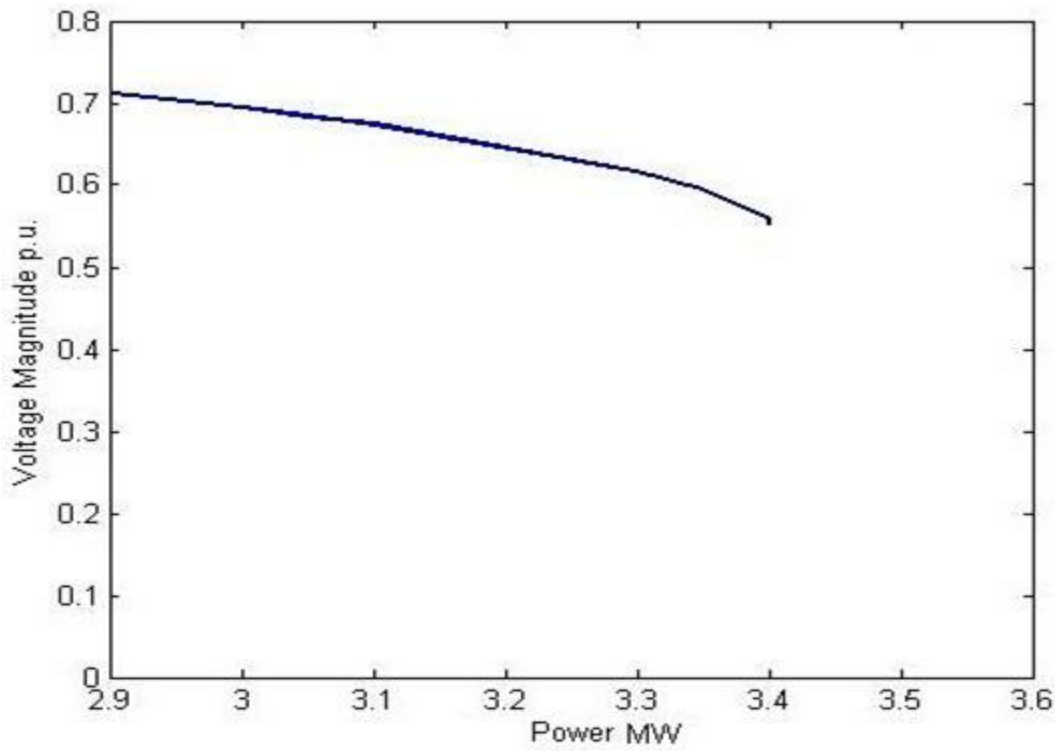


Figure 6. 4 P-V curve at bus 24

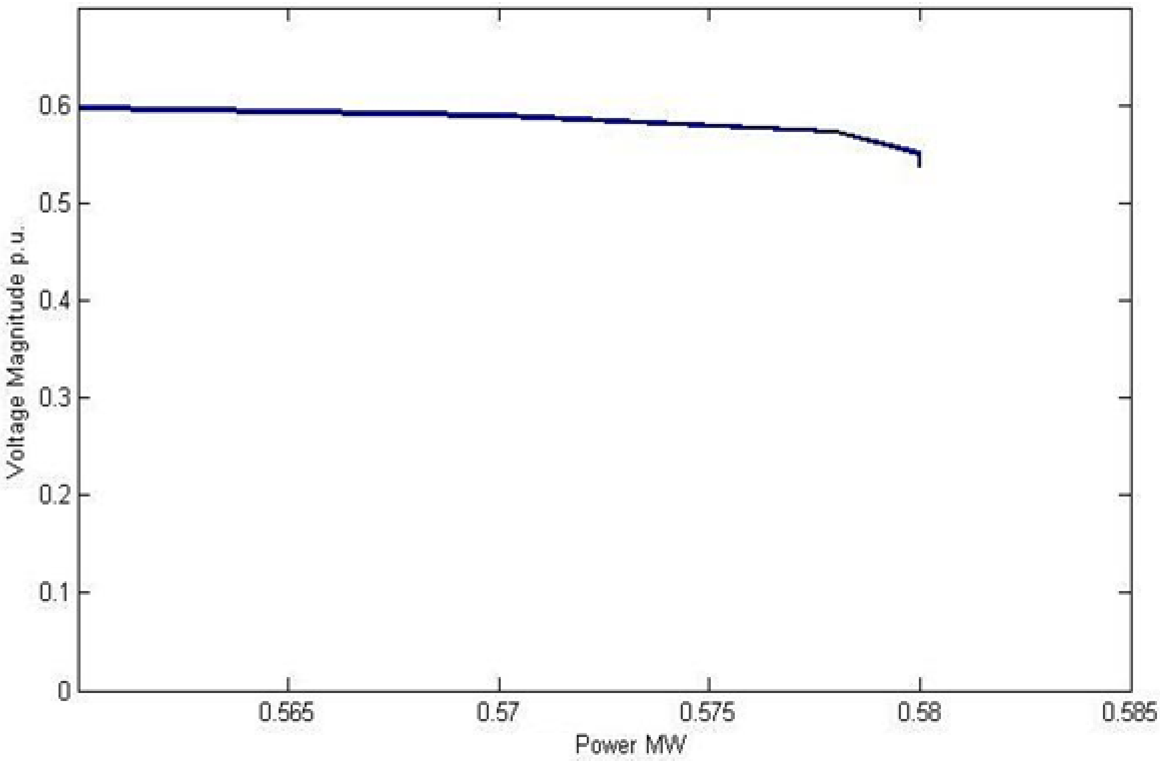


Figure 6. 5 P-V curve at bus 26

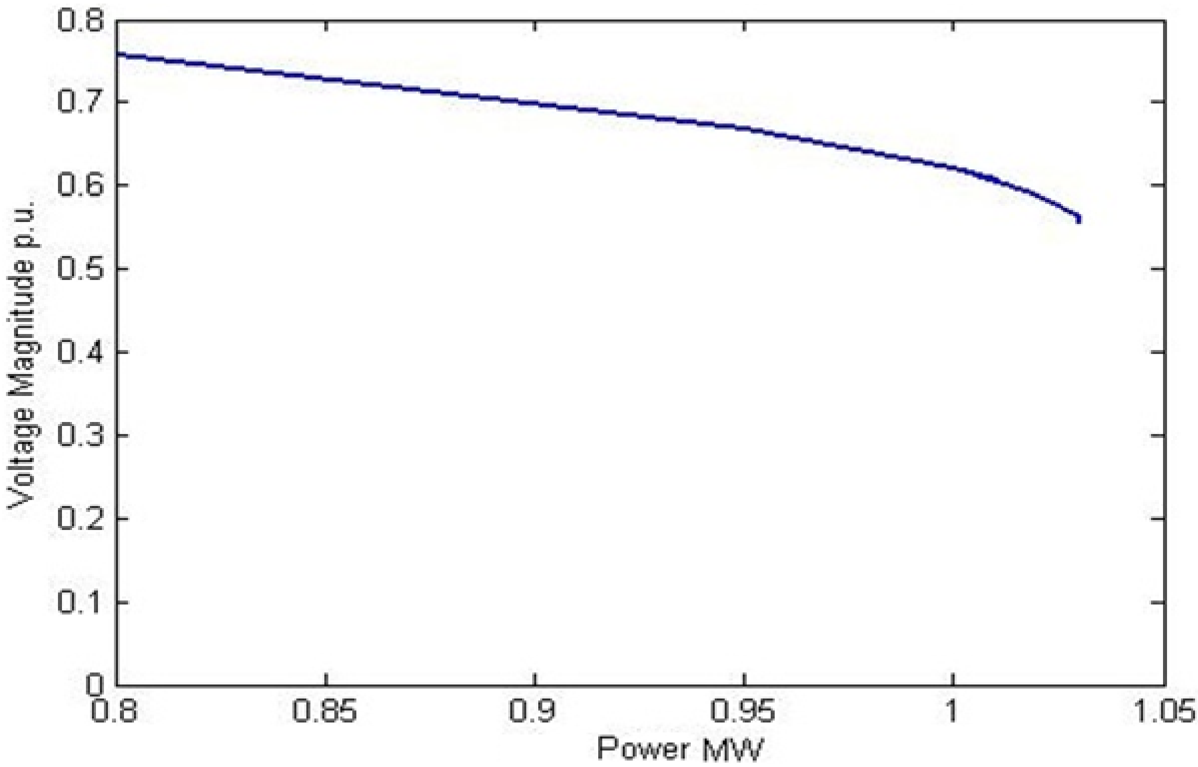


Figure 6. 6 P-V curve at bus 29

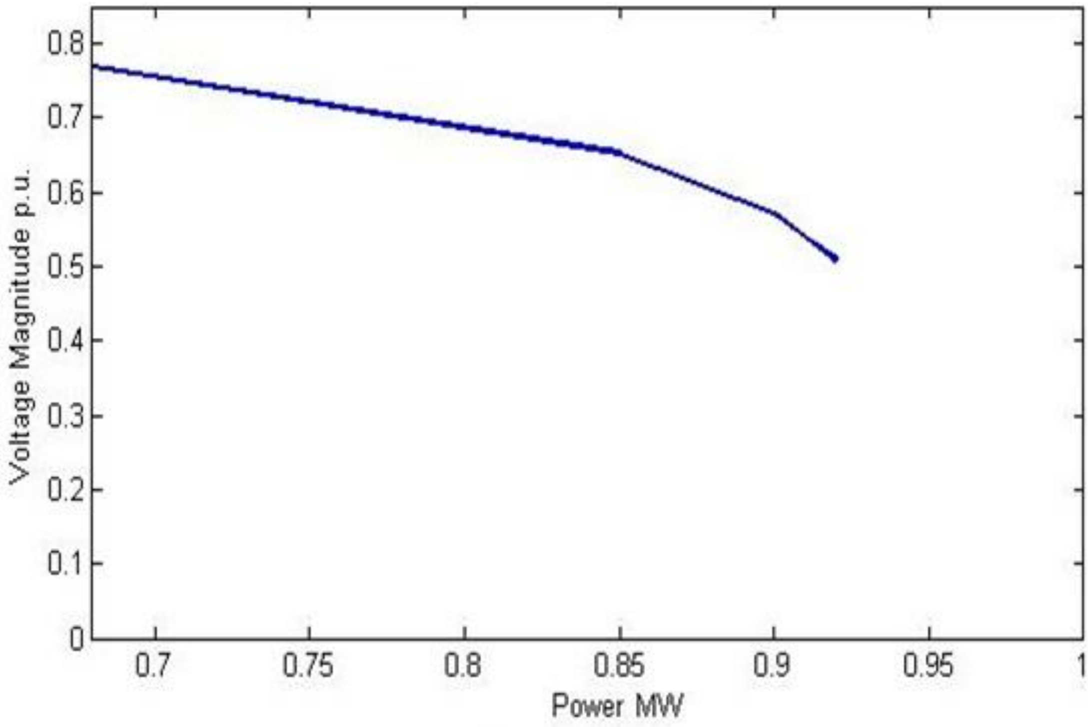


Figure 6. 7 P-V curve at bus 30

System stability is one of the most important parameters in power systems. System stability can be defined as the ability of the system to hold the voltage at a steady state level in all the buses after disturbances in the system. A disturbance might block out one of the pieces of equipment or increase gradually the load in the system. Voltage collapse occurs when increasing load leads to not having enough control over the voltage in some part of the system. Voltage instability is a regional phenomenon, which means it can become a huge voltage collapse in the system.

Voltage collapse can happen when there is not enough controllable reactive power or it is not available to provide to the consumers. If this shortage is big enough, the system voltage will decrease. There are different types of voltage collapse in power networks.

Long-term voltage collapse occurs when generators or power producers are far away from the loads and transmission lines are heavily loaded. So the system will not be able to handle acceptable voltage in the receiving area. This can happen in a couple of minutes or take up to several hours. In classic voltage collapse due to a fault, some part of the system will not operate and then the power system will not be able to provide power to the consumers and loads. A reactive power shortage in the system causes the voltage to decrease. This can happen in between 1 and 5 minutes. In transient voltage collapse, some of the motors stop working and we want to operate them again. This can happen in less than 15 seconds.

6.2. IEEE 30-Bus System with Static Var Compensator

In the section the IEEE 30-bus system will also be demonstrated. In this part, this study will discuss the problem and results after optimal allocation of the SVC in the network. In this case, problems were analysed through the imperialist competitive algorithm and also results related to those obtained using the GA (genetic algorithm) and PSO (particle swarm optimization) techniques were indicated. Different values of SVCs were obtained and power flow and line flow simulation were demonstrated.

The basic required parameters that are used in the optimization program are shown in Table 6.2:

Table 6. 2 Imperialist competitive algorithm basic parameters

Imperialist Competitive Algorithm	Amount
Number of initial country	30
β	2
θ	$\pi/4$
ζ	0.05

In this part a FACTS device which is SVC will be involved and also simulated results including iteration characteristics, voltage deviation and placement, size, installation cost and losses will be discussed. The aim of study is optimal allocation of FACTS devices taking into consideration the size in transmission lines.

The first goal in seeking the optimal place for FACTS devices is to assess the total transfer capability (TTC) in power systems. The total transfer capability in power systems is the maximum power that can be transferred in transmission lines without any disturbances. Also, this parameter can be limited by constraints such as thermal limit in transmission networks. Another aim in this study is to maintain voltage profile in a limited range.

In this section, two main objective functions have been considered in order to compare simulated results with other methods that have already been used. In that work, PSO and the GA have been implemented in the IEEE 30-bus study case.

The parameters are the same as those already used in the IEEE 30-bus study case because of the comparison that was made in the last part. Also, in this section the number of objective functions and constraints are the same as used by the imperialist competitive algorithm. The table below shows a summary of the comparison with other published techniques [88]:

Table 6. 3 Comparison with other published techniques

Method	Bus 1	Size 1 (MVar)	Bus 2	Size 2 (MVar)	Time(S)
PSO [88]	26	50	30	62	546
GA [88]	26	50	30	62	525
BFA [88]	26	51	30	62	8,453
Benders [88]	26	50	30	62	16,463
B&B [88]	26	42	30	62	735
ICA	24	70	20	55	428

In Table 6.3, it can be seen that particle swarm optimization achieved the solution after 546 seconds. In this case, the genetic algorithm obtained the solution faster than PSO. Indeed, both of the methods obtained the same solution in terms of size and place.

The PSO algorithm is an exploratory search method that is based on the idea of collaborative behaviour and swarming in biological populations. Particle swarm optimization is very similar to the genetic algorithm. They are both population-based search approaches and they both depend on information sharing among their population members to enhance their search processes. Basically, the genetic algorithm is a well-established algorithm which matches with various problems.

With regard to the SVC component, the program allocated a value of 70 $MVAr$ at bus 24. As an optimum place, the algorithm reached bus 20 with a value of 55 $MVAr$.

After allocation of the SVC at buses 26 and 30, the level of the voltage profile almost reached unit value. In terms of accuracy in finding an optimal solution to the problem, the PSO technique had a standard deviation of 0.04098. On the other hand, this parameter was 2.5 times bigger in the genetic algorithm, which was 0.10641.

In this case, statistical parameters were calculated for both of the algorithms. A set of 50 trials was carried out. In this case, the convergence ratio of the PSO technique was higher than that of the genetic algorithm: 100 and 34 per cent, respectively.

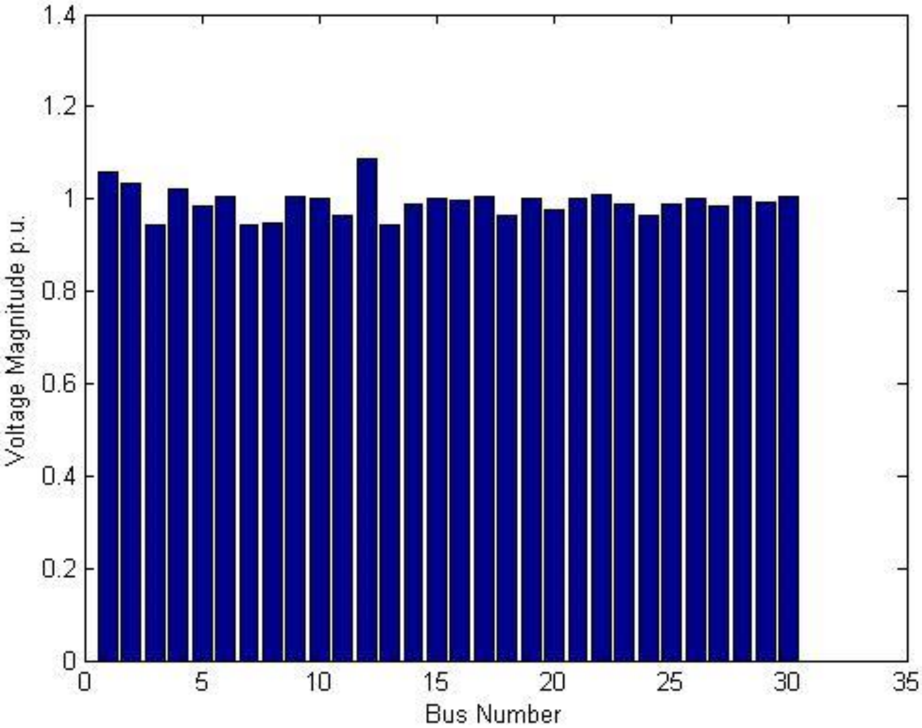


Figure 6. 8 Level of voltage after replacing the SVC by GA & PSO techniques

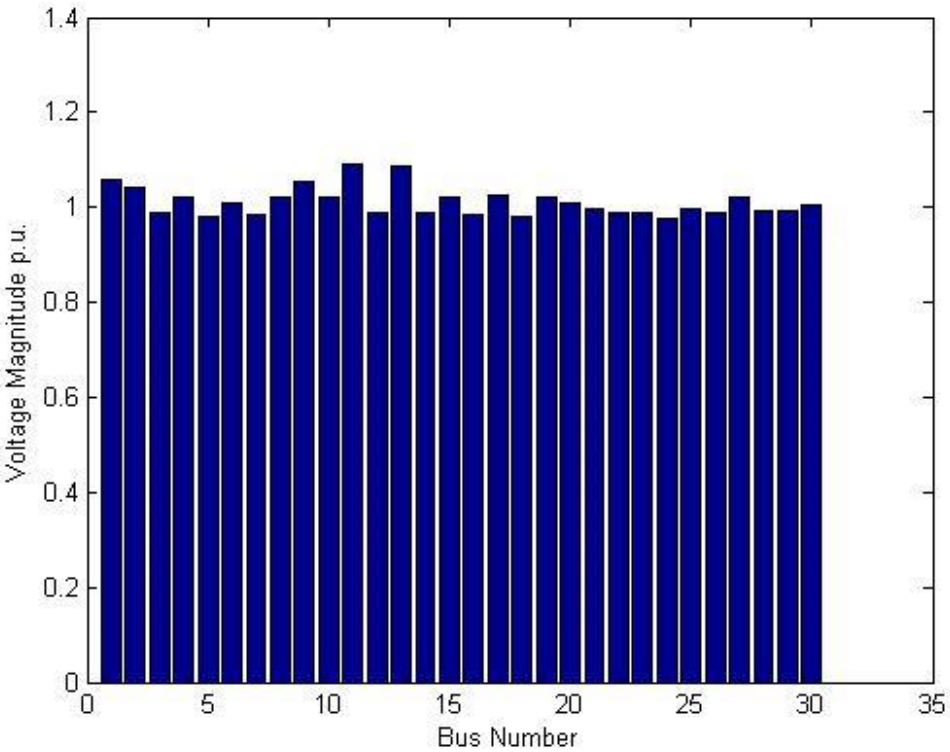


Figure 6. 9 Level of voltage after replacing the SVC at bus 24 & 20

After replacing the SVC at buses 20 and 24 it can be seen that the level of the voltage profile gradually improved.

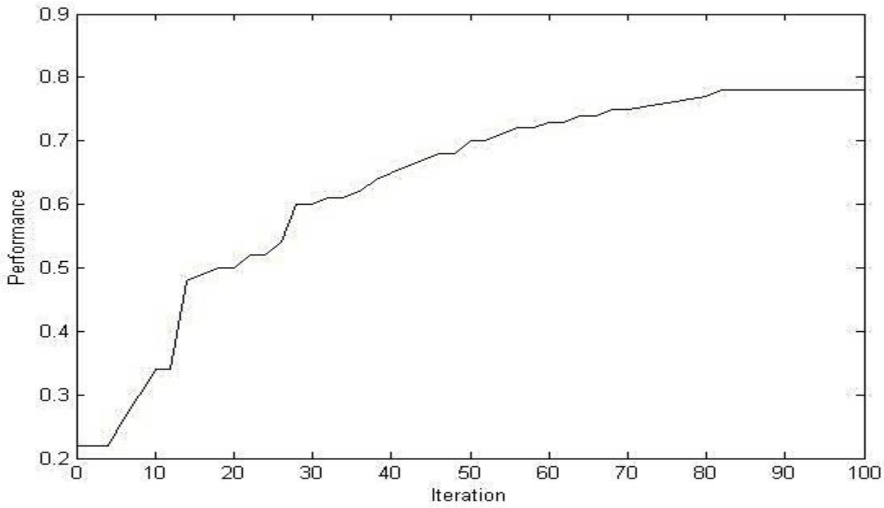


Figure 6. 10 Convergence characteristics after replacing SVC by ICA

In this case study, the imperialist competitive algorithm was implemented in the test system. In Fig. 6.10 it can be seen that the algorithm converged the solution after 83 iterations. It is important to improve the voltage stability in power plants.

Many failures have happened due to voltage instability around the world. To achieve this purpose a few tasks have to be fulfilled such as minimizing real power losses in the system and minimizing voltage deviation from the desired voltage value.

The proposed algorithm in this study gives encouraging results for the case study. This study has investigated different options and methods to increase the power transfer in a network. Several advantages can be seen by optimizing the system using the ICA. Firstly, this can improve the total transfer capability, and secondly, it can reduce losses.

In this regard, two objective functions have been considered: voltage deviation and FACTS size, which have the same number of objective functions as other techniques. The stopping criterion condition in the program was 10^{-4}.

Power flow and line flow simulations after allocating the SVC were carried out on the IEEE 30-bus case study. Also in the simulations, total losses of the power network were shown.

Tables 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.10 and 6.11 show a summary of the power flow and line flow simulations using the SVC in the network.

Table 6. 4 IEEE 30-bus power flow simulation after allocating SVC at bus 30

Bus	**V (p.u)**	**Phase (deg)**	**P gen (p.u)**	**Q gen (p.u)**	**P load (p.u)**	**Q load (p.u)**
Bus 01	1.06	0	7.8889	0.3166	0	0
Bus 02	1.033	-17.172	2.3115	3.725	0.8714	0.51
Bus 03	0.944	-25.655	0	0	0.0964	0.0482
Bus 04	1.02	-31.612	0	0	0.3052	0.0643
Bus 05	0.985	-49.989	0.9863	3.0151	3.7829	0.763
Bus 06	1.003	-37.404	0	0	0	0
Bus 07	0.945	-45.216	0	0	0.9156	0.4377
Bus 08	0.948	-39.621	1.4055	4.5256	1.2047	1.2047
Bus 09	1.005	-46.953	0	0	0	0
Bus 10	1.00	-62.423	0	0	0.2329	0.0803
Bus 11	0.965	-37.377	0.72	1.4573	0	0
Bus 12	1.085	-58.429	0	0	0.4498	0.3012
Bus 13	0.945	-52.456	0.6791	1.9693	0	0
Bus 14	0.988	-65.339	0	0	0.249	0.0643
Bus 15	1.002	-65.951	0	0	0.3293	0.1004
Bus 16	0.998	-62.046	0	0	0.1406	0.0723
Bus 17	1.003	-64.315	0	0	0.3614	0.2329
Bus 18	0.966	-72.565	0	0	0.1285	0.0361
Bus 19	1.002	-74.813	0	0	0.3815	0.1365
Bus 20	0.977	-72.001	0	0	0.0883	0.0281
Bus 21	1.002	-67.52	0	0	0.7028	0.4498
Bus 22	1.008	-67.395	0	0	0	0
Bus 23	0.988	-70.512	0	0	0.1285	0.0643
Bus 24	0.966	-73.523	0	0	0.3494	0.2691
Bus 25	0.987	-76.086	0	0	0	0
Bus 26	1.002	-81.093	0	0	0.1406	0.0924
Bus 27	0.984	-74.717	0	0	0	0
Bus 28	1.004	-40.723	0	0	0	0
Bus 29	0.993	-90.21	0	0	0.0964	0.0361
Bus 30	1.005	-101.524	0	0	0.4257	-1.0194

Table 6.4 presents the power flow results after allocation of the SVC at bus 30. It can be seen that the voltage level at bus number 30 reached the unity value. The voltage level at other bus-bars was also enhanced. Active and also reactive power losses are shown in Table 6.5. In the table it can be seen that losses are higher in some of the transmission lines, which are line numbers 1, 2, 3, 5, 6 and 18. In this problem the aim of the optimization was to improve the voltage profile by allocating the SVC at a bus-bar.

Table 6. 5 IEEE 30-bus line flow simulation after allocating SVC at bus 30

Line No	Line flow with applying SVC at bus 30						Losses with SVC at bus 30	
	Buses	P flow (p.u)	Q flow (p.u)	Buses	P flow (p.u)	Q flow (p.u)	P loss (p.u)	Q loss (p.u)
1	1-2	5.4626	-0.5211	2-1	-4.9486	2.0027	0.514	1.4815
2	1-3	2.4263	0.8377	3-1	-2.1597	0.2154	0.2666	1.0532
3	2-4	1.4993	0.5711	4-2	-1.3608	-0.1829	0.1385	0.3882
4	3-4	2.0633	-0.2636	4-3	-1.9919	0.4619	0.0714	0.1983
5	2-5	2.9108	0.2676	5-2	-2.5329	1.2766	0.3779	1.5442
6	2-6	1.9785	0.3736	6-2	-1.7573	0.2622	0.2212	0.6358
7	4-6	1.6511	-1.0608	6-4	-1.592	1.2592	0.0591	0.1984
8	5-7	-0.2637	0.9755	7-5	0.3111	-0.8748	0.0474	0.1007
9	6-7	1.2819	-0.2816	7-6	-1.2267	0.4371	0.0552	0.1555
10	6-8	0.1608	-2.4483	8-6	-0.0742	2.7431	0.0866	0.2948
11	6-9	0.6134	0.5318	9-6	-0.6134	-0.3741	0	0.1577
12	6-10	0.477	0.5702	10-6	-0.477	-0.2231	0	0.3471
13	9-11	-0.72	-0.9959	11-9	0.72	1.4573	0	0.4615
14	9-10	1.3335	1.3699	10-9	-1.3335	-0.7793	0	0.5906
15	4-12	1.3964	0.7175	12-4	-1.3964	-0.0092	0	0.7083
16	12-13	-0.6791	-1.4564	13-12	0.6791	1.9693	0	0.5129
17	12-14	0.3835	0.2005	14-12	-0.3508	-0.1325	0.0327	0.068
18	12-15	0.8895	0.6269	15-12	-0.7783	-0.4078	0.1112	0.2191
19	12-16	0.3526	0.337	16-12	-0.3207	-0.27	0.0319	0.0671
20	14-15	0.1019	0.0682	15-14	-0.0956	-0.0625	0.0063	0.0057
21	16-17	0.1802	0.1977	17-16	-0.1689	-0.1711	0.0113	0.0266
22	15-18	0.2962	0.185	18-15	-0.2678	-0.127	0.0284	0.058
23	18-19	0.1393	0.0909	19-18	-0.1339	-0.0801	0.0053	0.0108
24	19-20	-0.2476	-0.0564	20-19	0.2551	0.0715	0.0075	0.015
25	10-20	0.3812	0.1839	20-10	-0.3435	-0.0996	0.0377	0.0843
26	10-17	0.1957	0.07	17-10	-0.1926	-0.0618	0.0032	0.0082
27	10-21	0.675	0.4633	21-10	-0.6225	-0.3503	0.0525	0.113
28	10-22	0.3256	0.2048	22-10	-0.3014	-0.1549	0.0242	0.0499
29	21-22	-0.0803	-0.0994	22-21	0.0808	0.1006	0.0006	0.0011
30	15-23	0.2484	0.1849	23-15	-0.2275	-0.1427	0.0209	0.0422
31	22-24	0.2206	0.0543	24-22	-0.2034	-0.0275	0.0172	0.0268
32	23-24	0.099	0.0785	24-23	-0.0929	-0.066	0.0061	0.0125
33	24-25	-0.053	-0.1755	25-24	0.0756	0.2149	0.0225	0.0394
34	25-26	0.1672	0.1321	26-25	-0.1406	-0.0924	0.0266	0.0397
35	25-27	-0.2427	-0.347	27-25	0.2879	0.4332	0.0451	0.0862
36	27-28	1.0516	0.5797	27-28	-1.0516	0.0944	0	0.6741
37	27-29	0.3376	-0.1982	29-27	-0.2862	0.2954	0.0514	0.0972
38	27-30	0.4261	-0.3294	30-27	-0.2843	0.5964	0.1418	0.267
39	29-30	0.1898	-0.3315	30-29	-0.1414	0.4231	0.0484	0.0915
40	8-28	0.2750	0.5777	28-6	-0.2493	-0.5167	0.0257	0.061
41	6-28	0.8161	0.1065	28-6	-0.8024	-0.063	0.0138	0.0436
Total losses							**2.6105**	**11.0366**

Table 6. 6 IEEE 30-bus power flow simulation after allocating SVC at bus 26

Bus	V (p.u)	Phase (deg)	P gen (p.u)	Q gen (p.u)	P load (p.u)	Q load (p.u)
Bus 01	1.06	0	7.9026	0.3216	0	0
Bus 02	1.034	-17.208	2.3208	3.7451	0.8749	0.5121
Bus 03	0.894	-25.697	0	0	0.0968	0.0484
Bus 04	0.879	-31.666	0	0	0.3064	0.0645
Bus 05	1.006	-50.153	0.9903	3.0329	3.7981	0.7661
Bus 06	0.911	-37.463	0	0	0	0
Bus 07	0.907	-45.334	0	0	0.9193	0.4395
Bus 08	1.023	-39.682	1.4112	4.5373	1.2096	1.2096
Bus 09	0.822	-47.032	0	0	0	0
Bus 10	0.661	-62.704	0	0	0.2339	0.0806
Bus 11	1.091	-37.383	0.7229	1.4735	0	0
Bus 12	0.836	-58.721	0	0	0.4516	0.3024
Bus 13	1.088	-52.702	0.6818	1.9934	0	0
Bus 14	0.988	-65.713	0	0	0.25	0.0645
Bus 15	0.958	-66.317	0	0	0.3306	0.1008
Bus 16	0.975	-62.365	0	0	0.1411	0.0726
Bus 17	0.854	-64.648	0	0	0.3629	0.2339
Bus 18	0.847	-73.096	0	0	0.129	0.0363
Bus 19	0.987	-75.42	0	0	0.383	0.1371
Bus 20	0.974	-72.52	0	0	0.0887	0.0282
Bus 21	0.935	-67.865	0	0	0.7056	0.4516
Bus 22	0.895	-67.72	0	0	0	0
Bus 23	0.845	-70.859	0	0	0.129	0.0645
Bus 24	0.875	-73.747	0	0	0.3508	0.2701
Bus 25	0.877	-75.752	0	0	0	0
Bus 26	1.001	-80.745	0	0	0.1411	0.0927
Bus 27	0.815	-74.149	0	0	0	0
Bus 28	0.892	-40.773	0	0	0	0
Bus 29	0.988	-93.722	0	0	0.0968	-1.0189
Bus 30	0.988	-94.27	0	0	0.4274	0.0766

Table 6.6 shows the power flow results after allocating the SVC at bus 26. In this case, the voltage at this bus was improved and reached the unity value. The real power loss at buses 1, 2, 3, 5, 6 and 18 is higher than at other bus-bars. By allocating an SVC at bus 26, it can be seen that the level of the loss is lower than in the previous case. Overall, the level of the voltage profile by allocating the SVC at bus 30 compared with bus 26 was better. In this case, the size of the SVC had an effect on the level of voltage profile improvement.

Table 6. 7 IEEE 30-bus line flow simulation after allocating SVC at bus 26

Line No	Line flow with applying SVC at bus 29						Losses with SVC at bus 29	
	Buses	P flow (p.u)	Q flow (p.u)	Buses	P flow (p.u)	Q flow (p.u)	P loss (p.u)	Q loss (p.u)
1	1-2	5.4738	-0.5214	2-1	-4.9577	2.0092	0.5161	1.4878
2	1-3	2.4288	0.843	3-1	-2.1613	0.2137	0.2675	1.0567
3	2-4	1.5014	0.5761	4-2	-1.3622	-0.186	0.1391	0.3902
4	3-4	2.0646	-0.2621	4-3	-1.993	0.461	0.0716	0.1989
5	2-5	2.9216	0.2715	5-2	-2.5408	1.2848	0.3808	1.5563
6	2-6	1.9806	0.3762	6-2	-1.7588	0.2612	0.2218	0.6375
7	4-6	1.6475	-1.0685	6-4	-1.5882	1.2677	0.0593	0.1991
8	5-7	-0.267	0.982	7-5	0.3151	-0.8796	0.048	0.1024
9	6-7	1.2903	-0.2823	7-6	-1.2343	0.4401	0.056	0.1578
10	6-8	0.1586	-2.4565	8-6	0.0713	2.7536	0.0873	0.2971
11	6-9	0.6121	0.5426	9-6	-0.6121	-0.3823	0	0.1603
12	6-10	0.477	0.5789	10-6	-0.477	-0.2252	0	0.3537
13	9-11	0.7229	1.0030	11-9	0.7229	1.4735	0	0.4705
14	9-10	1.3351	1.3853	10-9	-1.3351	-0.7828	0	0.6025
15	4-12	1.4012	0.7289	12-4	-1.4012	-0.0105	0	0.7184
16	12-13	-0.6818	-1.4688	13-12	0.6818	1.9934	0	0.5247
17	12-14	0.3853	0.2027	14-12	-0.3519	-0.1334	0.0333	0.0693
18	12-15	0.8923	0.6335	15-12	-0.779	-0.4103	0.1133	0.2232
19	12-16	0.3539	0.3407	16-12	-0.3213	-0.2721	0.0326	0.0685
20	14-15	0.1019	0.0689	15-14	-0.0955	-0.0631	0.0064	0.0058
21	16-17	0.1802	0.1996	17-16	-0.1686	-0.1724	0.0116	0.0272
22	15-18	0.2988	0.1884	18-15	-0.2694	-0.1282	0.0295	0.0602
23	18-19	0.1403	0.0919	19-18	-0.1348	-0.0806	0.0056	0.0113
24	19-20	-0.2483	-0.0565	20-19	0.256	0.072	0.0078	0.0156
25	10-20	0.3838	0.1875	20-10	-0.3447	-0.1003	0.039	0.0872
26	10-17	0.1975	0.0699	17-10	-0.1943	-0.0615	0.0033	0.0085
27	10-21	0.6731	0.4649	21-10	-0.6199	-0.3503	0.0533	0.1146
28	10-22	0.3237	0.2051	22-10	-0.2993	-0.1548	0.0244	0.0503
29	21-22	-0.0857	-0.1013	22-21	0.0863	0.1026	0.0006	0.0013
30	15-23	0.2451	0.1843	23-15	-0.2243	-0.1423	0.0208	0.0419
31	22-24	0.2130	0.0522	24-22	-0.1966	-0.0267	0.0164	0.0255
32	23-24	0.0953	0.0778	24-23	-0.0894	-0.0658	0.0059	0.012
33	24-25	-0.1647	-0.1776	25-24	0.0891	0.2201	0.0243	0.0425
34	25-26	0.1677	0.1325	26-25	-0.1411	-0.0927	0.0266	0.0398
35	25-27	-0.2568	-0.3526	27-25	0.3044	0.4435	0.0476	0.0909
36	27-28	1.0431	0.5599	27-28	-1.0431	0.094	0	0.6539
37	27-29	0.4121	-0.4546	29-27	-0.2875	0.69	0.1246	0.2354
38	27-30	0.3265	-0.0829	30-27	-0.2718	0.1859	0.0547	0.103
39	29-30	0.1908	0.329	30-29	-0.1556	-0.2625	0.0352	0.0665
40	8-28	0.2729	0.5741	28-6	-0.2476	-0.5141	0.0253	0.06
41	6-28	0.8089	0.0884	28-6	-0.7955	-0.0458	0.0135	0.0425
Total losses							**2.603**	**11.0707**

Table 6. 8 IEEE -30 bus power flow simulation after allocating SVC at bus 24

Bus	V (p.u)	Phase (deg)	P gen (p.u)	Q gen (p.u)	P load (p.u)	Q load (p.u)
Bus 01	1.06	0	7.9516	0.3016	0	0
Bus 02	1.034	-52.258	2.4248	3.6441	0.8649	0.5320
Bus 03	0.987	-60.677	0	0	0.0988	0.0587
Bus 04	0.988	-66.644	0	0	0.4064	0.0747
Bus 05	1.006	-85.198	0.9953	3.0827	3.5983	0.6868
Bus 06	1.002	-72.474	0	0	0	0
Bus 07	0.907	-80.312	0	0	0.9193	0.4395
Bus 08	1.023	-74.584	1.4919	4.9379	1.2292	1.3097
Bus 09	1.006	-82.132	0	0	0	0
Bus 10	0.961	-97.605	0	0	0.1339	0.0906
Bus 11	1.091	-72.387	0.7829	1.4838	0	0
Bus 12	0.977	-93.721	0	0	0.4518	0.3028
Bus 13	1.088	-87.802	0.6919	1.8938	0	0
Bus 14	0.988	-100.951	0	0	0.25	0.0648
Bus 15	1.006	-101.321	0	0	0.3806	0.1007
Bus 16	0.979	-97.847	0	0	0.1811	0.0826
Bus 17	1.005	-99.528	0	0	0.3829	0.2834
Bus 18	1.005	-108.096	0	0	0.159	0.0368
Bus 19	0.978	-110.42	0	0	0.393	0.1371
Bus 20	0.987	-107.89	0	0	0.0887	0.0282
Bus 21	0.997	-102.741	0	0	0.7096	0.4816
Bus 22	1.005	-102.258	0	0	0	0
Bus 23	0.987	-105.951	0	0	0.159	0.0745
Bus 24	1.001	-108.421	0	0	0.3808	0.2755
Bus 25	0.988	-110.251	0	0	0	0
Bus 26	0.975	-115.644	0	0	0.1654	0.0966
Bus 27	1.007	-109.658	0	0	0	0
Bus 28	0.998	-75.522	0	0	0	0
Bus 29	1.005	-128.888	0	0	0.0978	-1.0219
Bus 30	1.002	-129.844	0	0	0.3574	0.0866

Table 6.8 presents the power flow results after allocation of the SVC at bus 24. It can be seen that the voltage level at bus number 24 reached the unity value. The voltage level at other bus-bars was also improved. Active and also reactive power losses are shown in Table 6.9. In the table it can be seen that losses are higher in some of the transmission lines, which are line numbers 1, 2, 3, 5, 6 and 18. The total real power loss was lower than when the SVC was allocated at buses 30 and 26.

Table 6. 9 IEEE 30-bus line flow simulation after allocating SVC at bus 24

Line No	Line flow with applying SVC at bus 24						Losses with SVC at bus 24	
	Buses	P flow (p.u)	Q flow (p.u)	Buses	P flow (p.u)	Q flow (p.u)	P loss (p.u)	Q loss (p.u)
1	1-2	5.4843	-0.5152	2-1	-4.9604	2.1237	0.5239	1.6085
2	1-3	2.4393	0.8492	3-1	-2.164	0.3282	0.2753	1.1774
3	2-4	1.5119	0.5823	4-2	-1.3649	-0.0715	0.147	0.5108
4	3-4	2.0751	-0.2559	4-3	-1.9957	0.5755	0.0794	0.3196
5	2-5	2.9321	0.2777	5-2	-2.5435	1.3993	0.2886	0.1678
6	2-6	1.9911	0.3824	6-2	-1.7615	0.3757	0.1296	0.7581
7	4-6	1.658	-1.0623	6-4	-1.5909	1.3822	0.0671	0.0315
8	5-7	-0.2565	0.9882	7-5	0.3124	-0.7651	0.0559	0.2231
9	6-7	1.3008	-0.2761	7-6	-1.237	0.5546	0.0638	0.2785
10	6-8	0.1691	-2.4452	8-6	0.0686	2.8681	0.2377	0.4229
11	6-9	0.6226	0.5488	9-6	-0.6148	-0.2678	0.0078	0.281
12	6-10	0.4875	0.5851	10-6	-0.4797	-0.1107	0.0078	0.0471
13	9-11	0.7334	1.0632	11-9	0.7202	1.588	0.0458	0.5287
14	9-10	1.3456	1.3915	10-9	-1.3378	-0.6683	0.0078	0.5284
15	4-12	1.4117	0.7351	12-4	-1.4039	0.104	0.0078	0.0854
16	12-13	-0.6713	-1.4626	13-12	0.6791	2.1079	0.0078	0.0648
17	12-14	0.3958	0.2089	14-12	-0.3546	-0.0189	0.0412	0.19
18	12-15	0.9028	0.6397	15-12	-0.7817	-0.2958	0.0125	0.3439
19	12-16	0.3644	0.3469	16-12	-0.324	-0.1576	0.0404	0.1893
20	14-15	0.1124	0.0751	15-14	-0.0982	0.0514	0.0142	0.1265
21	16-17	0.1907	0.2058	17-16	-0.1713	-0.0579	0.0194	0.1479
22	15-18	0.3093	0.1946	18-15	-0.2721	-0.0137	0.0372	0.1809
23	18-19	0.1508	0.0981	19-18	-0.1375	0.0339	0.0133	0.132
24	19-20	-0.2378	-0.0503	20-19	0.2533	0.1865	0.0155	0.1362
25	10-20	0.3943	0.1937	20-10	-0.3474	0.0142	0.0469	0.1258
26	10-17	0.208	0.0761	17-10	-0.197	0.053	0.011	0.1291
27	10-21	0.6836	0.4711	21-10	-0.6226	-0.2358	0.061	0.0258
28	10-22	0.3342	0.2113	22-10	-0.302	-0.0403	0.0322	0.171
29	21-22	-0.0752	-0.0951	22-21	0.0836	0.2171	0.0084	0.122
30	15-23	0.2556	0.1905	23-15	-0.227	-0.0278	0.0286	0.1627
31	22-24	0.2235	0.0584	24-22	-0.1993	0.0878	0.0242	0.1462
32	23-24	0.1058	0.084	24-23	-0.0921	0.0487	0.0137	0.1327
33	24-25	-0.1542	-0.1714	25-24	0.0864	0.3346	-0.0678	0.1632
34	25-26	0.1782	0.1387	26-25	-0.1438	0.0218	0.0344	0.1605
35	25-27	-0.2463	-0.3464	27-25	0.3017	0.558	0.0554	0.0215
36	27-28	1.0536	0.5661	27-28	-1.0458	0.2085	0.0078	0.0747
37	27-29	0.4226	-0.4484	29-27	-0.2902	0.8045	0.0258	0.1561
38	27-30	0.337	-0.0767	30-27	-0.2745	0.3004	0.0625	0.2237
39	29-30	0.2013	0.3352	30-29	-0.1583	-0.148	0.043	0.1872
40	8-28	0.2834	0.5803	28-6	-0.2503	-0.3996	0.0331	0.1807
41	6-28	0.8194	0.0946	28-6	-0.7982	0.0687	0.0212	0.1633
Total losses							**2.5882**	**10.8265**

Table 6. 10 IEEE 30-bus power flow simulation after allocating SVC at bus 20

Bus	V (p.u)	Phase (deg)	P gen (p.u)	Q gen (p.u)	P load (p.u)	Q load (p.u)
Bus 01	1.06	0	7.7027	0.3415	0	0
Bus 02	1.04	-40.116	2.2204	3.6457	0.7742	0.5628
Bus 03	0.988	-48.605	0	0	0.0958	0.0584
Bus 04	1.02	-54.574	0	0	0.3064	0.0455
Bus 05	0.97	-73.061	0.8925	3.0824	3.2621	0.9861
Bus 06	1.011	-60.371	0	0	0	0
Bus 07	0.983	-68.242	0	0	0.9243	0.4685
Bus 08	1.023	-62.59	1.5112	4.2473	1.1954	1.1996
Bus 09	1.055	-69.94	0	0	0	0
Bus 10	1.023	-85.612	0	0	0.3239	0.0847
Bus 11	1.091	-60.291	0.7549	1.4735	0	0
Bus 12	0.978	-81.629	0	0	0.4656	0.3085
Bus 13	1.088	-75.61	0.6852	1.9794	0	0
Bus 14	0.977	-88.621	0	0	0.25	0.0689
Bus 15	1.02	-89.225	0	0	0.3306	0.1054
Bus 16	0.986	-85.273	0	0	0.1847	0.0627
Bus 17	1.025	-87.556	0	0	0.2659	0.3229
Bus 18	0.952	-96.004	0	0	0.119	0.0469
Bus 19	1.023	-98.328	0	0	0.383	0.1479
Bus 20	1.01	-95.428	0	0	0.1087	0.0287
Bus 21	0.998	-90.773	0	0	0.8056	0.3525
Bus 22	0.988	-90.628	0	0	0	0
Bus 23	0.987	-93.767	0	0	0.1356	0.0745
Bus 24	0.978	-96.655	0	0	0.4306	0.2809
Bus 25	0.998	-98.66	0	0	0	0
Bus 26	0.978	-103.653	0	0	0.1411	0.0927
Bus 27	1.02	-97.057	0	0	0	0
Bus 28	0.992	-63.681	0	0	0	0
Bus 29	0.993	-116.63	0	0	0.0988	-1.0209
Bus 30	1.003	-117.178	0	0	0.5276	0.0964

Table 6.10 shows the power flow results after allocating the SVC at bus 20. In this case, the voltage at this bus was improved and reached the unity value. The real power loss at buses 1, 2, 4, 5, 6, 13 and 41 is higher than at other bus-bars. By allocating the SVC at bus 20, it can be seen that the level of the loss is lower than in the previous cases. Overall, the level of the voltage profile by allocating the SVC at bus 24 compared with bus 20 was better. In this case, the objective function was defined to allocate the SVC to improve the voltage profile. By adding another objective another solution can be found to minimize the losses in the network as well.

Table 6. 11 IEEE 30-bus line flow simulation after allocating SVC at bus 20

Line No	Line flow with applying SVC at bus 20						Losses with SVC at bus 20	
	Buses	P flow (p.u)	Q flow (p.u)	Buses	P flow (p.u)	Q flow (p.u)	P loss (p.u)	Q loss (p.u)
1	1-2	5.5525	-0.7063	2-1	-4.9509	1.0098	0.6016	0.3035
2	1-3	2.0123	0.4525	3-1	-2.1545	0.2565	0.1422	0.709
3	2-4	1.5349	0.3951	4-2	-1.4563	0.0277	0.0786	0.4228
4	3-4	2.0981	-0.247	4-3	-1.9862	0.6747	0.1119	0.4277
5	2-5	2.6551	0.2866	5-2	-2.534	1.4985	0.1211	1.7851
6	2-6	1.8557	0.3913	6-2	-1.752	0.4749	0.1037	0.0862
7	4-6	1.681	-1.5285	6-4	-1.5814	1.4814	0.0996	-0.0471
8	5-7	-0.2335	0.7991	7-5	-0.1219	-0.6659	-0.3554	0.1332
9	6-7	1.3238	-0.2672	7-6	-1.2275	0.6538	0.0963	0.388
10	6-8	0.1921	-2.3514	8-6	-0.1524	2.0673	0.0275	0.0819
11	6-9	0.6456	0.5577	9-6	-0.6053	-0.1686	0.0403	0.3891
12	6-10	0.5105	0.594	10-6	-0.4702	-0.0115	0.0403	0.0525
13	9-11	0.7564	1.0945	11-9	-0.5245	0.7558	0.2319	0.0781
14	9-10	1.3686	1.004	10-9	-1.3283	-0.5691	0.0403	0.0813
15	4-12	1.4001	0.2522	12-4	-1.3944	0.2032	0.0057	0.4554
16	12-13	-0.6483	-1.4537	13-12	0.4558	2.2071	-0.1925	0.0753
17	12-14	0.4188	0.2178	14-12	-0.3451	0.0803	0.0737	0.0298
18	12-15	0.7956	0.2356	15-12	-0.7722	-0.1966	0.0234	0.452
19	12-16	0.3874	0.3558	16-12	-0.3145	-0.0584	0.0729	0.0297
20	14-15	0.1354	0.084	15-14	-0.0887	0.1506	0.0467	0.2346
21	16-17	0.2137	0.2147	17-16	-0.1618	0.0413	0.0519	0.256
22	15-18	0.3323	0.2035	18-15	-0.2626	0.0855	0.0697	0.289
23	18-19	0.1738	0.107	19-18	-0.128	0.1331	0.0458	0.2401
24	19-20	-0.2148	-0.0414	20-19	0.1628	0.2857	-0.052	0.2443
25	10-20	0.4173	0.2026	20-10	-0.3379	0.1134	0.0794	0.316
26	10-17	0.231	0.085	17-10	-0.1875	0.1522	0.0435	0.2372
27	10-21	0.7066	0.48	21-10	-0.6131	-0.1366	0.0935	0.0343
28	10-22	0.3572	0.2202	22-10	-0.2925	0.0589	0.0647	0.2791
29	21-22	-0.0522	-0.0862	22-21	0.0931	0.3163	0.0409	0.023
30	15-23	0.2786	0.1994	23-15	-0.2175	0.0714	0.0611	0.0278
31	22-24	0.2465	0.0673	24-22	-0.1898	0.187	0.0567	0.2543
32	23-24	0.1288	0.0929	24-23	-0.0826	0.1479	0.0462	0.2408
33	24-25	-0.1312	-0.1625	25-24	0.0959	0.2335	0.0353	0.071
34	25-26	0.2012	0.1476	26-25	-0.1343	0.121	0.0669	0.2686
35	25-27	-0.2233	-0.3375	27-25	0.2114	0.6572	-0.0119	0.3197
36	27-28	1.0766	0.3255	27-28	-1.0363	0.3077	0.0403	0.0887
37	27-29	0.4456	-0.4395	29-27	-0.3807	0.9037	0.0649	0.0464
38	27-30	0.36	-0.0678	30-27	-0.265	0.3996	0.095	0.3318
39	29-30	0.1524	0.3441	30-29	-0.1488	-0.0488	0.0036	0.2953
40	8-28	0.3064	0.8854	28-6	-0.2408	-0.3004	0.0656	0.585
41	6-28	0.9525	0.1035	28-6	-0.7887	0.1679	0.1638	0.2714
Total losses							**2.5347**	**10.8879**

In this part, the IEEE 30-bus system was demonstrated as it is. The test system was analysed with and without using the SVC in the network. The voltage level was quite low before allocating the SVC in the network and it fluctuates in different bus-bars.

In this case, the SVC was allocated in four places: bus numbers 20, 24, 26 and 30. The voltage level was demonstrated individually in this regard. The power network approached to the different losses using the SVC in different places. In terms of losses, by allocating the SVC at bus 20, the network achieved the least losses.

The aim of this analysis was to discover the behaviour of an SVC using different optimization techniques. All the evolutionary algorithms, including the ICA, improved the voltage profile and security of the system.

6.3. IEEE 30-Bus System with Unified Power Flow Controller

In this study, the ICA technique was implemented in the IEEE 30-bus system. Also, the optimal place to allocate the UPFC was demonstrated. PSO and GA results were also discussed. In this case, PSO and GA techniques demonstrated different branches in terms of line priority in allocating the UPFC.

The voltage of the buses was also demonstrated before and after installing the UPFC. Line losses were also discussed taking into consideration the UPFC in different places with different techniques. The Load-ability of the network after installing the UPFC was enhanced and illustrated.

Table 6.12 presents a summary of the optimal place for the UPFC in the IEEE 30-bus system [23], [24], [53]:

Table 6. 12 IEEE 30-bus system using UPFC

Optimisation method	Optimal place	Losses	V_{se}	$\emptyset_{se}$	i_{sh}
PSO [23], [24], [53]	3-4	2.5503	0.2408	68	0.0106
	3-4 25-27	2.314	0.2125 0.2749	66 84	-0.0686 -0.0495
	5-7 21-22 1-2	1.9755	0.1018 0.0945 0.1182	114 218 102	0.1094 -0.0146 0.0174
GA [23], [24], [53]	16-17	2.5455	0.2302	74	0.0156
	3-4 12-15	2.1865	0.1892 0.2015	111 218	0.0365 -0.0187
	3-4 15-18 22-24	1.7841	0.1798 0.1875 0.1258	98 119 242	0.0589 0.1589 0.0254
ICA	24-23	2.5355	0.2389	85	0.0198
	24-23 20-10	2.1233	0.1158 0.2155	112 95	0.0158 0.0258
	24-23 20-10 30-27	1.6589	0.1101 0.1854 0.1154	211 245 80	0.0154 -0.0112 0.0685

In this case ICA has been run for three times to allocate the UPFC in the network. In the first run, algorithm placed the UPFC between bus 24 and 23. After allocating, algorithm was run again with considering the UPFC between bus 24 and 23. This time algorithm placed the UPFC between bus 20 and 10. So network got benefit of having two UPFCs. Algorithm also was run for the third time, this time algorithm reached bus 30 and 27 to allocate UPFC between them. With having three UPFCs in the system it can be seen that losses reduced to 1.6589. The level of the voltage profile after replacing the UPFC in the network is illustrated in the following tables.

It can be seen that the level of the voltage profile using a greater number of UPFCs was better than for the single component. Tables 6.13, 6.14 and 6.15 show the level of the voltage using one, two and three UPFC devices in the network, respectively.

Table 6. 13 Level of the voltage profile after replacing one UPFC in the network

Bus	Bus voltage before UPFC	Bus voltage with UPFC using GA	Bus voltage with UPFC using PSO	Bus voltage with UPFC using ICA
Bus 01	1.05	1.05	1.05	1.05
Bus 02	1.034	1.012	1.02	1.015
Bus 03	0.958	0.935	1.016	0.955
Bus 04	0.946	0.940	1.003	0.978
Bus 05	1.006	1.002	1.003	1.005
Bus 06	0.959	0.95	1.002	0.988
Bus 07	0.948	0.977	0.985	0.981
Bus 08	1.023	1.02	1.01	1.02
Bus 09	0.937	0.945	0.945	0.978
Bus 10	0.848	0.998	0.925	0.945
Bus 11	1.091	1.055	1.025	1.06
Bus 12	0.953	1.021	1.015	0.965
Bus 13	1.088	1.023	1.055	1.055
Bus 14	0.884	0.988	0.93	0.988
Bus 15	0.853	0.935	0.925	0.995
Bus 16	0.881	0.944	0.935	0.978
Bus 17	0.837	0.925	0.915	0.936
Bus 18	0.801	0.922	0.915	0.924
Bus 19	0.783	0.944	0.93	0.935
Bus 20	0.735	0.901	0.895	0.902
Bus 21	0.792	0.912	0.855	0.901
Bus 22	0.792	0.915	0.885	1.01
Bus 23	0.783	0.901	0.845	0.945
Bus 24	0.723	0.912	0.862	1.01
Bus 25	0.694	0.895	0.815	0.985
Bus 26	0.602	0.887	0.825	0.955
Bus 27	0.723	0.899	0.878	0.945
Bus 28	0.932	0.956	0.945	0.985
Bus 29	0.775	0.878	0.853	0.945
Bus 30	0.768	0.901	0.878	0.925

The table demonstrates the level of the voltage profile using one UPFC in the network. It can be seen that the level of the voltage before optimization has not reached the unity value. In this case, three evolutionary algorithms were implemented in the case study. As shown in Table 6.12, the UPFC was placed between lines 16 and 17 by GA and PSO technique placed UPFC between line 3 and 4. The ICA technique allocated the UPFC between lines 24 and 23. The voltage level in those lines was improved and reached the unity value. In this case, the loss from using the GA was lower than with the PSO technique and the ICA technique also achieved the least losses in this regard. The level of the voltage profile was improved in all the buses.

Table 6. 14 Level of the voltage profile after replacing two UPFCs in the network

Bus	Bus voltage before UPFC	Bus voltage with UPFC using GA	Bus voltage with UPFC using PSO	Bus voltage with UPFC using ICA
Bus 01	1.05	1.05	1.05	1.05
Bus 02	1.034	1.035	1.038	1.037
Bus 03	0.958	1.012	1.015	0.966
Bus 04	0.946	1.011	1.005	0.955
Bus 05	1.006	1.002	1.001	1.002
Bus 06	0.959	1.001	1.012	0.965
Bus 07	0.948	0.955	0.945	0.955
Bus 08	1.023	1.012	1.02	1.018
Bus 09	0.937	0.965	0.955	0.965
Bus 10	0.848	0.955	0.899	1.021
Bus 11	1.091	1.035	1.023	1.025
Bus 12	0.953	1.012	1.05	0.985
Bus 13	1.088	1.054	1.055	1.05
Bus 14	0.884	0.998	0.925	0.944
Bus 15	0.853	1.022	0.905	0.988
Bus 16	0.881	0.989	0.901	0.901
Bus 17	0.837	0.925	0.915	0.955
Bus 18	0.801	0.989	0.988	0.925
Bus 19	0.783	0.985	0.974	0.985
Bus 20	0.735	0.978	0.965	1.02
Bus 21	0.792	0.945	0.935	0.995
Bus 22	0.792	0.965	0.955	0.998
Bus 23	0.783	0.988	0.988	1.012
Bus 24	0.723	0.925	0.989	1.001
Bus 25	0.694	0.895	1.011	0.989
Bus 26	0.602	0.855	0.998	0.925
Bus 27	0.723	0.975	1.001	0.845
Bus 28	0.932	0.964	0.985	0.989
Bus 29	0.775	0.895	0.982	0.925
Bus 30	0.768	0.836	0.965	0.862

Table 6.14 presents the voltage level using two UPFCs in the network. In this case, the PSO technique placed the UPFCs between lines 3-4 and 25-27. The GA allocated the UPFCs between lines 3-4 and 12-15. The ICA allocated the UPFCs between lines 24-23 and 20-10. The level of the voltage profile in the allocated bas-bars reached the unity value. In

this case, the ICA technique was better than other algorithms in terms of losses. The voltage level using two UPFCs was better than using a single UPFC in the network. In this case, the level of the cost will be increased because of the number of components.

Table 6. 15 Level of the voltage profile after replacing three UPFCs in the network

Bus	Bus voltage before UPFC	Bus voltage with UPFC using GA	Bus voltage with UPFC using PSO	Bus voltage with UPFC using ICA
Bus 01	1.05	1.05	1.05	1.05
Bus 02	1.034	1.029	1.025	1.038
Bus 03	0.958	1.02	1.00	0.966
Bus 04	0.946	1.012	0.988	0.958
Bus 05	1.006	1.002	1.002	1.002
Bus 06	0.959	0.988	0.985	0.963
Bus 07	0.948	0.974	1.001	0.959
Bus 08	1.023	1.011	1.01	1.015
Bus 09	0.937	0.975	0.985	0.965
Bus 10	0.848	0.964	0.978	1.019
Bus 11	1.091	1.035	1.025	1.03
Bus 12	0.953	0.988	0.998	0.988
Bus 13	1.088	1.056	1.065	1.055
Bus 14	0.884	0.945	0.955	0.974
Bus 15	0.853	1.021	0.98	0.987
Bus 16	0.881	0.99	0.945	0.945
Bus 17	0.837	0.945	0.925	0.956
Bus 18	0.801	1.001	0.978	0.965
Bus 19	0.783	0.985	0.975	0.985
Bus 20	0.735	0.988	0.955	1.02
Bus 21	0.792	0.955	1.001	0.985
Bus 22	0.792	1.001	1.021	0.986
Bus 23	0.783	0.984	0.985	1.012
Bus 24	0.723	1.005	0.985	1.001
Bus 25	0.694	0.912	0.955	0.989
Bus 26	0.602	0.905	0.921	0.965
Bus 27	0.723	0.925	0.955	1.02
Bus 28	0.932	0.975	0.945	0.975
Bus 29	0.775	0.915	0.895	0.975
Bus 30	0.768	0.845	0.901	1.012

Table 6.15 presents the level of the voltage profile using three UPFCs in the network. In this case, PSO allocated a UPFC between lines 5-7, 21-22 and 1-2. The GA placed a UPFC between lines 3-4, 15-18 and 22-24. The ICA technique allocated a UPFC between lines 24-

23, 20-10 and 30-27. It can be seen that the level of the losses through the ICA technique was lower than with other techniques. The level of the voltage profile of the whole network was improved significantly. But the cost of installation and maintenance of the UPFC is another issue that should be considered through the design and optimization. The level of the voltage profile reached the unity value in the UPFC installation places. It can be seen that by using UPFCs in the network, losses can be reduced and the voltage profile improved.

After replacing the UPFC in the transmission networks using evolutionary algorithms, it can be seen that the level of the voltage profile almost reached the unity level and the voltage level at unstable bus-bars was improved.

In this case, the number of UPFC devices used in the network is important. Obviously if the network benefits from a greater number of UPFCs, it will have higher security in terms of breakdown or overload and disturbances. The other point that can be seen is that the network will be more stable by using a greater number of FACTS devices.

Another point to mention in this part is local networks. In this regard, some improvement can be made using local generators as it is not a good idea to install a compensator device in the network whenever it is required. This is because sometimes it will be less expensive to install a local generator rather than installing FACTS components.

Voltage deviation is one of the major issues that all industries must also consider; voltage level can be divided from a millisecond to a few seconds. Therefore, installing SVC and UPFC devices in different places can solve the voltage sag problem and supply high quality power in the network.

6.4. Results Comparison

In the last three parts this study has demonstrated IEEE-30 bus system simulation. In this case, the test system was allocated by the SVC and UPFC separately. Here in this part this study is going to present a comparison between the evolutionary algorithms. After installing FACTS components, it can be seen that the voltage level became quite stable. Table 6.16 presents a summary of losses using different algorithms. In this case, the PSO, GA and ICA techniques based on the allocation of SVCs were considered.

Table 6. 16 Summary of the losses Using SVC with different algorithms

Optimisation method	Bus no.	Total losses p.u.
PSO	26	2.603
	30	2.6105
GA	26	2.603
	30	2.6105
ICA	24	2.5882
	20	2.5347

In this case, the PSO and GA algorithms allocated the SVC in the same place in the transmission system. According to the results, it can be seen that the level of the loss that was achieved through the ICA was slightly lower than with other algorithms. Figure 6.11 presents a summary of the losses based on both compensators. A comparison of convergence time is illustrated in Figure 6.12.

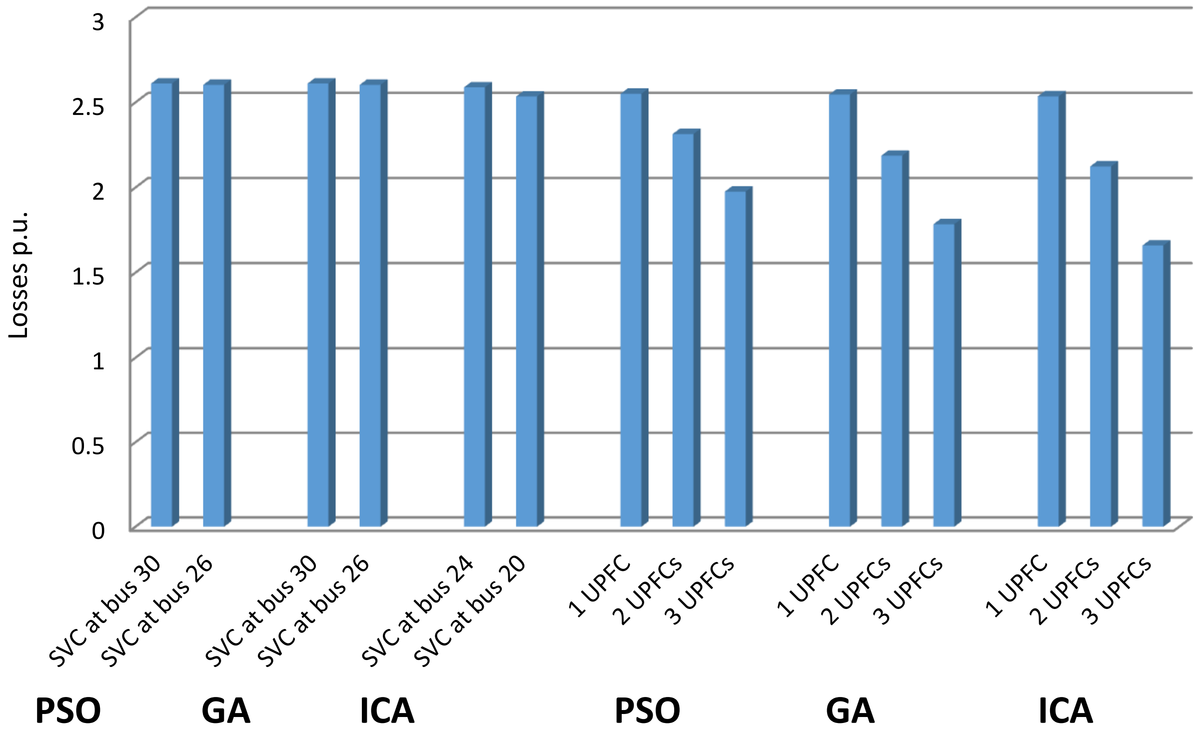


Figure 6. 11 Level of the losses with different scenarios

In Fig. 6.11, it can be seen that the level of losses with PSO and the GA in terms of allocating SVCs in the network was the same. In this case, the ICA technique was slightly better than both the other algorithms. The ICA technique achieved a lower amount of losses in the case of the SVC at bus number 20. With regard to the UPFC devices, three scenarios were illustrated. UPFCs were connected to the network individually and in combination. All three algorithms almost reached the same level of losses. When two UPFCs were used, the GA and ICA techniques were better than the PSO technique; however, the ICA technique was better than the GA in this case.

In terms of the three UPFCs, it can be seen that the level of losses dropped sharply. All three algorithms presented good achievement in terms of loss reduction. In this case, the ICA algorithm was better than both the other algorithms. In this analysis the cost of FACTS was not involved. Taking into considering the cost function it may obtain different results to those presented in this study. Fig. 6.12 presents the convergence time of all three algorithms in terms of allocation of SVCs in the network. It can be seen that the ICA was the fastest one to converge to the solution.

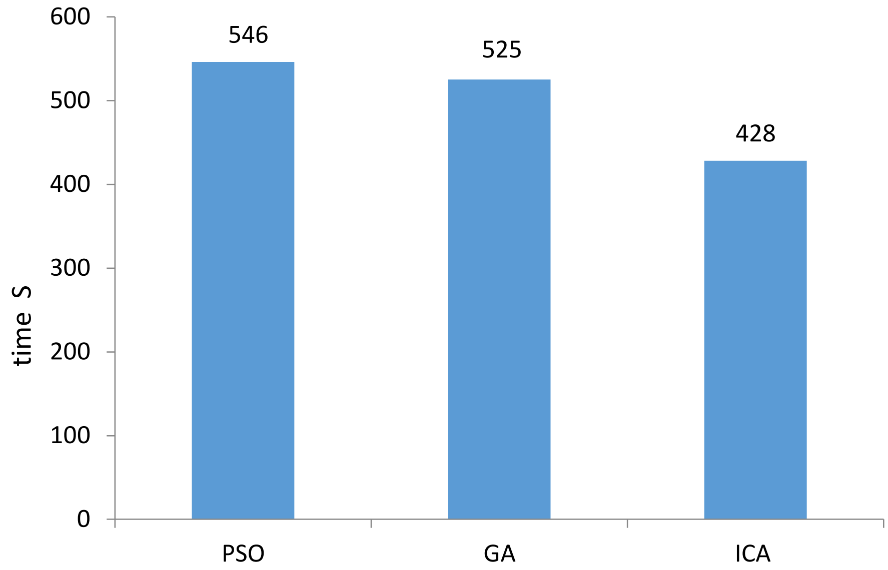


Figure 6. 12 Comparison of convergence time

Average bus voltages is shown next. Figures 6.13, 6.14 and 6.15 indicate the average voltage using different numbers of UPFCs in the network. By using one UPFC in the network, it can be seen that the level of the PSO algorithm was lower than the other techniques. However, by using two UPFCs in the network, the voltage level with the GA and ICA was almost the same.

In terms of three UPFCs in the network, the ICA technique was slightly better than the GA. The voltage level before optimisation was noticeable. The averages of the voltage almost reach the unity level after allocating the UPFCs in the network.

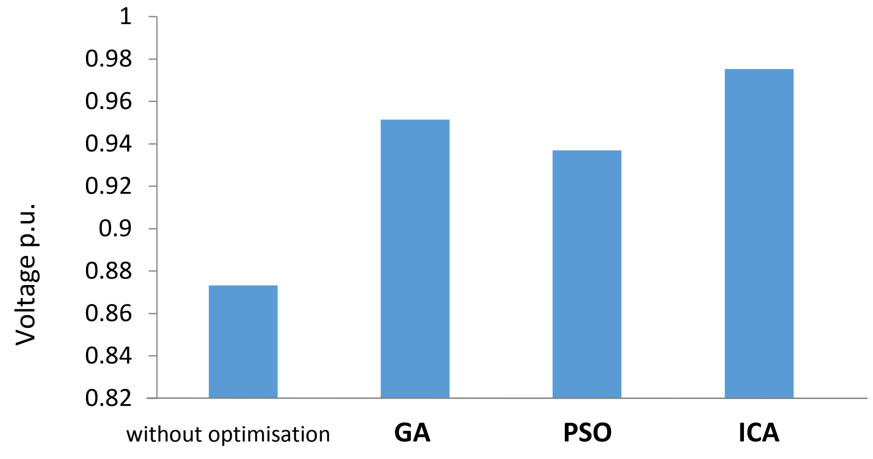


Figure 6. 13 Average of bus voltage using one UPFC

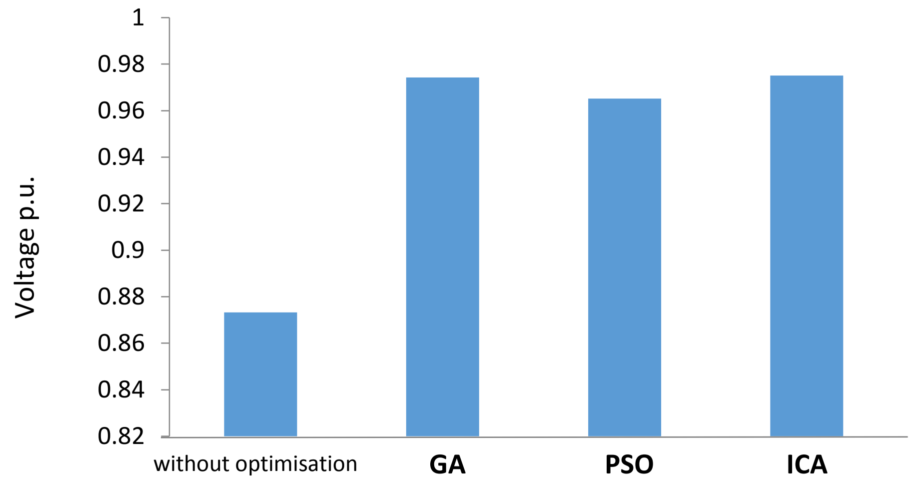


Figure 6. 14 Average of bus voltage using two UPFCs

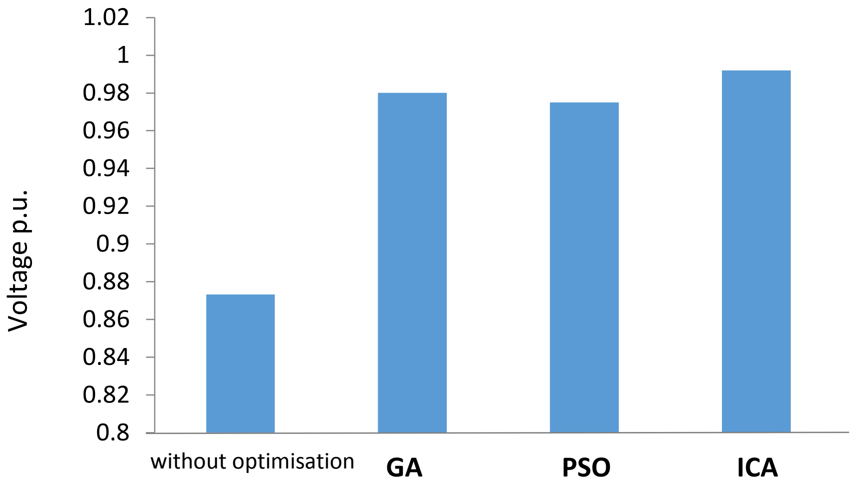


Figure 6. 15 Average of bus voltage using three UPFCs

The cost of FACTS devices is also important in power networks. According to the above figures it can be seen that the voltage level was improved by using the compensators. Using a greater number of UPFCs in power networks increases the maintenance cost as well. The Load-ability of the system was also enhanced. Voltage profile is one of the most important issues in power networks, as fluctuation of load variation in a power network causes systems to be stressed. By adjusting the transformer-tap ratio and installing UPFC devices, losses can be reduced and the voltage profile will be improved.

ICA technique in this study approached to the different solution. In this case genetic algorithm and particle swarm optimization reached the same solution. In case of SVC, GA and PSO were the same but ICA technique result was slightly different than those algorithms. It is because of the structure of the algorithms. As this study investigated case studies with optimization methods, GA and PSO techniques do not have a good characteristic in terms of searching globally for the solution. By implementing the solutions of GA, PSO and ICA techniques on the case study, it can be seen that ICA was better than other two algorithms in this case.

6.5. IEEE 68-Bus System

In this case study, there are 16 generators and 68 buses. Briefly this system is known as the 68-bus New England test system (NETS)–New York (NYPS) interconnected system. Generators $G1–G9$ are in New England, generators $G10–G13$ are in New York and $G14–G16$ are analogous generators in the neighbourhood of New York [89].

In this case, to prevent complicated analysis, the case study can be divided into five areas. The discussion below shows the optimal location and size of an SVC component. The Percentage of losses and total transfer capability (TTC) have been indicated. In this system, one type of FACTS device was involved and the results were analysed. Convergence characteristics in different iterations are shown in Fig. 6.16 and Fig. 6.17. Also, system losses are considered. For computing the total transfer capability, initially loads are increased. Increasing the load will be stopped when the situation exceeds one of the problem conditions. In this study case, voltage profile, convergence characteristics and P-V curves are illustrated. By allocating the SVCs in the study, the system load-ability and voltage profile can be enhanced.

6.5.1. Allocation of SVC in the Study Case

Fig. 6.16 and Fig. 6.17 indicate the convergence characteristics of the imperialist competitive algorithm in different numbers of iterations. It seems that after 150 iterations the algorithm is going to be converged after a couple of decades.

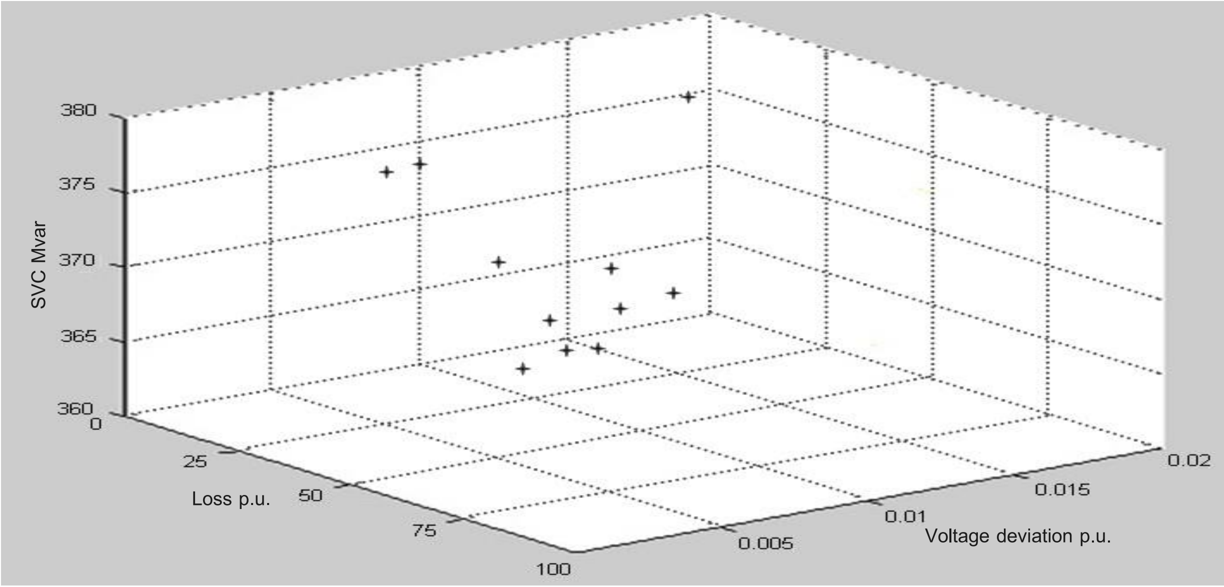


Figure 6. 16 Convergence characteristics after 100 iterations

(Size and voltage deviation and loss are the objectives)

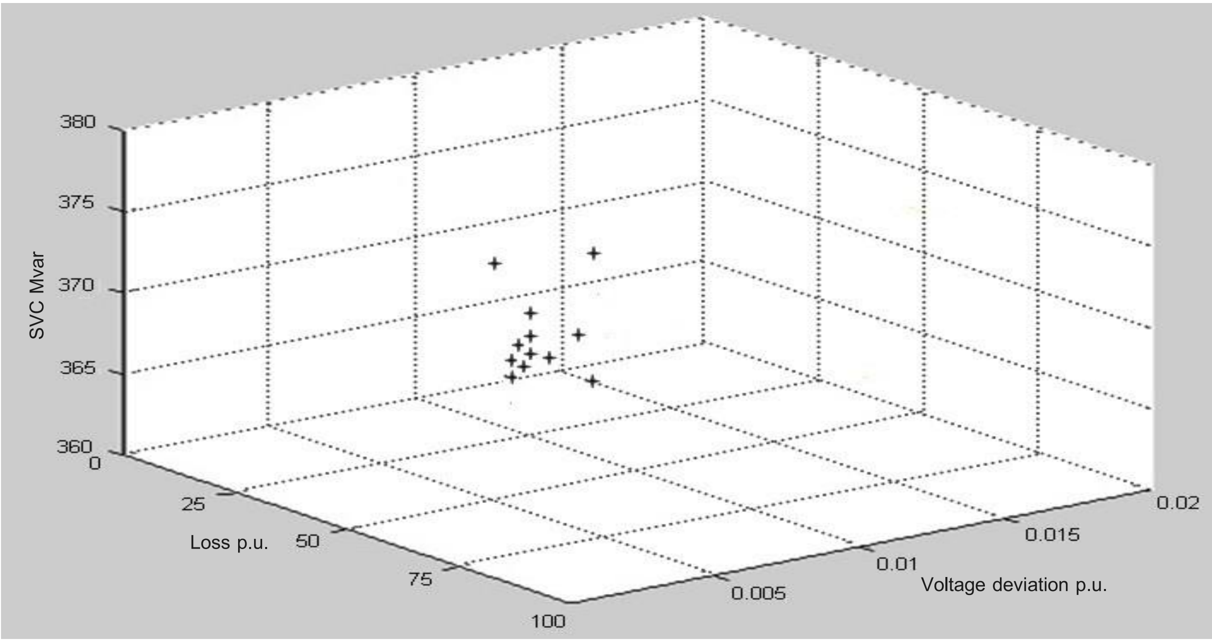


Figure 6. 17 Convergence characteristics after 150 iterations

(Size and voltage deviation and loss are the objectives)

In this case, after analysing the study case and power flow and implementing the imperialist competitive algorithm in the power network, buses 47 and 48 were found to allocate the SVC. In this case, attention should be paid to the percentage of TTC and losses.

Also, voltage deviation is the other parameter that is desirable. Table 6.17 presents a summary of the results. In this case, voltage profile should be considered separately and the effect of the compensation on the system observed.

Table 6. 17 Summary of the results with allocating of SVC

Bus	SVC (MVar)	Voltage deviation	TTC %	Losses reduction %
47, 48	320, 285	0.006	26.31	6.36

In Table 6.17, it can be seen that allocating the SVC devices at the bus 47 and 48 can increase the total transfer capability of the system by 26.31 per cent and reduce losses by 6.36 per cent. Voltage profiles are indicated before and after optimization by the imperialist competitive algorithm in Fig. 6.18 and Fig. 6.19, respectively.

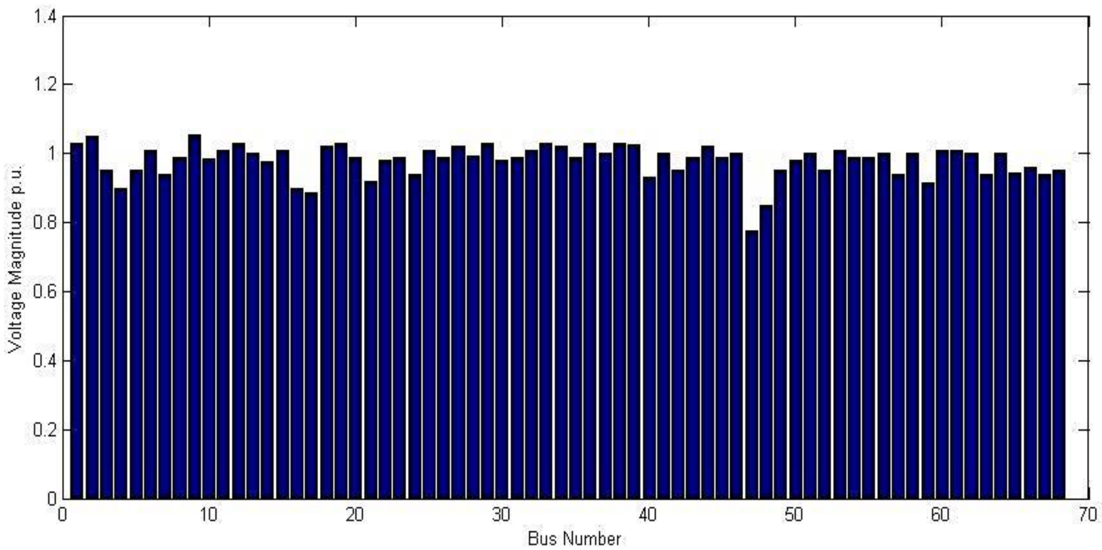


Figure 6. 18 Level of voltage before replacing SVC

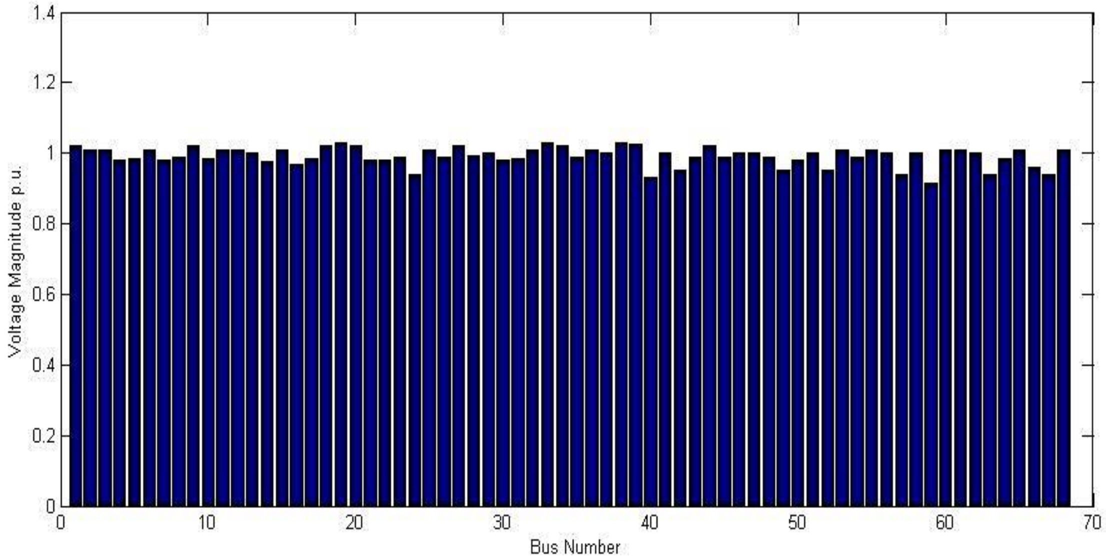


Figure 6. 19 Level of voltage after replacing SVC

P-V curves related to buses 47 and 48 are shown in Figs. 6.20 and 6.21. In this case, by increasing the load, the effect of the loads on the stability of the voltage can be seen and the unstable bar-bars observed. Many researchers and engineers have struggled with voltage stability problems. In this case, load behaviour is detected as one of the major driving forces of voltage collapse.

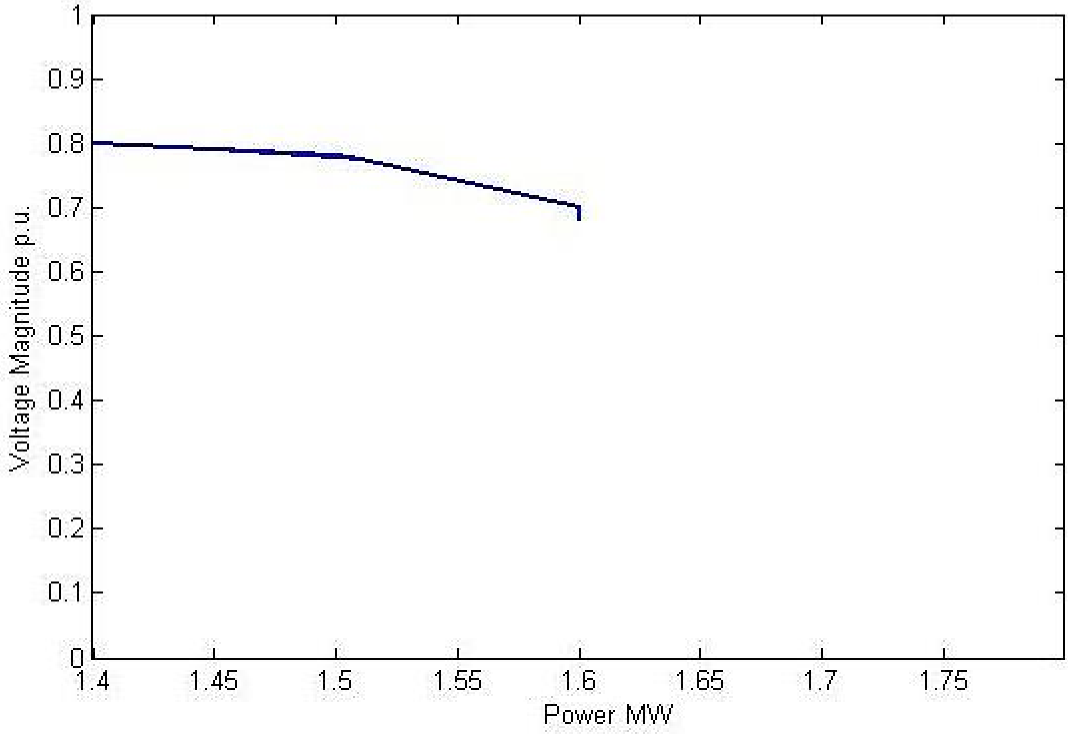


Figure 6. 20 P-V curve at bus 47

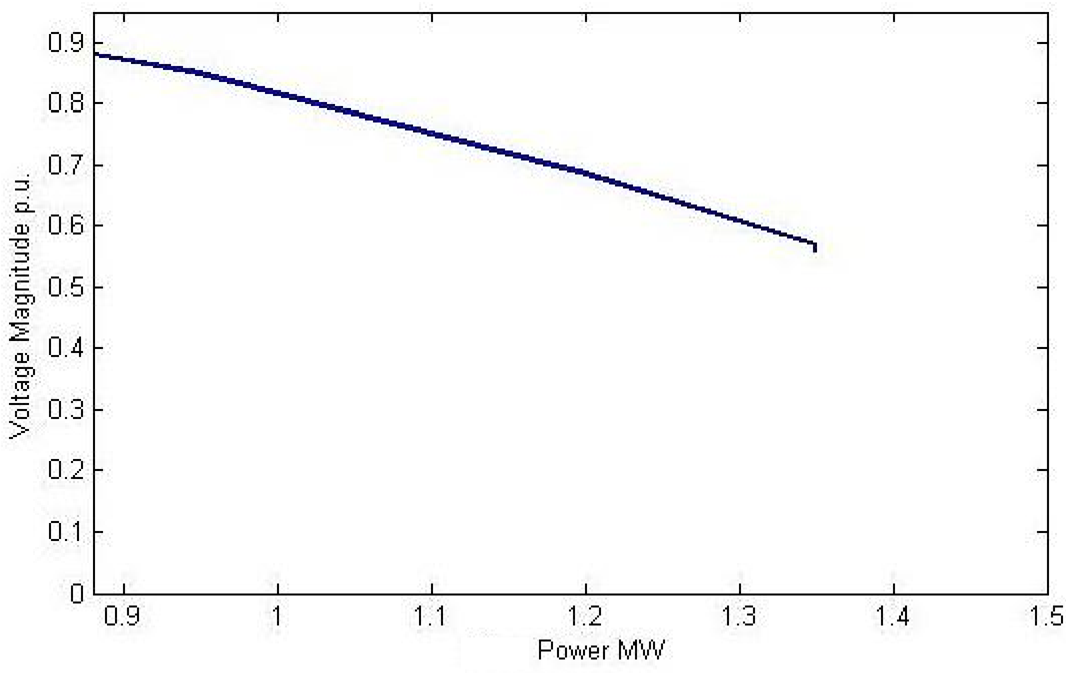


Figure 6. 21 P-V curve at bus 48

There are various reasons why voltage collapse occurs: for instance, due to inconvenient locations of FACTS controllers or high reactive power compensation at high levels of load, or because voltage sources are too far from load centers. In the case of using multiple types of FACTS devices, there should be good coordination between the FACTS controllers. After replacing the SVC component in the power network it can be seen that the voltage level was improved, but still there are some bus-bars that have not reached the unity level of the voltage and need to be investigated and further improved. In transmission networks everything should be used more efficiently and the capacity of power networks should be increased without massive investment but without compromising the security in the power network, and also when power networks operate at a marginal level of stability, a small amount of disturbance can affect the whole system and collapse may occur.

By installing more SVCs in different optimal places the level of losses can be reduced and the voltage profile level and security of the power systems improved. In this simulation, the imperialist competitive algorithm converged after 175 iterations. This number of iterations can be varied by adding or removing objective functions.

6.6. Summary of the Chapter

In this chapter, initially the IEEE-30 bus system was analysed, a case study with and without FACTS devices and also speed convergence and voltage profile were demonstrated and P-V curves were illustrated. Objective function and constraints were discussed in relation to the case study and all simulated results were compared with other optimization techniques.

Total transfer capability was also discussed. SVCs and UPFCs were assumed to be parallel (and series + parallel) compensators and were placed in the case study. The IEEE-68 bus test system was also demonstrated. The level of the bus-bars before and after SVC allocation was illustrated. P-V curves for unstable bus-bars were indicated. It can be seen that after installing FACTS components, the level of voltage profile and the load-ability of the system were enhanced.

Chapter 7

Conclusions and Future Work

7. Conclusions

This study has investigated the imperialist competitive algorithm, which is one of the most recently developed evolutionary algorithms for achieving solutions. The imperialist competitive algorithm was deployed in the case study and was compared with other intelligent algorithms. The speed of convergence of the imperialist competitive algorithm and loss reduction were the advantages of this algorithm over other techniques.

Initially, this study discussed the demand for and impact of Flexible AC Transmission System (FACTS) devices on power systems. In this case, maximum power transfer capability, which is one of the issues that researchers challenge themselves to optimize, was discussed. Available transfer capability (ATC) and total power transfer capability (TTC) were explained. Power network restriction during the delivery of power was also briefly discussed. FACTS devices, one of the most important components of power electronics, have been explained. The different types of FACTS devices and their operation have been discussed. In this case, several FACTS devices were demonstrated and briefly discussed in terms of connection and capability.

Then the importance of the algorithms in optimizations was indicated. In this case, 52 case studies were demonstrated and discussed.

The most common objective functions and constraints that are used to find the optimal locations for FACTS devices in power networks were demonstrated. And the advantages and disadvantages of the algorithms were presented. This comparison was made based on case studies with a known number of constraints. They can be affected by changing the number of objective functions and constraints.

The impact of optimization in science is briefly discussed. The aim of optimization is to improve the progress of a problem. The importance of optimization was discussed. Some types of optimizations that are used to solve problems were shown. Constraints in optimization were mentioned briefly. The imperialist competitive algorithm, one of the most recent optimization methods, was discussed. This algorithm is based on human evolution. The steps of the imperialist competitive algorithm were discussed in full. This algorithm, after processing answers and creating competition between them, approaches the solution. This algorithm follows eight steps. As a case study, initially the IEEE-30 bus system was analysed. A case study with and without FACTS devices and also speed of convergence and voltage profile were demonstrated and P-V curves were illustrated. Objective function and constraints were discussed in relation to the case study and all simulated results were compared with other optimization techniques. SVCs and UPFCs were assumed to be parallel (and series + parallel) compensators and were placed in the case study. The IEEE-68 bus test system was discussed as a second case study with the SVC component and all related simulated results were analysed. In this case, the imperialist competitive algorithm had good characteristics in terms of convergence. The imperialist competitive algorithm is one of the evolutionary algorithms that has recently been used frequently in optimization areas.

7.1. Future Work

In this case, by considering a greater variety of FACTS devices along with having knowledge of their characteristics they can be implemented in power networks. So, by involving different types of FACTS devices, different solutions and probably more accurate answers might be achieved. A greater number and different types of objective functions transfer problems to the different solutions. So, by considering many and new objective functions the accuracy of the answers can be enhanced.

Recently, researchers have combined the characteristics of the algorithms and obtained a new algorithm. So, with a combination of algorithms such as the genetic algorithm and the imperialist competitive algorithm, a new algorithm can be obtained including the characteristics of both of them.

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APPENDIX A

Table A. 1 Simulation of IEEE 30 bus system power flow

Bus	V (p.u)	Phase (deg)	P gen (p.u)	Q gen (p.u)	P load (p.u)	Q load (p.u)
Bus 01	1.05	0	5.1969	-0.2157	0	0
Bus 02	1.034	-11.242	1.785	1.9519	0.673	0.3938
Bus 03	0.958	-17.157	0	0	0.0744	0.0372
Bus 04	0.946	-20.869	0	0	0.2357	0.0496
Bus 05	1.006	-34.013	0.7617	1.9071	2.9213	0.5892
Bus 06	0.959	-24.39	0	0	0	0
Bus 07	0.948	-30.157	0	0	0.7071	0.338
Bus 08	1.023	-25.478	1.0854	2.8908	0.9304	0.9304
Bus 09	0.937	-30.67	0	0	0	0
Bus 10	0.848	-38.944	0	0	0.1799	0.062
Bus 11	1.091	-24.175	0.556	0.8417	0	0
Bus 12	0.953	-36.446	0	0	0.3473	0.2326
Bus 13	1.088	-32.386	0.5244	1.0714	0	0
Bus 14	0.884	-40.242	0	0	0.1923	0.0496
Bus 15	0.853	-40.494	0	0	0.2543	0.0775
Bus 16	0.881	-38.566	0	0	0.1085	0.0558
Bus 17	0.837	-39.785	0	0	0.2791	0.1799
Bus 18	0.801	-43.348	0	0	0.0992	0.0279
Bus 19	0.783	-44.173	0	0	0.2946	0.1054
Bus 20	0.735	-43.094	0	0	0.0682	0.0217
Bus 21	0.792	-41.299	0	0	0.5427	0.3473
Bus 22	0.792	-41.272	0	0	0	0
Bus 23	0.783	-42.588	0	0	0.0992	0.0496
Bus 24	0.723	-43.868	0	0	0.2698	0.2078
Bus 25	0.694	-45.408	0	0	0	0
Bus 26	0.602	-48.573	0	0	0.1085	0.0713
Bus 27	0.723	-44.66	0	0	0	0
Bus 28	0.932	-25.725	0	0	0	0
Bus 29	0.775	-53.964	0	0	0.0744	0.0279
Bus 30	0.768	-63.254	0	0	0.3287	0.0589

Table A. 2 Simulation of IEEE 30 bus system bus data

Bus_I	Bus_Type	P_D	Q_D	G	B	Bus_Area	V_M	V_A	Base_KV	Zone	Vmax	Vmin
1	3	0.0	0.0	0.0	0.0	1	1.060	0.0	132	1	1.05	0.95
2	2	21.7	12.7	0.0	0.0	1	1.043	-5.48	132	1	1.05	0.95
3	1	2.4	1.2	0.0	0.0	1	1.021	-7.96	132	1	1.05	0.95
4	1	7.6	1.6	0.0	0.0	1	1.012	-9.60	132	1	1.05	0.95
5	2	19.4	19.0	0.0	0.0	1	1.010	-14.37	132	1	1.05	0.95
6	1	0.0	0.0	0.0	0.0	1	1.010	-11.34	132	1	1.05	0.95
7	1	22.8	10.9	0.0	0.0	1	1.002	-13.12	132	1	1.05	0.95
8	2	30	30	0.0	0.0	1	1.010	-12.10	132	1	1.05	0.95
9	1	0.0	0.0	0.0	0.0	1	1.051	-14.38	1	1	1.05	0.95
10	1	5.8	2	0.0	0.19	1	1.045	-15.97	33	1	1.05	0.95
11	2	0.0	0.0	0.0	0.0	1	1.082	-14.39	11	1	1.05	0.95
12	1	11.2	7.5	0.0	0.0	1	1.057	-15.24	33	1	1.05	0.95
13	2	0.0	0.0	0.0	0.0	1	1.071	-15.24	11	1	1.05	0.95
14	1	6.2	1.6	0.0	0.0	1	1.042	-16.13	33	1	1.05	0.95
15	1	8.2	2.5	0.0	0.0	1	1.038	-16.22	33	1	1.05	0.95
16	1	3.5	1.8	0.0	0.0	1	1.045	-15.83	33	1	1.05	0.95
17	1	9	5.8	0.0	0.0	1	1.040	-16.14	33	1	1.05	0.95
18	1	3.2	0.9	0.0	0.0	1	1.028	-16.82	33	1	1.05	0.95
19	1	9.5	3.4	0.0	0.0	1	1.026	-17.00	33	1	1.05	0.95
20	1	2.2	0.7	0.0	0.0	1	1.020	-16.80	33	1	1.05	0.95
21	1	17.5	11.2	0.0	0.0	1	1.033	-16.42	33	1	1.05	0.95
22	1	0.0	0.0	0.0	0.0	1	1.033	-16.41	33	1	1.05	0.95
23	1	3.2	1.6	0.0	0.0	1	1.027	-16.61	33	1	1.05	0.95
24	1	8.7	6.7	0.0	0.043	1	1.021	-16.78	33	1	1.05	0.95
25	1	0.0	0.0	0.0	0.0	1	1.017	-16.35	33	1	1.05	0.95
26	1	3.5	2.3	0.0	0.0	1	1.000	-16.77	33	1	1.05	0.95
27	1	0.0	0.0	0.0	0.0	1	1.023	-15.82	33	1	1.05	0.95
28	1	0.0	0.0	0.0	0.0	1	1.007	-11.97	132	1	1.05	0.95
29	1	2.4	0.9	0.0	0.0	1	1.003	-17.06	33	1	1.05	0.95
30	1	10.6	1.9	0.0	0.0	1	0.992	-17.94	33	1	1.05	0.95

Table A. 3 Simulation of IEEE 30 bus system generator data

N	P_G	Q_G	Q_{max}	Q_{min}	V_G	M_{base}	Gen_Status	P_{max}	P_{min}
1	250	0	999	-999	1.04	100	1	250	10
2	545	0	999	-999	1.035	100	1	300	10
5	650	0	999	-999	1.012	100	1	270	10
8	632	0	999	-999	1.02	100	1	250	10
11	505.2	0	999	-999	1.011	100	1	300	10
13	700	0	999	-999	1.05	100	1	270	10

Table A. 4 Simulation of IEEE 30 bus system branch data

F_Bus	T_Bus	R	X	B_T	S_{LT}	S_{ST}	S_E	Tap	δ	BR_Status
1	2	0.0192	0.0575	0.0528	0	0	0	0.0	0.0	1
1	3	0.0452	0.1652	0.0408	0	0	0	0.0	0.0	1
2	4	0.0570	0.01737	0.0368	0	0	0	0.0	0.0	1
3	4	0.0132	0.0379	0.0084	0	0	0	0.0	0.0	1
2	5	0.0472	0.1983	0.0418	0	0	0	0.0	0.0	1
2	6	0.0581	0.1763	0.0374	0	0	0	0.0	0.0	1
4	6	0.0119	0.0414	0.0090	0	0	0	0.0	0.0	1
5	7	0.0460	0.1160	0.0204	0	0	0	0.0	0.0	1
6	7	0.0267	0.0820	0.0170	0	0	0	0.0	0.0	1
6	8	0.0120	0.0420	0.0090	0	0	0	0.0	0.0	1
6	9	0.0	0.2080	0.0	0	0	0	0.978	0.0	1
6	10	0.0	0.5560	0.0	0	0	0	0.969	0.0	1
9	11	0.0	0.2080	0.0	0	0	0	0.0	0.0	1
9	10	0.0	0.1100	0.0	0	0	0	0.0	0.0	1
4	12	0.0	0.2560	0.0	0	0	0	0.932	0.0	1
12	13	0.0	0.1400	0.0	0	0	0	0.0	0.0	1
12	14	0.1231	0.2559	0.0	0	0	0	0.0	0.0	1
12	15	0.0662	0.1304	0.0	0	0	0	0.0	0.0	1
12	16	0.0945	0.1987	0.0	0	0	0	0.0	0.0	1
14	15	0.2210	0.1997	0.0	0	0	0	0.0	0.0	1
16	17	0.524	0.1923	0.0	0	0	0	0.0	0.0	1
15	18	0.1073	0.2185	0.0	0	0	0	0.0	0.0	1
18	19	0.0639	0.1292	0.0	0	0	0	0.0	0.0	1
19	20	0.0340	0.0680	0.0	0	0	0	0.0	0.0	1
10	20	0.0936	0.2090	0.0	0	0	0	0.0	0.0	1
10	17	0.0324	0.0845	0.0	0	0	0	0.0	0.0	1
10	21	0.0348	0.0749	0.0	0	0	0	0.0	0.0	1
10	22	0.0727	0.1499	0.0	0	0	0	0.0	0.0	1
21	22	0.0116	0.0236	0.0	0	0	0	0.0	0.0	1
15	23	0.1000	0.2020	0.0	0	0	0	0.0	0.0	1
22	24	0.1150	0.1790	0.0	0	0	0	0.0	0.0	1
23	24	0.1320	0.2700	0.0	0	0	0	0.0	0.0	1
24	25	0.1885	0.3292	0.0	0	0	0	0.0	0.0	1
25	26	0.2544	0.3800	0.0	0	0	0	0.0	0.0	1
25	27	0.1093	0.2087	0.0	0	0	0	0.0	0.0	1
28	27	0.0	0.3960	0.0	0	0	0	0.968	0.0	1
27	29	0.2198	0.4153	0.0	0	0	0	0.0	0.0	1
27	30	0.3202	0.6027	0.0	0	0	0	0.0	0.0	1
29	30	0.2399	0.4533	0.0	0	0	0	0.0	0.0	1
8	28	0.0636	0.2000	0.0428	0	0	0	0.0	0.0	1
6	28	0.0169	0.0599	0.0130	0	0	0	0.0	0.0	1

APPENDIX B

Table B. 1 Simulation of IEEE 68 bus system power flow (Bus 1-34)

Bus	V (p.u)	Phase (deg)	P gen (p.u)	Q gen (p.u)	P load (p.u)	Q load (p.u)
Bus 01	1.05	-11.25	0	0	60.00	3.0000
Bus 02	1.06	-21.23	0	0	0	0
Bus 03	0.95	-27.17	0	0	24.70	1.2300
Bus 04	0.9	-18.95	0	0	32.520	0.5287
Bus 05	0.95	-24.52	0	0	0	0
Bus 06	1.01	-38.59	0	0	0	0
Bus 07	0.97	-42.187	0	0	6.8	1.0300
Bus 08	0.99	-32.48	0	0	0	0
Bus 09	1.08	-37.57	0	0	0	0
Bus 10	0.99	-62.44	0	0	0	0
Bus 11	1.01	-44.75	0	0	0	0
Bus 12	1.04	-28.46	0	0	2.74	1.1500
Bus 13	1.0	-41.86	0	0	0	0
Bus 14	0.98	-35.42	0	0	0	0
Bus 15	1.005	-48.94	0	0	10.254	1.0025
Bus 16	0.89	-24.66	0	0	2.48	0.8500
Bus 17	0.88	-51.85	0	0	0	0
Bus 18	1.03	-33.38	0	0	3.09	-0.9200
Bus 19	1.04	-32.73	0	0	0	0
Bus 20	0.99	-55.04	0	0	0	0
Bus 21	0.91	-36.29	0	0	2.24	0.4700
Bus 22	0.98	-31.72	0	0	0	0
Bus 23	0.99	-51.88	0	0	0	0
Bus 24	0.943	-33.88	0	0	1.39	0.1700
Bus 25	1.008	-55.48	0	0	0	0
Bus 26	0.99	-78.53	0	0	2.81	0.7600
Bus 27	1.02	-54.66	0	0	0	0
Bus 28	0.99	-45.75	0	0	2.06	0.2800
Bus 29	1.03	-63.94	0	0	0	0
Bus 30	0.98	-33.24	0	0	0	0
Bus 31	0.99	-24.36	0	0	0	0
Bus 32	1.001	-51.36	0	0	0	0
Bus 33	1.04	-17.68	0	0	2.84	0.2700
Bus 34	1.03	-43.21	0	0	0	0

Table B. 2 Simulation of IEEE 68 bus system power flow (Bus 35-68)

Bus	V (p.u)	Phase (deg)	P gen (p.u)	Q gen (p.u)	P load (p.u)	Q load (p.u)
Bus 35	0.99	-36.54	0	0	0	0
Bus 36	1.04	-41.22	0	0	2.035	0.3528
Bus 37	1.0	-57.37	0	0	0	0
Bus 38	1.03	-35.89	0	0	0	0
Bus 39	1.02	-28.13	0	0	11.258	0.458
Bus 40	0.94	-39.49	0	0	5.255	0.258
Bus 41	1.0	-50.17	0	0	0	0
Bus 42	0.95	-45.48	0	0	0	0
Bus 43	0.99	-30.77	0	0	1.12	0.124
Bus 44	1.02	-38.44	0	0	2.001	0.652
Bus 45	0.99	-44.55	0	0	0	0
Bus 46	1.00	-46.46	0	0	12.25	0.357
Bus 47	0.78	-32.36	0	0	1.85	-0.146
Bus 48	0.85	-60.32	0	0	1.025	0.874
Bus 49	0.95	-60.44	0	0	3.65	0.321
Bus 50	0.98	-88.56	0	0	2.67	0.150
Bus 51	1.0	-39.75	0	0	0	0
Bus 52	0.95	-33.38	0	0	0.6563	0.253
Bus 53	1.0	0	1.70	0.80	0	0
Bus 54	0.99	-33.04	4.10	1.35	0	0
Bus 55	0.99	-31.299	4.50	2.0	0	0
Bus 56	1.0	-41.22	5.20	1.12	0	0
Bus 57	0.93	-22.58	4.05	1.0	0	0
Bus 58	1.0	-33.88	5.0	2.0	0	0
Bus 59	0.91	-55.48	4.60	1.0	0	0
Bus 60	1.003	-58.53	4.30	1.10	0	0
Bus 61	1.003	-34.56	6.90	1.10	0	0
Bus 62	1.0	-45.75	3.90	1.10	0	0
Bus 63	0.93	-63.94	7.50	2.50	0	0
Bus 64	1.0	-53.24	11.50	2.0	0	0
Bus 65	0.935	-35.41	25.81	10.10	0	0
Bus 66	0.95	-25.48	12.50	5.35	0	0
Bus 67	0.925	-35.47	7.50	2.50	0	0
Bus 68	0.935	-62.51	30.50	9.50	0	0

Table B. 3 Simulation of IEEE 68 bus system load bus data

Bus Number	Real Load (p.u)	Reactive Load (p.u)
1	60.00	3.0000
3	24.70	1.2300
4	32.520	0.5287
7	6.80	1.0300
12	2.74	1.1500
15	10.254	1.0025
16	2.48	0.8500
18	3.09	-0.9200
21	2.24	0.4700
24	1.39	0.1700
26	2.81	0.7600
28	2.06	0.2800
33	2.84	0.2700
36	2.035	0.3528
39	11.258	0.458
40	5.255	0.258
43	1.12	0.124
44	2.001	0.652
46	12.25	0.357
47	1.85	-0.146
48	1.025	0.874
49	3.65	0.321
50	2.67	0.150
52	0.6563	0.253

Table B. 4 Simulation of IEEE 68 bus system machine bus data

Bus Number	Voltage (p.u)	Power Generation (p.u)
53	1.0450	2.50
54	0.9800	5.45
55	0.9830	6.50
56	0.9970	6.32
57	1.0110	5.05
58	1.0500	7.00
59	1.0630	5.60
60	1.0300	5.40
61	1.0250	8.00
62	1.0100	5.00
63	1.0000	10.00
64	1.0156	13.50
65	1.0110	35.91
66	1.0000	17.85
67	1.0000	10.00
68	1.0000	40.00

Table B. 5 Simulation of IEEE 68 bus system load line data

From Bus	To Bus	Resistance (p.u)	Reactance (p.u)	Line charging (p.u)	Tap ratio
54	1	0	0.0181	0	1.0250
58	2	0	0.0250	0	1.0700
62	3	0	0.0200	0	1.0700
19	4	0.0007	0.0142	0	1.0700
20	5	0.0009	0.0180	0	1.0090
22	6	0	0.0143	0	1.0250
23	7	0.0005	0.0272	0	0
25	8	0.0006	0.0232	0	1.0250
29	9	0.0008	0.0156	0	1.0250
31	10	0	0.0260	0	1.0400
32	11	0	0.0130	0	1.0400
36	12	0	0.0075	0	1.0400
17	13	0	0.0033	0	1.0400
41	14	0	0.0015	0	1.0000
42	15	0	0.0015	0	1.0000
18	16	0	0.0030	0	1.0000
36	17	0.0005	0.0045	0.3200	0
49	18	0.0076	0.1141	1.1600	0
68	19	0.0016	0.0195	0.3040	0
19	20	0.0007	0.0138	0	1.0600
68	21	0.0008	0.0135	0.2548	0
21	22	0.0008	0.0140	0.2565	0
22	23	0.0006	0.0096	0.1846	0
23	24	0.0022	0.0350	0.36)0	0
68	24	0.0003	0.0059	0.0680	0
54	25	0.0070	0.0086	0.1460	0
25	26	0.0032	0.0323	0.5310	0
37	27	0.0013	0.0173	0.3216	0
26	27	0.0014	0.0147	0.23	0
26	28	0.0043	0.0474	0.7802	0
26	29	0.0057	0.0625	1.0290	0
28	29	0.0014	0.0151	0.2490	0
53	30	0.0008	0.0074	0.4800	0
61	30	0.0019	0.0183	0.2900	0
61	30	0.0019	0.0183	0.2900	0
30	31	0.0013	0.0187	0.3330	0
53	31	0.0016	0.0163	0.2500	0
30	32	0.0024	0.0288	0.4880	0
32	33	0.0008	0.0099	0.1680	0
33	34	0.0011	0.0157	0.2020	0
35	34	0.0001	0.0074	0	0.9460
34	36	0.0033	0.0111	1.4500	0
61	36	0.0022	0.0196	0.3400	0
61	36	0.0022	0.0196	0.3400	0
68	37	0.0007	0.0089	0.1342	0
31	38	0.0011	0.0147	0.2470	0
33	38	0.0036	0.0444	0.6930	0
41	40	0.0060	0.0840	3.1500	0
48	40	0.0020	0.0220	1.2800	0
42	41	0.0040	0.0600	2.2500	0
18	42	0.0040	0.0600	2.2500	0
17	43	0.0005	0.0276	0	0

Continued on next page

Table B. 6 Simulation of IEEE 68 bus system load line data (continued)

From Bus	To Bus	Resistance (p.u)	Reactance (p.u)	Line charging (p.u)	Tap ratio
39	44	0	0.0411	0	0
43	44	0.0001	0.0011	0	0
35	45	0.0007	0.0175	1.3900	0
39	45	0	0.0839	0	0
44	45	0.0025	0.0730	0	0
38	46	0.0022	0.0284	0.4300	0
53	47	0.0013	0.0188	1.3100	0
47	48	0.0025	0.0268	0.4000	0
47	48	0.0025	0.0268	0.4000	0
46	49	0.0018	0.0274	0.2700	0
45	51	0.0004	0.0105	0.7200	0
50	51	0.0009	0.0221	1.6200	0
37	52	0.0007	0.0082	0.1319	0
55	52	0.0011	0.0133	0.2138	0
53	54	0.0035	0.0411	0.6987	0
54	55	0.0013	0.0151	0.2572	0
55	56	0.0013	0.0213	0.2214	0
56	57	0.0008	0.0128	0.1342	0
57	58	0.0002	0.0026	0.0434	0
58	59	0.0006	0.0092	0.1130	0
57	60	0.0008	0.0112	0.1476	0
59	60	0.0004	0.0046	0.0780	0
60	61	0.0023	0.0363	0.3804	0
58	63	0.0007	0.0082	0.1389	0
62	63	0.0004	0.0043	0.0729	0
64	63	0.0016	0.0435	0	1.0600
62	65	0.0004	0.0043	0.0729	0
64	65	0.0016	0.0435	0	1.0600
56	66	0.0008	0.0129	0.1382	0
65	66	0.0009	0.0101	0.1723	0
66	67	0.0018	0.0217	0.3660	0
67	68	0.0009	0.0094	0.1710	0
53	27	0.0320	0.3200	0.4100	1.0000
69	18	0.0006	0.0144	1.0300	0
50	69	0.0006	0.0144	1.0300	0