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IMPACT OF HIGH PENETRATION OF RENEWABLE ENERGY SOURCES ON THE RELAY COORDINATION OF DISTRIBUTION SYSTEM

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ABSTRACT

The rate at which the integration of distributed generation (DG) penetrates the public power supply has started to put various demands on the distribution system, since they are directly connected to the network. Distribution level protection is based on a time-overcurrent design. The design is to clear faults with as little impact and minimum time on the equipment and the customer. The increasing demands placed by grid services on the DGs, especially the PV types have a serious impact on the distribution system. For example, special protective devices are required to prevent the risk of danger in the event of mains interference. In this thesis, the main focus was on the contribution of fault currents to the distribution networks, and how the high penetration of DGs especially the renewable energy resources (R.E.S.) types affect the coordination of overcurrent (O.C.) protection.

In view of the changes in the international regulations, the DGs are expected to stay connected and perform grid-related control functions, instead of shutting down at the first sign of a fault. This problem becomes more acute when the DGs stay connected during faults, known as voltage ride through (VRT). This thesis presented its findings on the impact of the DGs of various types of DGs (synchronous generator, asynchronous and power electronic) on the protection coordination by the high increase of fault currents, and the mitigation techniques of the impact of the inverter interfaced DGs (whose fault current contribution was not so high) on the overcurrent protection.

The impact on system's over-current protection coordination in such hybrid AC and DC microgrid, how the fault current changes by the high penetration of DGs in the hybrid microgrid and their effects on the protection over-current coordination were presented, as the name microgrid was adopted for networks having a point of common connection (PCC).

The inverter interfaced-equipment were never in the conventional systems, the few that were there were all on the load side of the distribution system. The inverter interfacing DGs (PVs) and the synchronous types are the types of DGs that affect over-current protection of the distribution system and these were mitigated accordingly, considering the first few cycles of the fault events of the ride through capabilities.

The analysis of the different penetration levels of the DGs in an existing 33kV in the Nigerian distribution network, (CocaCola-Challenge Industrial feeder) was thoroughly analysed, for less than 20%, more than 60% and 100% of the feeder load. Most of the DGs, presently existing in that network are the synchronous types, but they are only used as standby sources of power, and the renewables (RES) like the photovoltaics (PV), run of flow (RoF) Hydo and the wind turbine generators (WTG) are proposed additions.

The objective of this thesis was to explain the fundamentals of distribution generation (DG) and especially the RES, in relation to distribution protection relay coordination to see why there should be urgency in carrying out the study especially in a developing environment where the grid is unstable, the load is rapidly expanding and RES is intermittent.

The radial distribution system (DS) with high penetration of DG was introduced. The motive was to critically investigate protection coordination problems and the solutions to the problems. The main objective was to optimally recommend the type, size and location of the DG for an actual distribution feeder in an unstable environment where the grid supply is not steady. The effect of 100% and above of feeder load penetration on such feeders formed the objective of this research. The literature review which was for investigating in greater details the technical aspects of the operation and control of the high penetration of RES in the distribution system were thoroughly analysed. The review of the existing radial distribution protection system and the effects of high penetration of DG on the protective relaying were thoroughly investigated. The issues of power electronic based inverters and the protection coordination problems, were investigated. The protection coordination as regards to fault level changes and grounding, intentional and un-intentional islanding were major important aspects which were treated in the technical review.

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LIST OF ABBREVIATIONS

1LG	Single-Phase-Ground Fault
3LG	Three-Phase-Ground Fault
LLL	Three-Phase Fault (Bolted)
AC	Alternating Current
AC-DC-AC	Alternating Current to Direct Current to Alternating Current
ASG	Asynchronous Generator
BDC DC-DC	Bidirectional DC-DC Converter
C & P	Control and Protection
CB	Circuit Breaker
CHP	Combined Heat and Power
CSI	Current Source Inverter
CT	Current Transformer
CTI	Coordinating Time Interval
D.G.	Distributed Generation
DFIG	Doubly Fed Induction Generator
DC	Direct Current
DC-AC	Direct Current to Alternating Current
DC-DC	Direct Current to Direct Current
DER	Distributed Energy Resources
DG	Distributed Generation
DMT	Definite Minimum Time (Relay)
DN	Distribution Network
DSTATCOM	Distribution Static Synchronous Compensator
EDF	Electricite de France
EA	Evolutionary Algorithm
EI	Extremely Inverse (overcurrent relay)
ERAC	Electrical Power Systems Analysis Software
ETAP	Electrical Transient Analyser Program

FACTS	Flexible Alternating Current Transmission System
FCL	Fault Current Limiter
GA	Genetic Algorithm
HREDS	Hybrid Renewable Energy Distribution System
IDMT	Inverse Definite Minimum Time (Relay)
IEEE	Institution of Electrical and Electronic Engineers
IG	Induction Generator
IGBT	Insulated Gate Bipolar Transistor
IIDG	Inverter Interfaced Distributed Generation
IOC	Instantaneous Over-Current
LFA	Load Flow Analysis
LL	Phase to Phase
LLG	Phase to Phase to Ground
LLL	Three Phase
LOG	Loss of Grid
LOM	Loss of Main
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
O.C.	Overcurrent
OCR	Over-Current Relay
OF	Objective Function
PCC	Point of Common Coupling
PE interface	Power Electronic Interface
PE	Power Electronics
PMSG	Permanent Magnet Synchronous Generator
PQ	Power Quality
PSM	Plug Setting Multiplier
PV	Photovoltaic
PWM	Pulse Width Modulation
R.E.S.	Renewable Energy Resources
RoF Hydo	Run of Flow Hydro

SCA	Short Circuit Analysis
SCL	Short Circuit Level
SG	Synchronous Generator
TCC	Time Current Curves
TDS	Time Dial Setting
THD	Total Harmonic Distortion
TOC	Time Over-Current
TSM	Time Setting Multiplier
UPEC	Universities Power Engineering Conference
VRT	Voltage Ride Through
VSI	Voltage Source Inverter
WTG	Wind Turbine Generator
ZSI	Impedance Source Inverter

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List of Publications

1. Olatoke, A.O.; Sultan, S.S.; Darwish, M.K. ‘‘Statistical Analysis of Power Quality in Office Buildings’’ *International Journal of Scientific & Engineering Research,* Volume 3, Issue 12, April-2012 -ISSN 2229-5518. IJSER Xplore® Research Paper Database. Paper ID: I019368

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3. Olatoke, A.; Darwish, M.K. ‘‘A study of the impact of Distributed Generation on power quality’’ *Universities Power Engineering Conference (UPEC),* 47th International Digital Object Identifier: 10.1109/UPEC.2012.6398662, 2012.

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Chapter 1

Introduction

1.1 Introduction

This chapter presents the concept that will be referred to in other chapters of this thesis. It also presents the thesis aim, objectives, outlines and the research original contribution to the knowledge.

For so many years, the only way to supply consumers with electricity was to transmit electrical power from power generation plants via transmission lines to distribution networks. There were always chances of short circuits occurring at the generation, transmission or distribution networks. In order to limit the damage which could be caused by such short circuits, protection zones were set using relay-controlled circuit breakers and fuses. Protection zones were made from at least one primary and one backup circuit breaker. The backup circuit breaker was a primary circuit breaker in another protection zone and was backed up by another breaker and so on. Relay coordination between the primary and the backup of such circuit breaker arrangement, although they need attention in setting them, but they were more or less straight forward and this topic is covered in details in many text books over many years. The relay coordination is necessary in order to check unnecessary tripping of the CBs causing more consumers to loose supply, unless the primary relays fail to trip.

Later, Distribution Generation (DG) was introduced; they are decentralized, modular and more flexible power generation and they are usually located close to the load they serve. They also have relatively small generation power of only 10 MW or less. The protection and relay coordination between the primary and the backup when DGs are integrated with the main grid is a challenge. This challenge is even harder when the percentage of DG generated power is getting higher in comparison to the loads connected to the grid. The research presented in this thesis looks at such challenges with some case studies in Nigerian power distribution network.

1.1.1 The Importance of This Topic

The present highly encouraged introduction of DG into the distribution system could to lead to its heavy penetration of up to and above 200% of feeder load in the distribution system in the nearest future. The high penetration of DG in the distribution system could bring major challenges on the reliability and efficiency of the system. Intermittent nature of the renewable energy sources results in the variations of voltage and power such as flicker and voltage instability. The need for reactive compensation could lead to variation in frequency and voltage level because of the variation in wind speeds. Due to the variable nature of the renewable energy sources, wind and solar, accurate forecasting could be difficult for operation and forecasting.

The incentives introduced by Governments by way of feed-in-tariff (FIT) and the rapid reduction in the manufacturing and installation of renewable energy resources (RES) like wind and solar would equally accelerate the heavy penetration. How would this impact on relay operation and coordination in existing protection of the distribution system? This would need urgent attention in the form of extensive study and simulations so that reliability and the gains of the DG could be achieved.

1.1.2 The gap in the research area

It could be seen that there exists a gap in the area of integration of RES into the distribution system which represents a challenge in the area of reliability under steady-state and transient stability state. This gap in the developing countries is further compounded by the fact that the grid could be very unstable with more unplanned outages than in the developed world. The developed world could afford to use the RES as peak-shaving in microgrid topology, while the under-developed world should now begin to think of using the grid as peak-shaving only. Peak-shaving is the top-up or additional generation needed in case the grid power is less than the required load, resulting in load-shedding usually at peak period. DG units could be used for load management for the purpose of decreasing the peak load demand. The grid, the load and the RES are stochastic in the under-developed countries, and so, there would be the need for more research especially in the area of protection of the distribution system with high penetration of DG particularly in under transient stability cases. With 100% of feeder load supplied by the DGs, the grid would become the peak-shaving source of energy production. 'Community solar' in high DG penetration, where different independent power producers (IPP) would generate and market out to individuals who cannot own their separate RES installations, would cause greater interest in the nearest future.

1.2 Motivations for the Project

The conventional power system comprises Generation, Transmission, Distribution and Marketing (the customer). Over the past years, Distribution system (DS) had been passive at the receiving end of the power system. There were few protection elements like fuses protecting the distribution transformers, sectionalizers, automatic reclosers, protecting the main distribution lines and circuit breakers at the injection substations. The problems in coordinating these protection elements were few, the major ones were the relays located at the injection substations. The introduction of distributed generation (DG) has immediately brought the challenges of so many issues like power quality, fault calculation, network stability, power factor corrections, power filter optimisations, etc. However, one of the most important impacts of DG on power distribution system (DS), which is impact on protection system was rarely investigated academically and most of the carried out relay coordination in DS were mainly based on engineers' experience in the field with very little evidence of a solid academic investigation of how the relay coordination could be carried out. It was obvious that usual relay protection is not fit for purpose particularly at high percentage penetration level of DS. This topic has been worked upon by many researchers and the challenge was mainly on how to design a complete protection system at distribution level for system incorporating renewable energy systems. The point common coupling (PCC) was where power quality (PQ) problems were measured and guidelines were set as to what level of total and individual harmonics could be transferred into the grid from the distribution load circuits. Such power quality problems include: voltage variation (limits must remain between 90% and 110%), frequency variation (limits must remain between 49.5Hz and 50.5Hz) and harmonic voltage (total harmonic voltage must be less than 8%, and 3rd, 5th, and 7th, harmonic less than 5%, 6% and 5%

respectively). Another source of relay coordination problems was the later developments in Power Electronics which brought quite a number of very sensitive equipment into the DS, (including DG) and its protection problems (which is also a part of PQ problems) became a major source of headache responsible for the mis-coordination of the DS relays and PQ.

Protection planning in the DS was simple, with few instruments, like over current relay (OCR) in the substation, reclosers in the middle of the circuit and fuses at the branch-offs/distribution transformers. Relay coordination was done by measuring the minimum fault current (I_{min}) and the maximum fault current (I_{max}) and making sure fault currents passing through these protective instruments do not fall outside these limits, as the flow of current is one direction only.

The new method of interconnecting the Distribution generation (DG) to the DS has complicated the whole PQ and Protection problems. High penetration of DG especially the renewable energy resources (RES) types are on the increase in the distribution circuits. This has made RES or green energy as it is called to become the bedrock of research. It is important to study and analyse how high can the penetration be, 20%, 100% of the feeder load before the protection coordination and power quality issues become major problems? What new technical problems will come up? Are the Power Grid's days numbered when the rooftop solar becomes the main power producer? (Cell phones suppliant, humble land lines). Protection coordination challenges that could be brought by these changes is the motivation for this project. The RES are intermittent and the load are variable, what impact have these two variables on the reliability of the Distribution supply system? The very challenging issue of proper placement of DG in the distribution circuits for obtaining maximum potential benefits would need more research, as DGs could be privately or utility owned. The rapid design and manufacturing development of the RES equipment is currently on the increase, scientific developments to improve their use, their future prospects and their development motivates this research.

1.3 Thesis Aim and Objectives

The main aim of this research work is to establish the effect of high penetration of DG in LV distribution networks considering in particular the effect on protection coordination issues. In order to achieve the aim, the following objectives were set:

1) To critically review and analyse the present protection coordination of a distribution network without penetration of DG.
2) To critically review and analyse the protection system of a distribution network with high penetration of DG, especially at 100% of the feeder load.
3) To optimally recommend the type, positioning, and the size of DG for the Nigerian distribution network.

The cluster of DGs now called microgrid must be operational effectively by making sure that the increased protection coordination for and backup are diagnosed and mitigated. The types of emerging microgrid structure would need further analysis especially at the point of common coupling (PCC), which is the point where the microgrid is connected to the main grid. The voltage and the frequency variations must be within the acceptable International limits whether the microgrid is connected to the grid or islanded intentionally or unintentionally, especially in areas where there is equal balance between the DG generated power and the feeder load, called non detection zone (NDZ) and for high penetration of inverter-based DGs with limited controlled fault currents. The two areas of concern in the modern distribution system are the power quality (PQ) and distribution network protection coordination. Power quality is concerned with the voltage disturbances affecting the customers' equipment and the current disturbances affecting the Utility's equipment. Protection of the distribution networks concerns the detection of faults in the system from measured voltages and currents and isolating them without causing any damage on the faulted feeder and without causing unnecessary outage on the other healthy feeders. Most research conducted presently are concerned with high penetration of DG into the distribution system and the thorough knowledge of the dynamic properties of distribution systems with different types of interfacing technologies need more research. There is need to properly analysis the relay coordination of power conversions of Synchronous (SG) and Asynchronous generators (ASG), power electronics (PE) interconnectors (inverters and converters) and direct connection, through transformers of different DGs to the distribution system. Their behaviour under transient conditions needs proper study as the percentage of penetration increases to more than 100% of feeder load.

Distribution system (DS) is designed to be radial and current flow are unidirectional, even when constructed as loop system, they are radially operated. The introduction of DG has brought the following challenges to the system: over/under voltage, harmonic problems, protection mis-coordination, islanding and increase in fault currents. Power distribution islands are formed as a result of microgrid terminology of high penetration of DG in circuits, which could be have a point of common coupling (PCC) to the grid. When the microgrid is disconnected from the grid at the PCC, an island is formed. The island consists of the DGs, load and the distribution circuit enclosed in that island. Coordination of overcurrent protection relays has become a major problem in how to maintain system stability under high penetration of DG

What could be the impacts of DG on the Radial distribution system? What impacts would the DS quality have on DG interconnection protection? The interconnection problems of harmonics, over/under-voltages, over/under frequency, fault coordination, increase in fault levels and islanding at high penetration would need research studies. Time overcurrent relay at the distribution substation, reclosers at the middle of the network and fuses at the distribution transformer are the design principles mostly used in distribution system where selectivity and coordination are paramount for the safety of human and equipment.

1.4 Layout of the Thesis

The arrangement of this thesis is as follows:

Chapter 2 was a presentation of the literature survey on the existing protection coordination system and the advancement on the power electronic interface with the radial distribution system. The impact of different penetration levels of DG on protection relaying are investigated. Technical impacts like protection coordination like changes in fault levels, effects of high penetration of DG on the primary and backup of relay were vigorously analysed. The impact DG on generation and transmission, the economic impact of DG on the Distribution system were also investigated. Grid interconnection and islanding and the different International Standards affecting DG connection to the distribution system and PQ in the protective relaying were presented.

The Chapter 3 was a critical investigation of the challenges in protection coordination and PQ of radial distribution system by high penetration of DG. The control strategies for hybrid RES in the distribution systems (HREDS) were analysed. The interfacing configuration of HREDS sources, converters and inverters were investigated as to the operation and coordination control. The protection system in radial distribution network with DG was analysed and fully investigated in chapter 4. Chapter 5 was the analysis of the modelling and simulation of (RES) for optimal location and sizing in the distribution circuit. The methodology for the stochastic nature of the RES and the grid interface (inverters and transformers) for minimum tripping time, creating zones of protection for discrimination purposes of the OCRs, and the analysis especially when over 100% of feeder-load is connected to the distribution system was considered. Zones of protection were the areas created for discrimination purposes for backup protection in cases where primary relays or CBs fail to protect their equipment in their respective zones. The Electrical Transient Analyser Program (ETAP) software was used for the simulation and analysis.

The genetic algorithm was used to optimally coordinate the OCR where the objective function (OF) for the minimum time of operation was developed to solve the miscoordination problem of the plug setting (PSM) and the time setting (TSM) of the OCR. The Leaf-Node algorithm was the most suitable for the analysis of radial distribution system.

An existing industrial feeder was chosen for this purpose. The effects of more than 50% and 100% of DG were modelled considering the protection, power loss and this was also included in Chapter 5. The analysis of the result of the case study was covered, noting the inherent problems and how to mitigate them. Finally, the conclusions and future work were presented in Chapter 6

1.5 Contribution to front of Knowledge

The retrofitting of the existing dual constructed radial distribution circuits to be converted to hybrid radial distribution system (HREDS), the high voltage (11KV) would be converted to DC circuit, while the LV (0.415KV) would still be AC distribution system. The resultant microgrid, consisting the DG, generating dc and connected through DC-DC converter to the common DC bus, while the bidirectional DC-AC-DC converter on both sides of the distribution system (11 & 0.415) KV could make the 100% generated power of the feeder load possible, with some adjustments to the distribution protection system. The addition of the electric storage system (ESS) would act as the power sink both for excess and shortage in generation even under variable generation conditions. The ESS could become the swing for the microgrid in the islanded mode.

The synchronizing and re-synchronizing of microgrid after faults occurrence would not be necessary by this method, and harmonic problems present in the high penetration issues would not exist again.

This new development would make the standardization of DC distribution system necessary, so that all manufacturers of the control technologies for the converters, inverters and bidirectional converters {(DC-DC), (DC-AC), (DC-AC-DC)} could adopt the common voltage and current standards, as we have in the AC distribution system.

Chapter 2

Literature Review

2.1 Introduction

The most important investigations in the high penetration of DG into the distribution systems are in the areas of:

- Protection coordination
- Power Quality,
- Voltage magnitude,
- Voltage frequency

The changes in the mode of energy dispatch in the power grid as it affects transmission and distribution systems are along these lines. Microgrid emerges as a result of a cluster of DGs, the RES types like wind turbines generator (WTG), Photovoltaic (PV), micro Hydro, Fuel cells, Batteries and Combined heat power (CHP) micro turbine. The customer load completes the small grid system called microgrid. This is the future of the electricity power supply. The type, location and the size make DG not only acts as another source of electric supply but will surely substitute and reduce losses for transmission and high voltage distribution facilities in future, as indicated in Figure 2.1

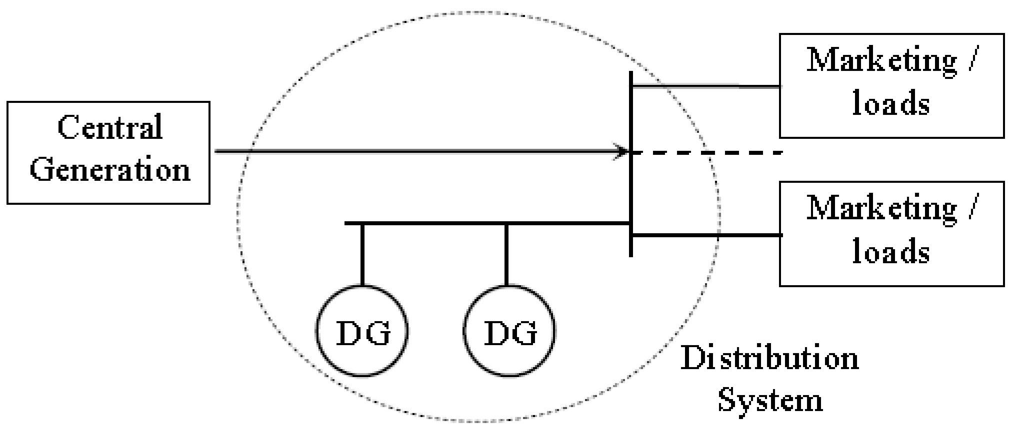


Figure 2.1. Present/future power system (Olatoke & Darwish, 2012)

These changes bring better economical ways of supplying electrical power to the customer. New levels of protection problems are emerging in the new concept. Variations in voltage and frequency can become critical because of the size, location and the stochastic nature of the RES. Islanding and harmonics are other major treats in the steady-state and dynamic state (under fault conditions) of the new microgrid structure emerging. The high penetration of DGs in these passive networks can cause reverse power flows which will result in protection system malfunctioning.

The quality of power has gained so much importance nowadays due to the sensitivity of ever-increasing power electronic equipment in the distribution customer load. The power electronic elements are extremely sensitive to various PQ problems which affects all connected electrical and electronics equipment. PQ is a measure of deviations in voltage, current, frequency, temperature etc. of power systems and the components. Any power system must make protection coordination, which is the most important part of PQ security and reliability as its main objective, whether industrial, commercial or residential. Protection must be selective, fast, reliable and cost effective. The security of the distribution system is compromised when issues like protective relaying, coordination, voltage variation, islanding and short-circuit fault protection especially in highly penetrated distribution system by DG are not thoroughly investigated and mitigated. There is the need to understand what type of PQ disturbances that exist in any industry or distribution systems in order to automatically detect, characterize and classify such disturbances. The types of DG inter-connections and their respective effects on the grid must be properly investigated because high penetration of power electronic elements into the distribution systems by DG leading to poor power quality and resulting in high production costs and heavy financial losses. Therefore, this chapter reviews all these issues and the recent progress made on the solutions to major problems arising from them.

2.2 Review of the existing PQ Monitoring System

Traditional power system was not designed originally to include DGs in the distribution system, and as the DGs penetration increases, the earlier regulations that these alien power sources must be disconnected from the network at the instant of PQ problems. Power system comprises generation, transmission, distribution and marketing divisions. Generation and Transmission are known as active sections where transient planning are carried out, since electricity is considered as 'manufacture and use' without storage. Most generation stations are massive in planning and construction, both in size and financial cost. The environmental cost in land acquisition is also important. Distribution was known as passive network where management and protection are not of major importance. The system frequency, voltage variations, protection parameters, active and reactive power are determined by the generation and transmission (G & T), thus the communication facilities form a major part of those sections. These communication facilities which are essential for interconnected G & T networks include power line carrier (PLC) and lately, supervisory control and data acquisition (SCADA) systems. The distribution system is passive, only meant to deliver whatever it is given by generation and transmission. Generation did not take place in the distribution system, and so communication is not of major importance, except for operation and maintenance purposes. The protection system control in the distribution system are very few, they include overcurrent protection at the distribution substations, circuit reclosers on the distribution lines and fuses at the distribution transformers. The marketing section deals with consumers where the customers are billed and payments are made. The important PQ disturbances in the distribution system are: Transient (impulsive and oscillatory), Interruptions, Sag/Swell, Under/Overvoltage and Waveform distortions. Waveform distortions include: DC offset, Harmonics, Interharmonics, Voltage fluctuations, Notching, Noise and Power frequency variations. (SlideShare, 2014) (Golovanov, 2013). Interharmonics are frequencies between harmonics of power frequency voltage or current (f_1). They are parts of spectral components of harmonics, with multiple zero-crossing voltage waveform, thereby causing distortions and they are defined as (nf_1) which are not integers of the fundamental component frequency. The main effect of interharmonic is its interference with control and protection in power supply lines and causing saturation of current transformers of relays.

2.2.1 Principles of Distributed Generation

. Distributed Generation is defined as the installation and operation of small generators, usually between 2 kW and 10 MW, in electric power system. DGs are small generators that are connected to the distribution network which includes: generators powered from renewable energy sources (except large scale hydro and very large wind farms), combined heat and power (CHP) systems and standby generators in the grid system, but operate only when the grid supply becomes inadequate. There are two types of DGs, the renewable energy sources (RES) and non-renewable energy sources (NRES). There is no acceptable international definition of the size, many definitions regard 30 MW as the upper limit. DG is used to improve reliability and power quality at electricity service level; it can be used to protect sensitive loads from momentary voltage variations and voltage ride-through during short outage in the distribution system. Power loss reduction and power factor improvement are other important advantages that can be derived from optimized installation of DG. The types of prime movers, engines, turbines and models identify the classification of the DG. The consideration for renewable energy sources (RES) types of distributed generation (DG) was main bases of this thesis.

As the name implies, DGs are generations at the distribution low voltage (LV) level, near the customers. There were DGs for a very long time under the name of Stand-by Generators (off-grid); they were never connected to the system supply. Nowadays they could be inter-connected with the distribution circuits (grid-connected), thanks to the rapid development in power electronics, such as the metal oxide semiconductor field effect transistors (MOSFET) and insulated gate bipolar transistors (IGBT). There is a huge penetration of the DGs especially the renewable energy resources (RES) type such as the photovoltaic (PV), the wind turbine generators (WTG), gas turbine and the run of flow (RoF) hydro turbine at the distribution level by the use of bidirectional interface. Recent developments show that wave on the high seas are good generators. DG is meant to improve the operations and costs of the electricity delivery systems at the customers' end. The raw materials needed by the RES are free, but the intermittency in them causes more PQ problems. The sensitivity, selectivity, speed and reliability of the protection-relay-system coordination become worse at higher penetrations of RES in the distribution system.

Distribution systems have always been radial in nature, but loop or mesh distribution circuits are used in densely populated areas. The radial circuits are unidirectional where power flow are converted from the high voltage (HV) to low voltage (LV) through step-down transformers, and the customers are fed from the low voltage circuits. The co-ordination of the protection in the distribution system is simple, consisting of circuit breakers (CB) and over-current protection relays at the bus station, reclosers are installed at some distance from the substation. Fuses are used to protect individual distribution transformers supplying LV to the individual customers and metering is carried out at this point, known as the point of common coupling (PCC). Industrial customers are fed from medium voltage (MV) level. The usual protection problems were well taken care of in this type of unidirectional distribution systems. Principal among such problems are the unnecessary and unintentional islanding, sympathetic tripping of OCR, and even safety of personnel and equipments, etc. The PQ and Protection problems have now become complex with the introduction of DG into the receiving end of the power system. Distribution circuit loads are mostly linear and non-linear, such power electronic loads include: rectifiers, inverters, variable speed drives (VSD), arc furnaces, fluorescent lamps, etc. These are existing sources of harmonic distortion, and detailed study has been made to find out how they interact with PQ and Protection system and also to find out whether the net distortion is within the international standards like IEEE 519 limits. (Patidar & Singh, 2009)

2.3 Different types of DG, the RESs and Interfacing Technologies

The prime mover associated with each type of generator indicates the name of such generator (e.g. wind, water, solar, gas, etc.). The wind generator's prime mover is the wind, the flowing river is the prime mover of the hydro, the solar radiation is the source of photovoltaic (PV) while coal, fossil fuel and natural gas are the sources of the energy for the non-renewable types of generators. The combined heat and power (CHP) type of distributed generator uses the high speed synchronous prime mover with power electronics grid interfacing. The branch-current flows, the bus voltages and the protection schemes (fault currents and circuit breaker ratings) must be modelled before connecting new major generators to the grid. Both the prime mover and the grid coupling must be thoroughly investigated before connecting the new sources to the grid. The harmonics investigation is very important when the grid coupling is through power electronic converters of the PV and the DFIG variable speed turbine. Doubly-Fed Induction Generators (DFIG) have power electronic converters (which are sources of harmonics), and when they are form part of the high penetration, they affect the relays' CTs causing saturation and causing miscoordination of the relays. There are many types of DG, some of which will be mentioned in passing (the non-RES) while the renewable energy sources (RES) are described in greater detail. (Leon Freris; David Infield, 2008)

Table 2.1 Types of DG and their interfacing technologies

DG Types and mode	Interfacing Technology
PV (DC)	PE Inverter or Converter
Wind (AC and DC)	Permanent Magnet or Induction or PE Converter
Fuel cells (DC)	PE Converter
Mini / Micro Hydro (AC)	IG or SG or PE Converter

RES include Wind energy (onshore and offshore), Hydro (reservoir and run-of-flow), Solar (PV, Concentrating solar and Solar heating), Geothermal, Marine and Bioenergy. Wind energy, Hydro and Solar which are intermittent in nature to varying degrees; have been on the major research list for many years and progress have been recorded in all the three types. This research is directed to these three forms only. The prime movers determine the name of such RES (wind, solar energy, and water-hydro) and they can be off-grid or on-grid. The wind generators are of two major types, the induction generators (IG) and the Doubly-Fed Induction Generator (DFIG). Hydro-generator is defined as large, medium, mini, micro and picro types, but mini and micro are the focus of this thesis. The synchronous and asynchronous types are to be investigated for PQ and Protection purposes especially the steady state and transient analysis.

2.3.1 Wind Energy

The technology of wind turbine is of two types, the horizontal and the vertical shaft turbines, the horizontal shaft type have become the dominant of the two types. The amount of converted kinetic energy in wind turbines is not more than 50% of the available wind energy. The number of blades and their orientation determine the power output, while the cubed relationship between the wind energy and the wind speed is the major determinant of the energy output. Either AC or DC generators are able to be used in wind turbine, with DC classified into compound, shunt or series generators and AC are either Induction or Synchronous generators. Some wind turbines use the permanent magnet synchronous generator (PMSG), but it is more expensive than fixed speed induction generator.

The on-shore was first to develop, until environmental opposition and space availability in the form of economy of scale make the off-shore to become dominant nowadays (Omar.Ellabban et.al, 2014). The on-shore wind plants range from 5 MW to 300 MW in size, while the distribution or the small scale domestic wind turbines are of 400 W to 50 kW. (Winrock International, 2004). The squirrel-cage induction generator (IG) were the earlier forms of wind turbine generator (WTG), with fixed speed and very cheap to construct. The major deficiency of these types of generators is that they consume reactive power which has to be supplied by external sources (either from the grid or separate capacitors or static var compensator SVC) for voltage control when generating.

IGs are motors made to run above the synchronous speed before they become generators.

The newer types of WTGs are the Doubly-Fed Induction Generators (DFIG) which are variable speed in nature. The other type of variable speed wind turbine generator is the synchronous generator with pitch-controlled rotors (SG) that are capable generating real and reactive power. There is no need of external provision of reactive power as in fixed speed IG. Other advantages include power quality improvements as they can withstand severe fault having voltage ride-through capabilities (Omar Ellabban, et.al, 2014) Wind power is no more considered to be DG because the size and location of most wind farms are large enough to be conventional and the heavy investment in this type are by large Independent Power Producer (IPP) rather than by small individual consumer. (IPP are private owned power producers, who sell electric power to utilities or individuals). But for the purpose of this project, wind generation is grouped as DG.

Power from the wind is computed according to following equation:

$$P_w = k \rho Cp V^3 A_S \qquad \textbf{2.1}$$

where:

P_h is the power in Watts; k is a constant, usually 0.5; ρ is air density; Cp is the coefficient of performance; V is the wind speed in m/s; and A_S is the area swept by the turbine blades. (Alaska Wind Energy Applications Training Symposium)

From the equation, it could be derived that:

- Doubling the wind speed V^3 will result in 8 times the power produced.
- The air density ρ is affected by the altitude and temperature. The density is inversely proportional to the altitude and the temperature.
- The coefficient of performance Cp is dependent on the type of wind turbine usually between 0.4 – 0.5.
- The area ***A*** swept by the wind blades A_s is depended on its axial length D of the blade, as $A_s = \pi D^2/4$

Power generated is maximally dependent on the wind speed, this is the reason for high fluctuation in power generated, especially the flicker.

2.3.2 Hydro generation

Hydro power generation falls into many categories: Large-hydro (above 100 MW), Medium-hydro (about 15 – 100 MW), Small-hydro (between 1 – 15 MW), Mini-hydro (0.1 – 1 MW) Micro-hydro (5 – 100 kW) and Pico-hydro (below 5 kW). Large, Medium and Small scale hydro have large reservoir and are usually connected to the grid while Mini can be stand-alone or grid connected, but Micro and Pico hydro are for rural communities and farms usually as stand-alone generators. Only the Small and the Mini hydro are considered for the purpose of this thesis (Practical Action, 2000). These are hydro schemes without significant water storage capacity, located in mountainous area, which may experience large variations in available water flow throughout the year round. Their output varies with rainfall, which leads to variable flow in the rivers and consequently variable power generated at different periods of the year (Jenkins, Ekanayale, & Strbac, 2010).

The power available is proportional to the product of head and flow rate:

$$P_H = \eta \rho g Q H \qquad \mathbf{2.2}$$

where:

- $\boldsymbol{P_H}$ is the energy produced at the turbine in Watts (W)
- η is the turbine efficiency
- ρ is the water density (1000 kg/m^3)
- g is acceleration due to gravity (9.81 m/s^2)
- $\boldsymbol{Q}$ is the volume flow rate passing through the turbine (m^3/s)
- $\boldsymbol{H}$ is the pressure head of falling water between intake and the tail-race (m)

The efficiency of Micro-hydro could be as much as 80%, the two most important being the volume and the pressure head of the water in any hydro generating power station. (EEP, Researches and Projects (RaP), 2014) (British Hydro Power Association, 2012)

The variable pumped storage hydro generator is the latest development in hydro generation. The pumped storage has improved by Variable technology which makes the same machine to be convertible as pump motor and generator. A frequency converter is used to vary the speed which makes the pump to become generator depending on the speed of operation. The Electricity de France (EDF) is a typical example in this arrangement. The synchronous generators are retrofitted to become variable speed machines. The two types of variable speed generators are synchronous generator with full converters and the doubly fed induction generator with converter, crowbar and chopper in the circuit. The Francis type of machines reversible and thus run as pump/generators that allow bigger output of over 200 MW per set. (Henry, 2013) It is also noted that like the wind, the hydro can be central generation, but micro-hydro is definitely DG.

2.3.3 Photovoltaic Generation

The photovoltaic (PV) manufacture is the direct conversion of sunlight energy to electricity. The cost of manufacture is decreasing rapidly due to the intensive on-going research in recent times. Although the cost of PV is still very high, it is the cost of installation that is prohibitive than the cost of manufacture itself. The operating and maintenance cost are the least of all DGs, it generates no heat and can be installed on rooftops which makes suitable as small scale generation. Large PV farms are now available in the field nowadays which makes it conventional, but the intermittency is major drawback that needs a form of storage if it is to be used as base or central generation (generation is only during the daylight hours). The capacity factor is very low unlike the hydro and even wind. PV can be off-grid or on-grid with incentive for individual customers in form of feed in tariff (FIT).

2.4 Power Electronics applications in power system control interface

Power Electronics is all about switching power by electronic means in any electrical circuit. Almost all the DG have power electronic elements interfacing them to the existing distribution system before the point of common connection (PCC). Such DGs include:

- Wind systems
- Photovoltaic Systems
- Micro Hydro, known as run of flow hydro
- Micro Turbine
- Battery Storage Systems
- Internal Combustion Engine Systems and others

These DGs are connected to the distribution circuits by different types of power electronic technologies before the consumers can access them. The power electronic interface is specific for each type, but they all follow the same principle. A generalised control design of power electronics is explained in this section which is common to all the DGs. The general topologies include:

- Input converter circuit
- The inverter module
- Output interface module and
- The controller module

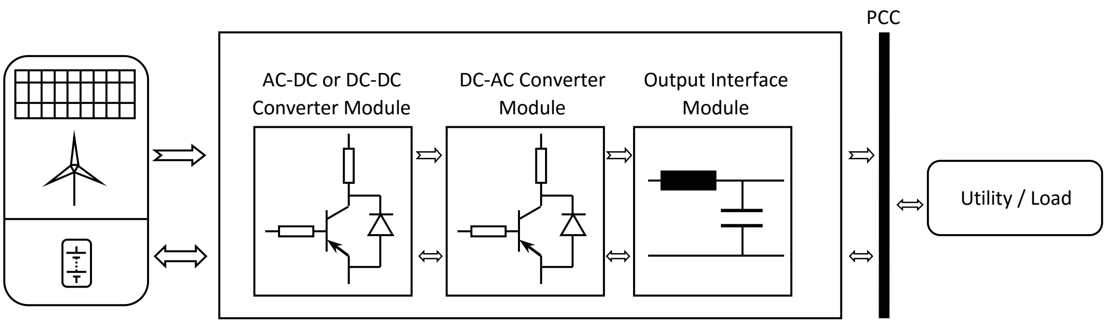


Figure 2.2 Generalised control design of PE interface

Traditional methods of voltage magnitude control and power flow is unidirectional with voltage drop over the network elements never reversed. This would no longer the case with the DG embedded in the system as depicted in Figure 2.2 in which it is illustrated how the bidirectional generalised control of Power Electronics interface can be utilised. The over/under voltage protection is required to be redefined as the power flow could bidirectional when storage is involved as shown above in Figure 2.2. The power electronic interface is the most essential part of the control system. The wind turbine generator (WTG), hydro turbine, etc. that generate AC power need the AC-AC-DC interface for proper control, while the PV, fuel cell, etc. generating DC need DC-DC-AC power electronic interface to connect to the grid. The input converter PE is dependent on the type of the DE:

- If the output from the DE is alternating current (AC), this will need to be converted from AC-DC as this will help to get rid of variable frequency and other PQ disturbances in the process. The name of this type of interface is called the rectifier or cycloconverter. Such types of RES include wind, microturbine and other synchronous generators.
- Other types of RES that generate DC still need DC-DC buck-boost converters and choppers in order to change the dc voltage level and the intermittent nature of the supply when in combination with other high penetration of RES. Such types of DE include the PV, fuel cells, even batteries.
- The common PE module in the group is the DC-AC, named inverter which converts the DC to grid compatible AC voltage, but with ripples and interharmonic currents and voltages.

- The output interface module is the filters which removes the ripples and other PQ and protection problems from and to the grid.
- The monitoring and control module operates the interface for protection coordination at the PCC connection. This module does not have to be a separate communication system, but embedded in the other modules.

The control offered by the PE interface include:

- Supplying to or draw active and reactive power from the grid at controlled rate
- The DG must automatically be disconnected from the grid when the PQ disturbance occurs in the grid system.
- Must re-synchronise the DG back to the grid when steady state of the grid is re-established after planned or unplanned islanding.

The DC-DC module has changed since the discovery of MOSFETs and IGBTs, and the bidirectional properties are now possible than when only diodes were used. The Multi-Port Bi-Directional DC-DC (BDC DC-DC) converter has become the most important interface in modern power electronic component as it interfaces the sources with the load along with energy storage devices, as shown in Figure 2.2. The storage capabilities if present in RES circuit topology is a major advantage in stand-alone microgrid, hybrid electric vehicle (HEV), Residential and Commercial buildings. The HBDC could be used to combine different types of energy sources and be used as power sink for excess power produced in RES especially in islanding situations. Others, like fuel cell energy systems and uninterrupted power supplies (UPS) could make use of the BDC. The BDC has greatly improved the high efficiency, dynamic performance and the reliability of the hybrid system of RES and the microgrid. The buck-boost type of bi-directional converter (BDC) is used for charge and discharge of the battery (Venmathi & Ramaprabha, 2013).

The advantages of the buck-boost BDC over the conventional dc-dc converter of the diode type include:

- High step-up and step-down voltage ratio
- Large voltage power flow variations
- Soft switching ability which are few in number
- Zero voltage switching with reduced switching losses
- The conduction losses are minimal
- There is no need for any transformers and therefore there is no magnetising current saturation and less weight and volume (Hasan & et al, 2008).

2.5 Technical Impacts of DG on the Distribution System

Distributed generation is by definition of size limited to few kilowatts up to few megawatts connected to the distribution system at the customers' or distribution lines or at the distribution injection substation. Technical issues like power losses, power quality, voltage control, system protection coordination and reliability are some of the important impacts that have to be investigated to determine the penetration level of DG. Flicker is another problem emerging in the high penetration of wind turbines in the distribution system (DS). Since DG is penetrating into the DS at an alarming rate, it has become very important to investigate the adverse effects caused by these impacts on the DS, especially the critical issues like protection coordination. The technologies to be considered in this thesis include synchronous generator, asynchronous generator and power electronic converter-inverter interface. The recent major development on power electronic has made the interface to have the greatest impact on the distribution system and this thesis concentrates on the impact of power electronic interface. Synchronous and asynchronous generation are now using power electronic interface to interconnect the DG to the DS (Hager, Sollerkvist, & Bollen, 2006). Finally, the new transformerless technology (DC-DC) conversion using power electronic has made the technical interface to become very important now and in the nearest future. It should also be mentioned that the consumers' power electronic equipment consumption has increased tremendously thus becoming more sensitive than ever before to voltage variations and harmonics. Excess residential solar generation causes voltage instability and power quality problems for the distribution utility because of massive intermittency of daylight/night supply and demand. The utility has to deal with the measurement and control of its transformers, static compensators and other transmission line upgrades.

2.6 Impact of High Penetration of DG on Protective Relaying.

The penetration of the DG into the distribution system causes the down-stream fault of the DG's fault current to increase at the fault point, due to the DG, the sensitivity of protection is improved, the scope of protection is increased, but it could cause protection loss.

Distorted waveforms have profound effects on protective relays especially the earlier electromechanical and static relays, but the filtering provided by microprocessor-based relays have taken care of these PQ problems. Harmonics (high frequency) waveforms influences are well taken care of by filtering of the microprocessor relays such that a microprocessor relay using the digital filter is exempt from the effect of harmonics by extracting the fundamental from the complex waveform (Hart & et al, 2000).

Table 2.3 gives a tabulated summary of categories, the typical frequencies, voltage magnitude, typical durations, effects and the possible causes.

Table 2.3 Summary of PQ disturbances (Hart, 2000) (IEEE PSRC, 2000)

Disturbance Category	Typical Frequency	Voltage Magnitude	Typical Duration	Effects	Possible Causes
1. Transient					
Impulsive	unidirectional	Mega volts/mega amps	50ns to 3ms	Loss of data, possible damage, system halts	Lightning , ESD, switching impulses, utility fault clearing
Oscillatory (low to high frequency)	< 5 kHz to 5 MHz		50ms to 5µs	Loss of data, possible damage	Switching of Inductive/Capacitive loads
2. Interruptions					
Interruption		<0.1 pu	0.5-30 cycles	Loss of data, possible damage, shutdown	Switching, utility faults, circuit breaker tripping, component failures
3. Sag / Undervoltage					
Sag		0.1-0.9 pu	0.5-30 cycles	System halts, loss of data, shutdown	Startup loads, faults
Undervoltage		0.8-0.9 pu	>1 min	System halts, loss of data, shutdown	Utility faults, load changes
4. Swell / Overvoltage					
Swell		1.1-1.8 pu	0.5-30 cycles	Nuisance tripping, equipment damage/reduced life	Load changes, utility faults
Overvoltage		1.1-1.2 pu	>1 min	Equipment damage/reduced life	Load changes, Utility faults

Disturbance Category	Typical Frequency	Voltage Magnitude	Typical Duration	Effects	Possible Causes
5. Waveform Distortion					
DC offset		0-0.1%	Steady State	Ground fault current, Transformer heated nuisance tripping	Faulty rectifiers, power supplies
Harmonics	0-50th	0-20%	Steady State	Transformers heated, system halts	Electronic loads (non-linear loads)
Interharmonics	0-6 kHz	0-2%	Steady State	Light flicker, heating, communication interference	Control signals, faulty equipment, cycloconverters, Induction motors, arcing devices
Notching			Steady State	System halts, data loss	Variable speed drives, arc welders, light dimmers
Noise	Broadband	0-1%	Steady State	System halts, data loss	Transmitters (radio), faulty equipment, ineffective grounding, proximity to EM/RFI source
Voltage fluctuations	<25 Hz	0.1-7%	intermittent	System halts, data loss	Transmitters (radio), faulty equipment, ineffective grounding, proximity to EM/RFI source
Power frequency variations			<10 s	System halts, light flicker	Intermittent operation of load equipment

PQ is characterised by different definitions: magnitude, duration and frequency components but all waveforms do not possess the same PQ problems, thus different types of PQ disturbances are first studied in order to proffer solutions to individual types. The disturbances are first evaluated to design measurement equipment requirements and the measures to correct such PQ problems.

Specifically, PQ is referred to as any electrical disturbance that could adversely affect customer load or power system equipment, and this could also be called power reliability (outages). IEEE 1159 defines PQ electromagnetic phenomena, while IEEE 519 details harmonic disturbances on power system.

Transients

The lightning strikes are typical examples of impulsive transients and are characterised by magnitude and duration and are unidirectional. The rate of rise is very steep, and the high frequency components need very fast sampling for characterising the impulses and waveforms. Some lightning strokes could be up to 6 kA impulsive transient current with 3ms rise time.

Protective line relay may not operate for this of current, but the lightning arresters are meant to protect the equipment. However, flash-over may be caused by lightning strokes resulting in high incident energy having high power frequency current that may result in relay operation. Oscillatory transient changes polarity, unlike the impulsive transients that are unidirectional. The rate of changing polarity is further classified into: high, medium and low frequency impulsive transients.

High oscillatory transients are caused by switching circuits and bank of capacitances having frequencies in the order of 10 kHz and above. The transmission line resistance could help to dampen these waveforms and so do not last for more than some few cycles. Protective equipment could ride-through these types of disturbances.

The medium frequency transients are in the order of less than 1 kHz for times of 0.5 to 3 cycles. Protective equipment can also ride-through these types of transients.

Low frequency impulse transients (called ferroresonance of voltage) are caused by transformer inrush currents. Transformer saturation is caused by ferromagnetic materials like iron that have reached their maximum magnetic field (H) and cannot increase their magnetization anymore. The total magnetic flux density (B) reaches the limit. Low frequency transients are the result of ferro-resonance caused by transformer saturation and also capacitor saturation. The frequency and duration of these oscillatory transients cannot be prevented by the protective relays but relay coordination is set such that the transformer may ride-through or isolate the transformer before causing damage. The current transformers attached to the relays can also reach saturation, thereby send the wrong signal currents to the relay for activation. This affects the directional relays and cause miscoordination.

2.7 Software Tool Options

Most commercial power system simulation software for transmission and distribution analysis have different approaches to their user functionalities. These approaches depend on the requirements of their intended customers, with different interfaces, but all have models that analyse load flow, short-circuit, protection coordination, stability, cable parameter calculations, harmonics etc. Almost all operate on 32-bit Microsoft Windows operating systems for their user interface, but some few have advanced to the 64-bit operating system.

To compare these software due attention was paid to the following:

1) User Documentation – Manual and examples for beginners
2) Data Portability – Exporting and importing data between different software
3) User Interfaces – Easy access to activate special functionality
4) Printing Problems – Exporting to Microsoft windows for excel, words, etc.
5) Unit Price – Most software prices are out of the roof for young consultants and training institutions.

2.7.1 Decision Matrix

Relay coordination in the distribution system, considering the high penetration of RES and the hybrid configuration, the different software options types considered include: ETAP, Matlab/Simulink, ERAC, NEPLAN, Power-World, Power-Factory from DigSILENT, Eurostag, SIMENS PSS/E and a host of others.

ERACS is an integrated suite of programs allowing load-flow, fault, harmonics, protection co-ordination, arc flash and transient stability studies to be carried out via the graphical user interface. It has a large library of equipment data and comprehensive customer support service.

It is not possible to give a detailed analysis of each of these software, but the table below shows why ETAP software was chosen for this case study.

Table 2.4. Software Decision Matrix

Type of Software	User Documentation	Specialities	Data Portability	User Interface	Unit Price	Total
Neplan	4	4	4	3	2	**17**
Simens Pss/E	4	5	4	3	2	**18**
Etap	5	5	5	4	2	**21**
Power World	3	2	2	2	2	**11**
Dig Silent/ Power Factory	4	4	2	2	2	**14**
Erac	4	4	4	4	2	**18**

The decision matric shows that ETAP which specialises in Power system design and analysis, Real Time power management system and RES is ideal for this simulation. It has also developed the user interface, easily exporting to Excel, and reports are complete with details.

Numerical calculations can be performed with tremendous speed by ETAP software, automatically applies industry accepted standards, and the reports are easy to interpret. ETAP, can handle more than 1000 buses and contains a load schedule program that can track up to more than 10,000,000 load items. The reports of the voltage and short-circuit current at the terminals of each load item are displayed vividly. Many of the Top 10 electrical design firms rely on ETAP.

This capability makes ETAP suitable for large industrial facilities, as well as utility systems (Brown & et al, 1990) (Kulkarni & Sontakke, 2015).

The latest ETAP 14 has more capabilities than the earlier versions and printing is possible without screenshots (Khan, Junaiki, & Asgher, 2009),

2.8 Summary

High penetration of distributed generation (DG) in the distribution system (DS) could cause protection coordination problems, as the load-flow analysis, short-circuit analysis and protection mis-coordination become very important. Micro-grid has emerged as a result of high penetration of renewable energy sources (RES) in the DS, with the customer load completing the small grid system. This would be the future of electricity power supply. New levels of protection problems have emerged in the new concept, islanding and harmonics under fault conditions would change as a result of the high penetration. Less than 20% penetration of the DG of the customer load would not change the protection coordination, but, above 50% penetration would need to be treated as micro-grid, having a point of common coupling (PCC) to the main grid. Power loss reduction and power quality improvement could be achieved if accurate analysis and recommendations could be implemented at high penetration. In the recent past, high penetration of the RES types, the photovoltaic (PV) and the wind turbine (WTG), have been connected to the distribution system through the power electronic interface (converters, inverters and bi-directional converters), which have made the quality and reliability of the electricity supply become worse.

The DC-DC and the bi-directional DC-AC-DC modules, and the electric storage system (ESS) are the main important interface power electronic equipment in the hybrid system if the high penetration of the DG would be achieved, especially, for more than 100% penetration. These converters' performances have improved since the discovery of MOSFETS and IGBTS as their bidirectional properties have made them to become the most important interface in modern power electronics. The hybrid system of RES and the microgrid have improved the high efficiency, dynamic performance and the reliability of the hybrid system. Current transformer saturation could wrong signal currents for relay activation, which could lead to mis-coordination.

The 64-bit operating system of ETAP software was found to be more adequate for large industrial facilities and large utility for user documentation, data portability, user interface and other specialties in form of real-time power management which is important for analyzing renewable energy system.

The control strategies for hybrid RES in the distribution system was next to be considered for the high penetration of the DGs, since the control of interfacing techniques must be employed.

Chapter 3

Control Strategies for Hybrid RES in Distribution Systems

3.1 Introduction

The level of penetration of hybrid renewable energy sources in distribution systems depend on the interfacing techniques and the control strategies employed. The integration of HREDS considering the control, protection and stability for effective power quality and reliability of the system was considered in this chapter. The hybrid of AC and DC have become the important issues in the distribution system nowadays as most equipment in the residential, commercial and industrial circuits have high level of power electronic inputs which depend on DC supply and are still on the increase. Table 3.1 is an example of the type of loads in the distribution system. The present topology is AC-DC conversion in order to supply the equipment, but if local distributed generation is now DC, the conversion becomes DC-AC-DC, becoming high proliferation of power electronics in the distribution system. (Basak & et al, 2012)

Table 3.1 Types of Loads and their mode of supply

Types of Loads			
	AC	**DC**	**AC converted to DC**
Computers & UPS		✓	
Printers &Energy Storage		✓	
Electronic Chargers		✓	
Televisions & Recorders	✓	✓	
Washing Machines & Frig.			✓
Heating (HVAC)	✓	✓	✓
Light Emitting Diodes (LED)		✓	
Industrial Equipments			✓
Motor Speed Drives			✓

The different types of interfacing configurations and their controllability for high penetration of RES are considered, so as to regulate their intermittent nature and the variations in the loading. It is noted that an LVdc microgrid is easier for connecting loads, sources and energy storage using simpler and more efficient power electronic interfaces than the LVac microgrid (Solomonsson & Sannino, 2007). The control design in dc systems is significantly simpler than in ac systems since there are no reactive and harmonic power flows or problems of synchronization. There is improved reliability in dc systems than in ac systems since the number of active elements in dc-dc power electronic devices is smaller than in dc-ac converters (Dragicevic & al, 2014)

3.2 Interfacing Configuration of HREDS sources

DGs are by definition and construction are small in size (5 kW – 10 MW), usually located in the distribution system (low voltage LV or medium voltage MV) and do not pose any PQ, protection, stability or operational problems to the distribution system when they are few in number until they become high. Most of the DGs, especially the RES are intermittent in nature, thus becoming harder to control considering the fact that the loads also vary and having its own PQ problems. Some of them generate AC voltages (synchronous SG or asynchronous IG generators) while others generate DC voltages.

High penetration of RES, of different generation technologies, both AC and DC otherwise called hybrid renewable energy distribution systems (HREDS) is now regarded as micro-grid where the load demand matches the local generated power, or the local generation could be bigger than the load. Of importance is the design of the appropriate control techniques embedded into the power converter control unit. Appropriate control strategy is a challenge to overcome all the PQ, protection and stability issues in order to supply reliable steady power. Some of the challenges include protection coordination, power factor control, phase sequence (resynchronising after islanding), flicker, frequency control, voltage deviation and power fluctuation (and reverse power) in the hybrid RES and the load demand. The design must be able to mitigate all these issues and deliver reliable steady power. Two known methods of interfacing the HREDS with the grid include the AC bus line connecting directly to the distribution grid as shown in Figure 3.1(a) Another method is to first integrate the local generation into a common DC distribution bus and then link the bus with the grid AC line through appropriate power converters, Figure 3.1(b). This later method is considered to be of importance because the storage could easily be located on the dc bus line. The rapid growth of DC loads in the distribution systems due to advanced power electronic technologies makes the hybrid DC and AC in a distribution circuit very attractive development. Almost all residential and commercial loads consume DC supply. (Arul & et al, 2014). Table 3.1 is an indication of loads types and their mode of supply indicating that both residential and even industrial loads will all soon be taking DC supply (Wang & et al, 2013).

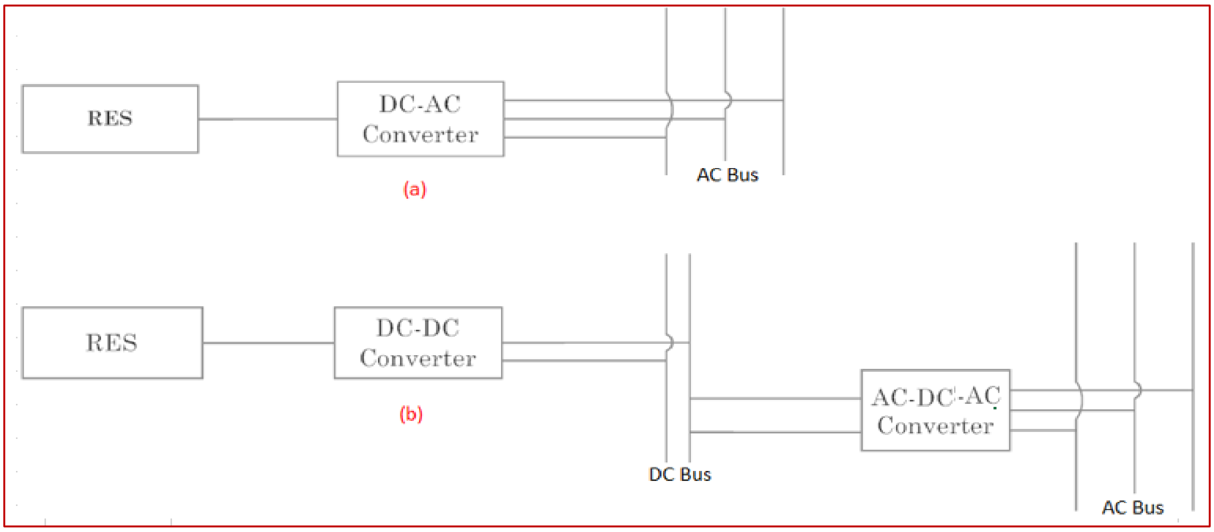


Figure 3.1. Interfacing methods of hybrid RES with the grid. 3(a). Direct conversion of DC-AC to the grid. 3(b). Interfacing with the DC and AC bus to the grid.

The issues addressed in the interfacing integration included interconnection requirements, response to abnormal conditions like protection miscoordination to isolate the smallest part of the system and at the shortest time possible. Others include safety of personnel and equipment, islanding problems when transitioning from grid connected mode to islanded mode and resynchronising. Therefore, both the power converters and their control strategies are of importance and are both thoroughly investigated in the next topic.

3.2.1 Converters and Inverters Strategies for Interfaced HREDS

There are no standards for the generating voltages of the different DGs unlike the conventional AC systems that have been in operation for over hundred years. Therefore, converters and inverters are used to interface them with the distribution AC voltages. More focus is placed on rapidly increasing converter - inverter – interfaced DGs which place more problems on utility network integration. The different types of interfacing topologies include: converters (AC-DC), inverters (DC-AC, bi-directional converters (AC-DC-AC) and (AC-AC) or (DC-DC). The recent progress made in power electronics like BJT, MOSFET, IGBT and IGCT and others have made the interfacing easier than the days of diodes. The ever increasing interface technologies have become the bedrock of more research in the distribution system. These scenarios make it necessary to investigate new and up-to-date DG and network protection schemes. Identification of the main problems relating to protection schemes under different types of DGs and continual varied network-operational conditions have become major limiting factors affecting the high penetration of DGs into the distribution system. Appropriate power conversion circuits and the controllers are needed in order to maximise the high penetration of these DGs in the distribution system. The bi-directional AC-DC-AC converter linking DC microgrid to the main AC grid in the HREDS encounters major protection problems during various types of faults, line to line, line to ground and DC faults and needs to be protected.

The simulations carried out were for flexible network operations and modern DG technologies. Electrical transient's application programs (ETAP) software was deployed for this study. The standards according to IEC and ANSI were used for comparisons of the results from the simulations. IEEE P1547-2003 provides the general guidelines for interconnecting these DGs to the distribution system, especially the abnormal conditions in PQ, islanding, resynchronising and safety operational conditions. (Basak & et al, 2012) There is no reactive power flow which causes voltage drop in the DC distribution, but the intermittency of the

RES (WTG or PV) result in voltage flickers due to high resistance of LV cables, supply and load variations that cause equipment to malfunction. Maintaining bus voltages could only be ascertained by storage units at regular intervals with bi-directional converters.

3.2.2 Power quality Improvements of converters/inverters in HRES

Non-linear load currents are the sources of voltage harmonics resulting in serious PQ problems. Active power filters (APF) are generally used to compensate the load unbalance and current harmonics in the distribution system. With the interconnection of the RES, a better way is the use of inverters of the RES to perform the APF functions thus reducing the extra cost of APF to perform the same function. The inverter can be fully utilized to carry out ancillary services in addition to its actual work of transferring intermittent active power from the RES to the grid/load. The other additional functions include:

1. Supply of reactive power control to or from the grid, especially when it is not in active power transmission mode.
2. Load following.
3. Compensation of continuous PQ disturbances (waveform distortions and voltage unbalance),
4. Supply of the unbalance and neutral currents in a 3-phase system. (Bracale & et al, 2009)

Thus, the linear/non-linear unbalance load at the PCC appears as balanced load to the grid by the adopted control system (Temerbaev, Dovgun, & Shevchenko, 2014). Distribution Static synchronous compensators (DSTATCOMs) are the most convenient dynamically and efficiently rectifier/inverter topologies that are used in interfacing HREDS. They consist primarily of rectifier/inverter that are shunt connected to the distribution system so as to compensate the reactive power requirement dynamically, using the PWM technology. DSTATCOM is a voltage source converter which converts DC power into AC power of variable amplitude and phase angle. Controlling the amplitude and the phase angle of the three phase AC currents that it is shunt-connected to, the DSTATCOM can dynamically supply a variable and accurate amount of reactive power to the AC power system. (Singh., Mukherjce., & Tiwar., 2015) (Tanisha. & Shilpi., 2014) (Polishetty. & Prasad., 2014)

Other improvements that DSTATCOM connection brings to the distribution system include:

- Major reduction of voltage fluctuations at the load end.
- Dynamic power factor correction (PFC) for large industrial load.
- Increasing the power transfer capability of AC distribution lines.
- Stability of the distribution system during sudden changes in the load.

DSTATCOM in the distribution system is effective enough to provide the stability over the system. (Festo Didactic Ltd., 2014)

The current controlled voltage source inverter (VSI) are mostly used for interfacing RES to the distribution grid. The important points in the interfacing is the conversion of the generated DC to AC and the next important is the control system employed for the inversion. Some control strategies include:

- Using the active inductor to remove the harmonic current, but this takes place at a prescribed frequency only.
- Using FACTS controllers as in conventional power supply.

There are three types of FACTS controllers, mechanically switched, Thyristors switched and IGBT switched. The FACTS controllers improve the controllability of power flow and stability limits. Their technology is a collection of controllers that can be applied individually or with other devices to control current, voltage, series impedance, shunt impedance and can be used in damping oscillations. One of the best controller is the unified power flow controller (UPFC) that combines the quality of series and shunt FACTS controllers, as shown in Figure 3.2.

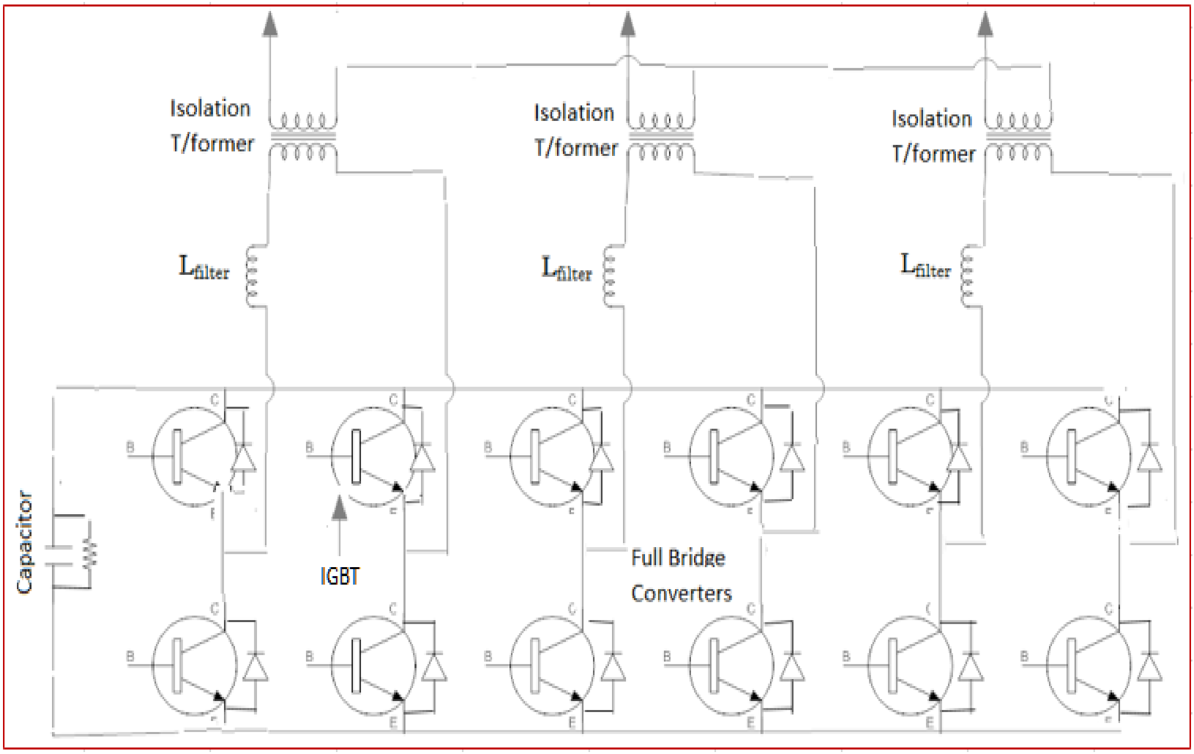


Figure 3.2: Schematic Diagram of DSTATCOM (Mitra & Venayagamoorthy, 2010)

(Singh & Arya, 2012)

3.2.3 Operation and Coordination Control of Hybrid AC&DC in the DS

Integrating ever increasing RES into the distribution system (DS) puts several demands on both the DS and the RES. Mains interference by the integration requires special protective devices and as the penetration becomes high, so also the demands on the grid become high. Therefore, interfacing techniques becomes very important, especially the converters and the inverters and these must be incorporated into the grid system.

Grid codes for different countries exist for regulating how these micro-generating sources should be connected to the distribution grid, the important ones are the grid power quality (PQ) in the areas of voltage and frequency and harmonic component limits. Others include the safety of the workers during mains disturbances and the latest is fault ride through (FRT) where the RESs are supposed to support the distribution grid instead of shutting down at the first sign of fault. Interfacing techniques for connecting the HRES include the converters, inverters, transformers and bidirectional converters. The literature on different types of converters (AC-DC) topology have been studied and practised for many years. Inverters (DC-AC) and bidirectional converters (DC-AC-DC) are now extensively employed in the storage and energy management in the HREDS. The next investigation is how to combine both the ac and dc in the same microgrid structure since the conventional distribution system is wholly ac and any form of dc is on the load side that requires conversion to dc for the purposes of loading only.

3.3 Integration/harmonization of AC and DC in the hybrid structure

In the HRES configuration, the PV panels are interfaced through a DC-DC converter to regulate their fluctuating DC output. The wind turbine connected to the IG generates fluctuating AC output which is first converted to DC and connected to the DC bus through the DC-DC converter. The common DC bus is the source of the regulated power from various RES and supply DC loads and maintaining a constant DC voltage at the input terminal of the DC-AC inverter. But the DFIG wind turbine generates three-phase AC voltage with constant frequency by controlling the frequency of the converter exciter even with fluctuating wind speed. This can be coupled to the directly to the AC bus. In the integration and harmonization of ac and dc of the hybrid structure, dc sources, dc loads and the battery are connected to the common dc bus, while the ac sources, ac loads and the grid are connected to the common ac bus. The bi-directional AC-DC-AC converter connects the two buses together. This makes the control of the system easier to configure, protection-wise implementable and easier to operate. Both the distribution circuits and the distribution loads (residential, commercial and industrial) can adopt this hybrid system conveniently. (Arul., Ramachandaramurthy, & Rajkumar., 2014)

The various converter techniques of importance in the proposed HREDS include: DC-DC converters, DC-AC inverters, AC-DC-AC bidirectional converters, the DC bus and the supercapacitors (SC) as indicated in Figure 3.3. These power converters and their control strategies are considered in the next subsection.

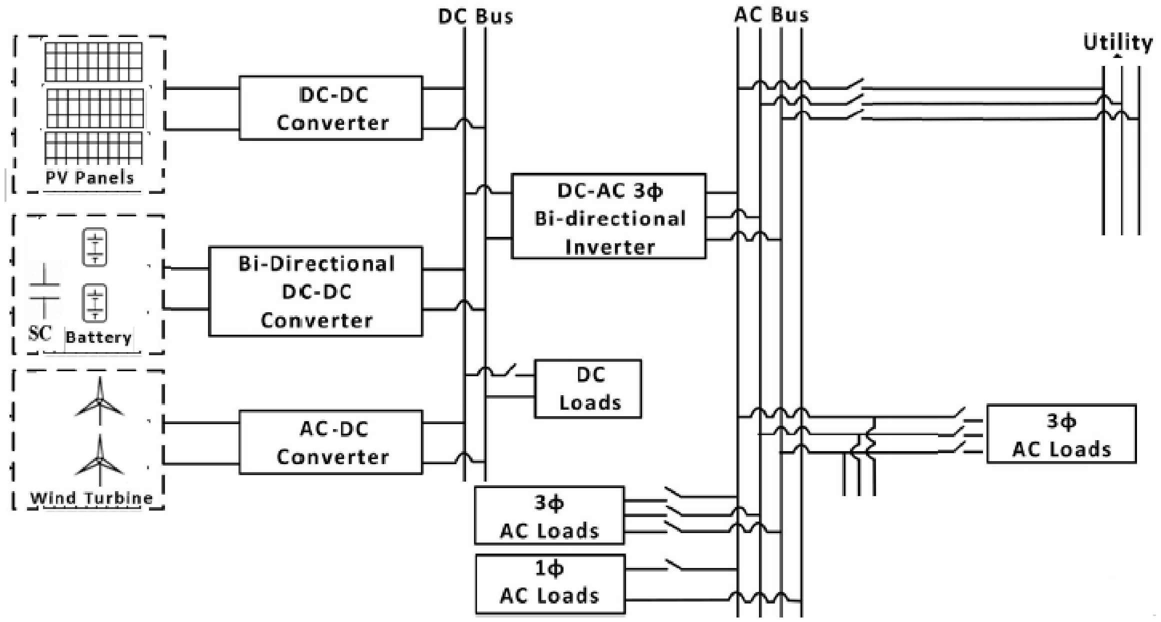


Figure 3.3 The HREDS configuration of the different converters and inverters

Maximum real power with minimum losses is possible with this configuration because the converters do not need complicated control algorithm. The DC bus is only responsible for the real power and the voltage regulation from the RES sources which are DC based and the AC bus is responsible for the power quality, voltage control, and harmonics, active and reactive power of the ac loads. The bidirectional converters help to control power flow on both sides, the dc storage on the dc side while the grid controls the power flow on the ac side. The DC storage in the form of battery banks is augmented by supercapacitors (SC) which helps to prolong the lifetime of the battery. (Arul, Ramachandaramurthy, & Rajkamar, 2014) (Bracale & et al, 2009)

Though the various converters of importance in this design are DC-DC, AC-DC, DC-AC Converters, DC-AC-DC and Bi-directional DC-DC Converters,

3.3.1 Voltage Control in Microgrid Considering Coordination Issues

The high penetration of RES is now treated as microgrid for purposes of operation and protection analysis where the PCC is the point where the microgrid is connected to the main grid. The voltage control in the microgrid is carried out at the interface of the renewable and the circuit. Different types of power generation sources combine to form microgrid, RES, CHP, DER etc. which are the sources and the distribution load completes the microgrid.

The main advantages of the microgrid are the low transmission and distribution losses, high reliability, high efficiency and low environmental impact. Operation of microgrid is in two parts, grid-connected and islanded modes. The protection of the microgrid and the effect on the main distribution grid protection could be of importance. Unlike the conventional power system, the power flow is not unidirectional and so the usual protection relays are not adequate for the microgrid, because there are multi-sources of fault currents. Also, the short-circuit level in the islanded mode is smaller than the grid-connected mode this is due to power electronics interface that limits fault currents. The protection issues in the steady state and the transient states of the microgrid (i.e. HREDS) during the grid-connected and the islanded mode are considered in this part. During the dynamic response conditions, the following protection problems exist: At what time should the island be formed and what are the protection problems in the unintentional islanding? (Feero, Dawson, & Stevens, 2002). The main interface between the RESs, the ac and dc grid are the DC-DC, DC-AC and the bidirectional AC-DC-AC interface, and these affect the relay coordination in the microgrid during fault conditions.

3.3.2 DC-DC Converters

The DC-DC converters are necessary to unify the generating voltages of the different DGs and also to regulate the fluctuating dc output especially from the fluctuating dc output of each DG before connecting to the common DC bus. Different sources produce power at different voltages and the converters are meant to convert them to a uniform DC voltage. DC is easier to control since it has nothing to worry about regarding power factor, phase sequence, power angle and frequency.

DC-DC topologies were based on high frequency transformers, but nowadays the development of IGBTs has made these topologies possible at higher power applications. Although the use of transformers provides a sort of isolation in grid connected circuits, but their bulky weight is not an advantage at lower frequency. At higher frequencies (the higher the frequency, the smaller and lighter the weight becomes) but the higher the losses of the design becomes. Therefore, the Zero Voltage Switching (ZVS) techniques, called soft switching were developed to reduce such losses especially in RES which operate in DC voltage. The PVs generate at low voltage but high current levels and DC-DC converters are needed to change the parameters to the higher voltages. (Guillaume & et al, 2006) Power DC-DC converters are used to step up and regulate the output voltage since the generated power is low voltage dc. In order to reduce the current ripple in the input stage of current-fed dc/dc converters, many solutions have been proposed. A new method for filtering the high frequency current ripple generated by current-fed DC-DC converters was analysed.

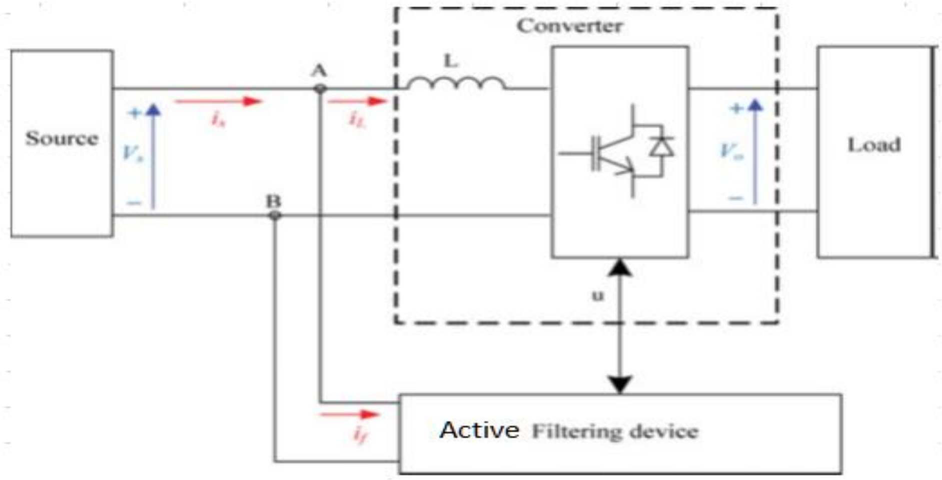


Figure 3.4 The filtering device for a DC-DC converter (Shahin, & et al, 2011)

An active filter is connected in parallel with the source that does not contain any passive filter between the source and the power converter. The active filter injects harmonic currents equal but opposite to those generated by the non-linear loads. The coefficients of the harmonics generated by the active filter are controlled in order to eliminate the undesired harmonics. (Shahin, & et al, 2011)

3.3.3 DC-AC converters (Inverters) in the hybrid microgrid Structure

Power electronic inverters have become very important in the penetration of RES in the distribution system using the inverters in their conversion. The different types of such renewable energy sources include PV modules, micro-turbines, fuel cells or full-scale inverter-interfaced WTG. The control of grid-connected inverters has become very important in the distribution system as the high penetration of DGs has become the norms because the incentives attract the customers. Until recent past, DG is regarded as negative load because the customers or the independent power producers (IPP) are only interested in real power at near-unity power factor (PF). But due to high penetration, the associated inverters are needed to supply ancillary services to support the grid stability. The inverters can now support the grid with power factor and reactive energy control to maintain the grid voltage (instead of capacitors). Grid integration control capabilities of PV inverters to provide the reactive energy instantaneously in the distribution system are an advantage without the help of any system operator. The integration controls are employed in this regard. The control services that inverters support the grid with include:

- Active power.
- Reactive power.
- Power factor improvement.
- Voltage and frequency control

The ETAP simulation software manages these controls in the following categories:

- Swing.
- Voltage control.
- Frequency control.
- MVAR control.
- PF control.

In the modeling, inverter operating conditions are made similar to a generator for all the possible applications. When an inverter is powering an islanded or isolated microgrid, the setting is in the swing or voltage control mode, but when it is grid-connected, like in solar farms the inverters are set in Mvar or PF control mode. In the load flow studies, the swing inverter does the control of the slack of the microgrid where the voltage magnitude and angle of the 'generator' terminals constant at the specified operating values. In motor acceleration studies, the initial load flow conducted, the swing inverter is represented as an infinite bus, and considering the Thévenin equivalent the point '0+' the inverter is modelled as a voltage source with its equivalent impedance.

When an inverter operates in voltage control mode, the inverter regulates its var output to control the voltage, its terminal operating real power (kW), voltage magnitude (kV) and its set maximum (Q_{max}) and minimum (Q_{min}) reactive power (kVAR) are specified for voltage control inverters.

In the MVAR control mode, the kW and kVAR are fixed, while in the PF control mode, the kW output real power and the %PF are fixed, while the ratio of active power to reactive power is controlled by supplying or absorbing the VARs in order to control the voltage and increase the efficiency of the distribution system.

The three major types of inverters are the current sourced inverters (CSI) and the voltage sourced inverters (VSI) and the impedance source inverter (ZSI), as shown in figure 3.5. The output from the inverters could be square waves or quasi-square wave or low distorted sine wave, and could be single phase or 3-phase. The PWM techniques are used to control the output voltage if non-sinusoidal, and such inverters are called PWM inverters, which contain harmonics. Different control schemes are used to reduce such harmonics to acceptable international standards. When the source voltage of the inverters are constant e.g. batteries, the inverter is called voltage fed inverter (VFI), and if the input current is maintained constant, it is called current fed inverter (CFI). The IGBT has made the VSI better efficient than the CSI in the industrial field as it has higher reliability and has faster dynamic response and the life cycle is higher than that of CSI. (VanderMeulen & Maurin, 2014)

The newest in the inverter technology is the single stage impedance source converter (ZSI) which has the added advantages of being low cost and of high performance than the VSI and the CSI especially for interfacing the PV with the grid. It does not need to be two stages in converting to higher power conversion. It is capable of tracking the MPPT, control the battery and output power all at once (Sudakar & Annadurai, 2014).

The Figure 3.5 shows the typical configuration of the different types of the inverters topologies that are in the industrial setup either at generation or the load side of the distribution system.

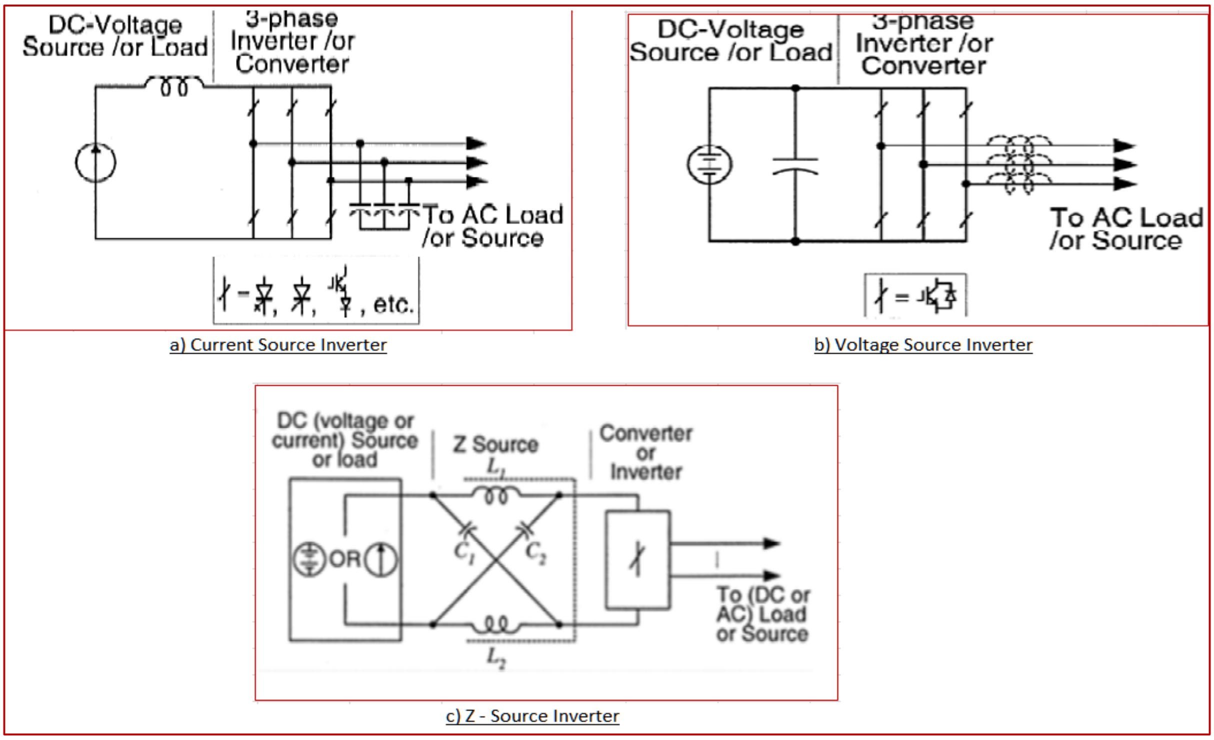


Figure 3.5 Comparison of a) CSI. b) VSI. c) ZSI (Sudakar & Annadurai, 2014)

3.3.4 AC-DC-AC Bidirectional Converters in the hybrid system

The increasing use of DC power equipment in the distribution industrial, commercial and residential consumers has made the design of hybrid AC-DC circuit inevitable. AC-DC-AC converters are commonly used as drives in order to control the speed of ac motors in industrial plants.

A hybrid AC-DC microgrid is necessary to reduce processes of several bidirectional conversions in a microgrid and to speed the connection of various RES of AC and DC, storage and loads to the power system. The hybrid microgrid of DC and AC circuits must be able to operate under the grid connected mode as well as during the islanding mode with the aid of AC-DC-AC bidirectional converter. The bidirectional converter provides power balance and voltage stability for the system, while the storage and the bidirectional converter provides stability for the microgrid during the islanding mode.

The bidirectional AC-DC converter incorporates galvanic isolation between the AC and the DC microgrid and is a power flow coordinator, it is capable of marching different voltage levels, has fast response to the transient load demand, etc. The battery type of DC-DC bidirectional converter is located on the DC side of the hybrid microgrid between the battery (which is supported by the supercapacitors) and the DC bus. The DC-DC bidirectional converter is a buck and boost converter in principle where the diodes have been replaced by controllable switch (MOSFET or IGBT), characterized by a voltage fed or current fed input.

3.4 Summary

Most of the equipment in the distribution system (residential, commercial and industrial) have power electronic interface in their circuits, and most DGs generate direct current which must be converted to AC and again reconverted to DC in order to be used by the equipment. The proliferation of power electronics for conversion should be reduced from DC of distributed generation to AC of the conventional distribution system before reconverting to DC of the power electronic equipment (DC-AC-DC). The hybrid distribution system has become important in order to reduce the number of power electronic interface, since the control of DC would be simpler than the AC since the reactive and the harmonics are non-existent in the DC system. PQ problems would reduce as the inverters of the RES could perform the functions of the active power factor (APF) in compensating for the load unbalance and the harmonics. Intermittent RES would be taken care of by the addition of ESS in the DC part of the hybrid and fault current contributions from the SG and ASG would be easier to control. The high penetration of 100% and above could become possible and the control would be easier by the HREDS, even islanding problems when transitioning from grid connected mode to islanded mode and resynchronizing in the microgrid could be overcome.

Two known methods of interfacing the HREDS with the grid include direct linking to the AC bus line of the grid. The second method is to integrate the local generation into a common DC distribution bus and then link the bus with the grid AC line through the bi-directional DC-AC-DC converter. The storage located in the DC side could maintain bus voltages and deliver power shortage or absorb excess generation, thus, taking over the swing duties during the islanding conditions. There would be no need of the proliferation of DC-AC inverters for each power electronic equipment which could cause them to be on the increase again. But the bi-directional DC-AC-DC converter encounters major protection problems during various types of faults including DC faults.

Interfacing techniques for connecting the hybrid renewable energy distribution system (HREDS) include the converters, inverters, bidirectional converters and transformers. Both inverters (DC-DC) and bidirectional converters (AC-DC-AC) could be actively used in the storage and energy management in the HREDS and are used in the hybrid of DC bus system and the AC grid circuits at high penetration level. Major interfacing problems at high penetration include: PQ in the areas of fluctuation, voltage, frequency and harmonic component limits, safety of the workers and the FRT. Fluctuation of dc output rectified by the DC-DC converter for the PV panels, and the fluctuations of the ac output of the WTG are converted to dc and then to the DC-DC converter, before connecting to the DC bus. A regulated DC bus power could then be interconnected with the grid ac system. This would make the control of the system easier to configure, operate and protection-wise implementable. The (HREDS) of dc and ac buses could be the new adoptable distribution system for residential, commercial and industrial circuits conveniently. The protection of the highly penetrated by DG hybrid system could be implemented by considering the system as microgrid having the point of common connection with the main grid. The two important current flows in any distribution system are the load currents and the fault currents, and how they affect the relay coordination in the hybrid distribution system. These are considered in the next chapter.

Chapter 4

Analysis of Relay Coordination in Distribution Systems

4.1 Introduction

A reliable protective system devoid of faults, overload, over-voltage, under-frequency and other forms of interruptions in the distribution system is of outmost importance in system sensitivity, selectivity, speed and reliability. Relay setting to provide backup protection in case of failure of primary relay is of importance in order to protect equipment and operators and to prevent unnecessary outage of consumers. Genetic Algorithm (GA) is a form of Artificial intelligence system used to solve the directional coordination problem in the DS in order to obtain the optimal coordination of overcurrent relays in the form of backup protection.

The two important current flows in any distribution system are the load currents (I_L), and the fault currents (I_F), alternatively known as the short-circuit current (Isc) which appears only whenever there is a fault in the circuit. Whenever excessive currents flow (above the rated stipulated current), they are called overload or overcurrent, which must be prevented. Different types of relays are employed to protect the circuit from overload or short-circuit currents. Each relay in the distribution system (DS) needs to the coordinated with other relays of the adjacent circuits and equipment in the form of backup protection in the event of the primary relay failure. The mal-operation of such primary relay is the major cause of unnecessary outages of the adjacent equipment.

Originally, overcurrent relays are used in distribution systems which are radial in nature (no ring and no mesh) before the introduction of DG into the distribution system. Two types of overcurrent relays (OCR), non-directional and unidirectional are used in the distribution protection to control tripping since (I_L) and (I_{SC}) can flow in either direction when the circuit is either mesh or ring, but there is only one direction of flow in the radial system without the DGs. (from source to load). (Bedekar, Bhide, & Kale, 2009). A typical mesh or ring system is shown in Figure 4.1. The load flow (I_L) direction indicated in red are along the buses and lines as shown, while short circuit (I_{SC}) current flow direction is away from the breakers, as indicated by black arrows.

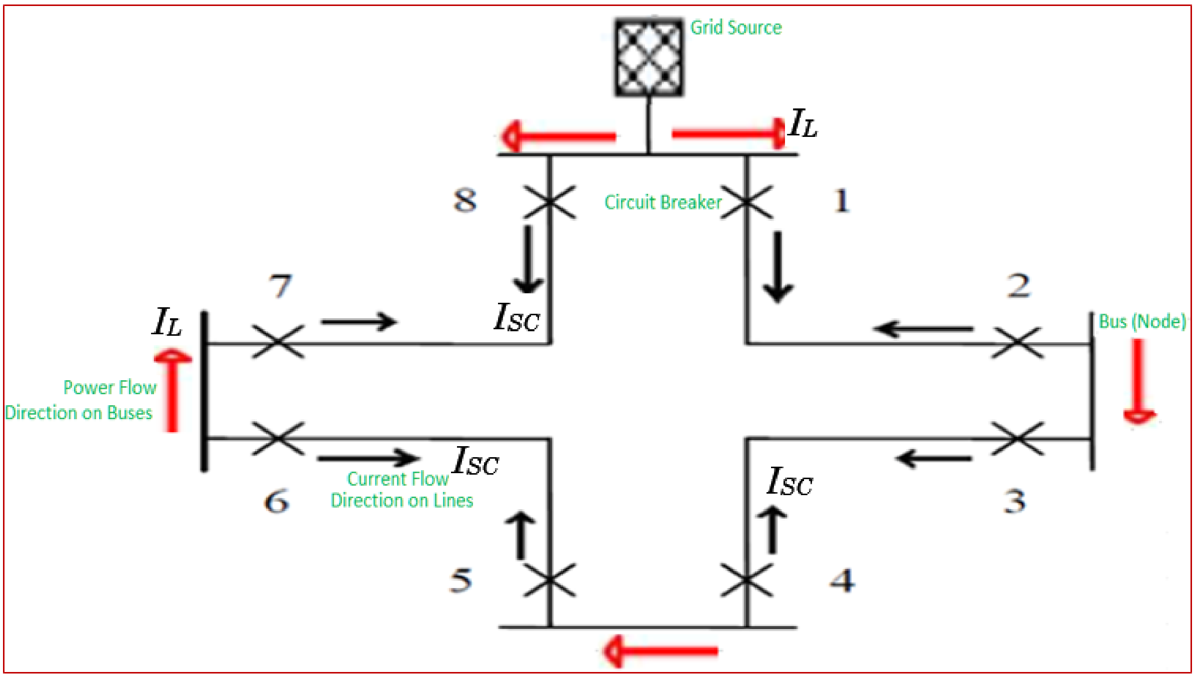


Figure 4.1 Mesh or Ring distribution circuit (Bedekar, Bhide, & Kale, 2009)

All the relays are directional relays having their tripping directions away from the concerned bus CB, as indicated in Figure 4.1

The relays are set for optimum performance to avoid mal-operation and the relay could be the primary or backup (in case the primary fails to operate).

In the ring system the directional relays must be coordinated in the forward and backward direction in which the coordination must be for the same direction of current flow and also with the relays behind them. The coordination necessary in the radial DS is unidirectional since the current flow is in one direction only (without DG)

4.2 Principles of Relay Coordination

The relay has two settings, the plug setting which decides the current required for the relay to pick up and the time setting which decides the operating time of the relay. Since currents are measured through current transformers having primary/ secondary coils, (e.g. 200/5 A) and it is desired that the overcurrent relay should operate when the system current crosses 120% of the rated secondary current then, the relay will operate when the current is 120% of the current,

i.e. 120% of 5 A. = 120/100 × 5 A = 6 A. The current setting is 120% and the pickup current is now 6 A instead of 5 A. i.e. this is the plug setting.

4.2.1 Plug Setting Multiplier (PSM)

The Plug Setting Multiplier (PSM) is the ratio of the fault current (If) in the relay to its pickup current (Ip)

$$PSM = \frac{Fault\ Current\ in\ Relay\ Coil\ (If)}{Pickup\ Current\ (Ip)}$$

$$= \frac{Fault\ Current\ in\ Relay\ Coil\ (If)}{Rated\ CT\ Secondary\ Current \times Current\ Setting}$$

Therefore, if the actual fault current in the primary of the CT is 1500 A, this translates to 1500 × 5/200 = 38.5 A. in the secondary, this is now (If).

Then the PSM of the relay = 38.5/6 = 6.42

Since the pickup current (Ip) has changed to 6 A, the relay will not operate at 5 A which was the 100% of the 200/5 A, but the 6 A which is the 120% of this value. The current setting of the overcurrent relay is generally in the discrete range of 50% to 200% in steps of 25%, while the earth fault relay is in the lower range of 10% to 70% in steps of 10%.

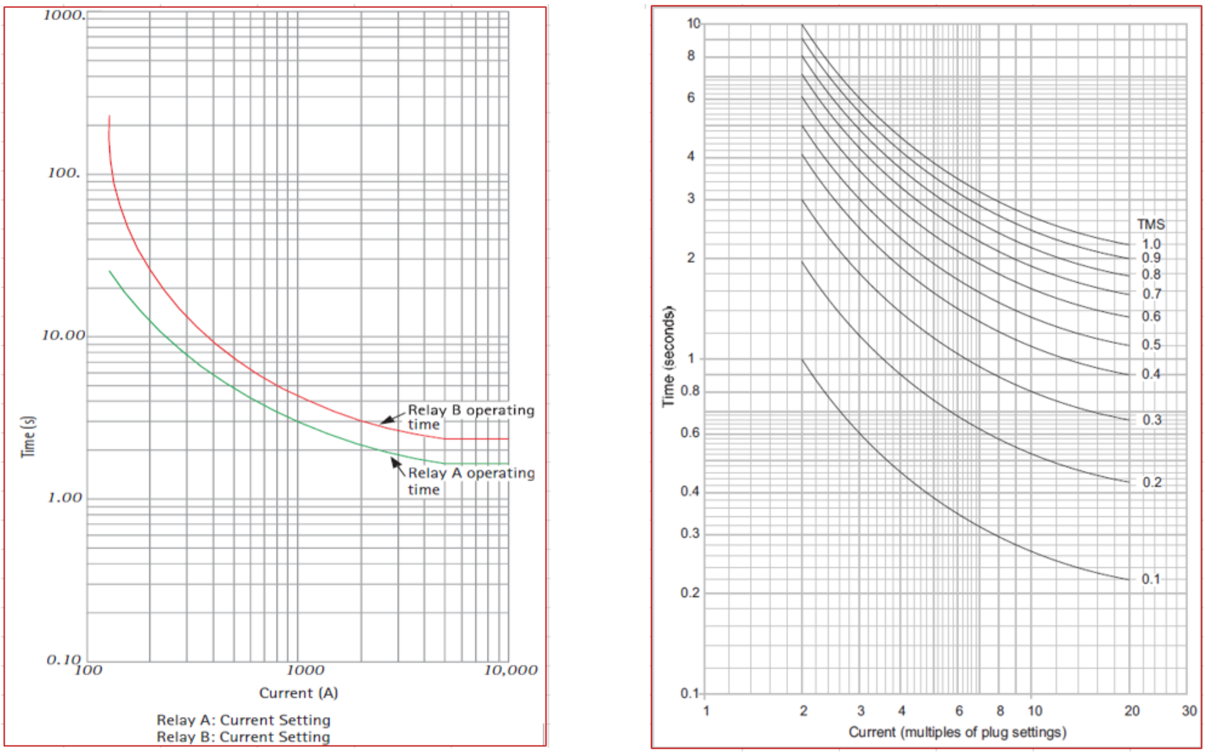
4.2.2 Time Setting Multiplier

Two factors determine the adjusting time of an electrical relay:

1. The distance to be covered by the moving parts of the relay when closing its contacts and
2. The speed at which this distance is covered

This is the principle of the time setting of the relay, and the time setting multiplier dial is calibrated from 0 to 1 in steps of 0.05 secs. But adjusting the multiplier alone will not determine the actual time of operation because the speed of operation of an electrical relay also depends on the level of the fault current, which is a function of the plug setting. The relationship between the time of operation and plug setting multiplier is as shown the Figure 4.2. (NPTEL-Electrical Engineering -Power system protection, 2006)

It should be noted that even though the time current curves (TCC) in Figure 4.2b are shown as discrete values of TSM, but continuous adjustment is possible in electromechanical relays. Other types of relays may have relay settings that are so small which tends to become continuous adjustment.



a) The characteristics of different relays. b) Typical multiples of pickup setting currents

Figure 4.2 (a) & (b). Relay Characteristics of Different Plug Settings of IDMT relays (AREVA T&D Automation & Information Systems, 2005)

TSM is the adjustment of the travelling distance (in factor 1) of an electromechanical relay which is calibrated in steps of 0.05 sec, but the actual time of operation (in factor 2) depends also on the speed of operation, which equally depends on the level of the fault current in the relay coil. The level of the fault current depends on the plug setting multiplier (PSM) as shown in Fig. 4.2 (a), and so, the total time of operation is a function of the PSM as indicated in Figure 4.2 (b). for different TSMs. Figure 4.2 (b) gives the total time taken by the moving parts for a particular PSM, and this time is multiplied by its TSM, thus, giving the actual time of operation for that PSM and TSM. Figures 4.2 (b) shows that for lower values of overcurrent, time of operation is inversely proportional to the current but as the current approaches 20 x full-load value, the operating time of relay becomes asymptotic with the PSM. This is a definite minimum value of operating time, and this feature is necessary in order to ensure that relay trips instantaneously without regard to the timing on very heavy fault currents flowing through healthy feeders. The fuse has inverse time-current characteristics also. The backup protection to the fuse is provided by extremely inverse (E.I) overcurrent relays at the feeder point. TSM is also referred to as TDS (Time Dial Setting). With the knowledge of PSM and TSM (plug and time setting), the desired relay operating time is evaluated.

4.2.3 Instantaneous Relay Protection:

Traditionally, this type of relay has only the pick-up setting and it does not have any TMS, this relay is not used for backup protection. Pickup current ($\mathbf{I_p}$) should be above maximum load current seen by the feeder to prevent the relay from tripping on load. Typical norm is to set $\mathbf{I_p > 1.25 I_{Lmax}}$. Also, pickup current should be below the minimum fault current i.e. $\mathbf{I_{fmin} > I_p > 1.25 I_{Lmax}}$. If this relationship is not strictly applied, it will make the relay's backup protection ineffective, and backup protection is impossible for the OCR considered, and so, other methods will have to be considered (Distance or Pilot protection). This coordination occurs at light load condition when minimum number of generators are on load and usually at the remote loading end of the feeder. In distribution networks OCRs are the main protection instruments, whereas in HV and EHV networks, OCRs are used only as backup protection (Siemens Pakistan Engineering Company Ltd., 2012)

4.2.4 The Coordination Time Interval (CTI) for Definite Time Relay

In backup protection principle, the relay should provide sufficient time for the corresponding primary relay to act before it issues tripping command. This interval is called CTI (co-ordination time interval or discrimination time). Typically, CTI is about 0.3 sec. and it is the summation of CB operating time+ Relay operating time+ Overtravel (for electromechanical relay only) + Factor of safety. The terminal relay (R_1) at the end of the feeder is exempted from CTI since it is not backing up any relay, as explained in Figure 4.3. (NPTEL - Electrical Engineering - Power System Protection Group, 2006)

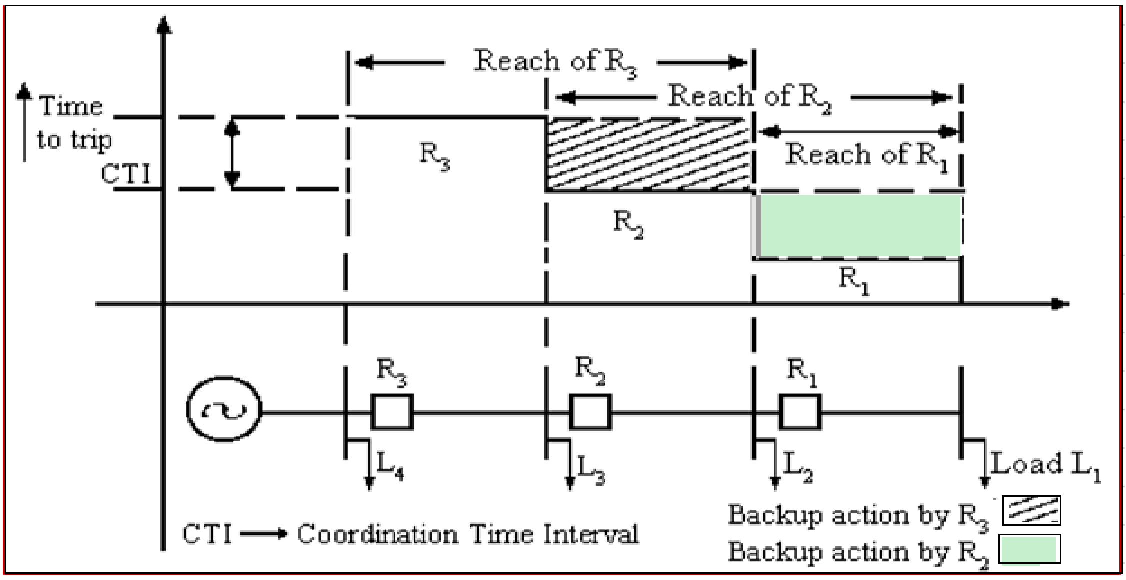


Figure 4.3. Overcurrent Protection Zones of Radial Distribution System (NPTEL - Electrical Engineering - Power System Protection Group, 2006)

This is Definite Minimum Time (DMT) Relay with fixed delay, independent of plug setting multiplier value, both the time setting and the pickup current are discreet and adjustable. It could be used for short-length feeders where the fault current would not change significantly with the location of the fault across the feeder.

4.2.5 Relay setting and coordination constraints

Coordination problem is solved by consideration of two important parts, pickup current and operating time. Minimising the two becomes non-linear programming problem. If the pickup current is fixed, then the minimisation becomes linear programming problem. Predetermining the pickup current and then optimising the TMS is achieved through GA technique. In predetermining the pickup current, the overload current problem is also considered.

The main objective function (OF) is to minimize the summation of all the operating times (t) of all the relays in the power system:

$$min\, OF = \sum_{i=1}^{n} ti \qquad 4.1$$

When n is the total number of the relays and t_i is the operating time of the i^{th} relay. The other objective function is to prevent mal-operation of the relays. The four major constraints to achieving this OF are:

- Operating time constraint, which depends on the plug setting (PSM)
- Time multiplier setting (TMS) constraint
- Coordination criteria constraint (CTI)

- Relay characteristic constraint, which depends on type of relay, either microprocessor or electromechanical.

4.3 Protective Relay Coordination Setting of OCRs by GA

Overcurrent relays normally have current setting multipliers or plug setting multipliers (PSM) ranging from 50% to 200% (in steps of 25%), while the earth fault relay ranges from 10% to 70% in steps of 10%. PSM for each relay is determined by two parameters: the minimum fault current and the maximum load current. The other multiplier is the time setting multiplier (TSM). The evolutionary algorithm (EA) solved the problem of discrete TSM or TDS and changing it to continuous by adding the new expression to the normal existing OF equation.

The main aim of relay coordination is to achieve the objective function of solving the problem of miscoordination and the problem of discrete and continuous current setting and plug setting usually adjusted by time setting multiplier and plug setting multiplier respectively.

In a mesh or loop system, fault and load current can flow in either direction, but in the radial system the current flow is in only direction (from source to load). Therefore, in loop system, relays protecting the line are subject to fault currents flowing in both directions, and non-directional relays cannot be used in such systems, as they would have to coordinate with relays at the remote end of the line, and also the relays behind them. Since directional relays operate only when the fault current flows in the specified tripping direction, they avoid compromising line protection.

Directional overcurrent relays have two types of settings:

- Time Multiplier Setting (TMS) which is continuous and
- Pickup current setting (Ip) which is discrete.

The problem of determining the settings of the relays using optimization techniques was stated as a linear programming problem because the Ip was fixed, as it was considered to be the source of the non-linearity. The main objective then becomes how to minimize the time of operation of the relays by optimization of the TMS. Some of the techniques used to optimally coordinate directional overcurrent relays include simplex, dual simplex and genetic algorithm. Unfortunately, although the problem becomes simple, the Ip is discrete and could not lead to minimizing the OF. (Ghogare & Bapat, 2015)

In other formulations, the pickup current was left as a variable, thus the problem becomes a nonlinear programming problem. In this case, the optimal values of TDS and Ip, are calculated. The optimal pickup currents are then rounded to the nearest discrete values. Unfortunately, rounding off the pickup currents will not lead to minimizing the OF. (Zeienldin, El-Saadany, & Salama, 2004)

Intelligent optimization techniques such as GA have come up which can adjust the settings of relays. In these methods the constraints are included as part of Objective Function. The use of GA for optimal coordination has two problems, one of them is miscoordination between 2 adjacent relays and another is discrete time setting and discrete plug setting, which are both predetermined during manufacture of the relays as multipliers. (Razavi & et al, 2008).

The first problem of miscoordination of directional OC relays is solved in which optimal operation characteristic (OF) and also optimal current setting by plug (PSM) and time setting (TSM i.e. TDS) of OC relays are determined simultaneously. This method helps to solve the miscoordination problems.

The second problem of discrete TSM and PSM cannot be solved by the use of binary code, because using binary code for continuous TSM's and PSM's make many binary numbers which are obviously difficult to solve by mathematical calculation even with computers. The GA can handle both continuous and discrete TSM's and PSM's. Both time setting multiplier (TSM) and plug setting multiplier (PSM) of OC relays are used in the in optimization procedure. Such backup procedure should only operate after the failure of the primary relay by a form of coordination time interval (CTI) between the primary and the backup relays. The CTI is usually referred to as 'discrimination time' between the main (primary) and the backup relays. (Asadi & et al, 2008) (Koochaki & Naghizadeh, 2008).

In using GA technique to adjust the setting of relays, the objective function and the constraints must be defined accordingly. The objective function (OF) must be to minimize the time interval between the main and backup relays subject to constraints preventing optimization, and the constraints are time setting multiplier (TSM) and the plug setting multiplier (PSM) of the relays, which are either in continuous or non-continuous values, to give the required optimal values. The miscoordination problems are solved by using the continuous and non-continuous PSM and TSM together for optimization in this project.

4.4. The Constraints of the Coordination of OCRs

The main and the backup relay curves are separated by coordination time intervals (*CTI*) which are defined as below in equation 2, while equation 1 depicts the objective function (*OF*) for the grading of the relays:

$$\mathrm{OF} = \sum_{i=1}^{n} \mathrm{ti} \tag{4.2}$$

$$t_b - t_m \geq CTI \tag{4.3}$$

Where n is the number of relays and ti is the time of the i^{th} primary relay.

t_b is the operating time of backup relay.

t_m is the operating time of primary relay (the main relay)

CTI is the coordination time interval between t_b and t_m.

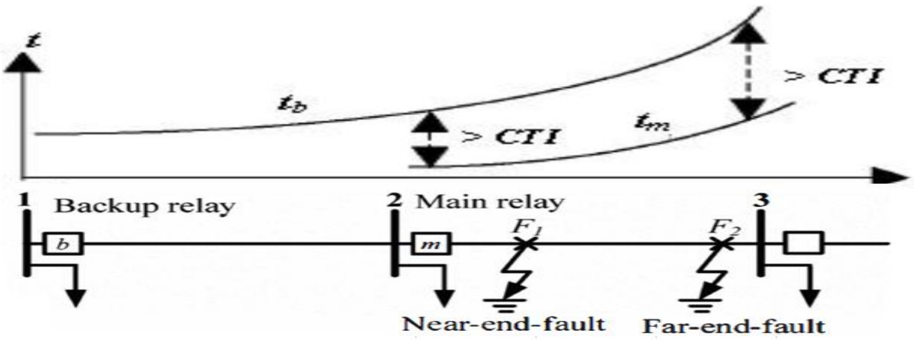


Figure 4.4 OCR Coordination Constraints (Koochaki & et al, 2008)

The difference in operating time between the backup and main relays for faults at *F1* or *F2* must be more than CTI for proper coordination. *Figure 4.3* shows the positions of *F1* and *F2*, the near-fault and far-fault from the main relay at bus *m* (the primary zone of the fault location). The new GA can handle both continuous and discrete PSM and TSM by introducing a new weighting control to correct the miscoordination (β). The Objective Function is then defined as indicated below.

$$OF = \alpha_1 \Sigma (t_i)^2 + \alpha_2 \Sigma (\Delta t_{mb} - \beta_2(\Delta t_{mb} - |\Delta t_{mb}|))^2 \qquad 4.4$$

TSM and *PSM* of the main relay and *TSM* and *PSM* of the backup relay can then be expressed for the Discrete and Continuous values of *TSM* and *PSM* of a pair of Main/Backup relays. Discrete values are inaccurate because you need to roundup to the next higher level which can lead to miscoordination. The introduction of coordination time interval (CTI) as another form of constraint between the primary and the backup relays leads to optimum objective realisation. Thus for optimal coordination, the constraints of the primary and backup relays are set and their parameters for the minimum operating time for all the constraints to be met are then set.

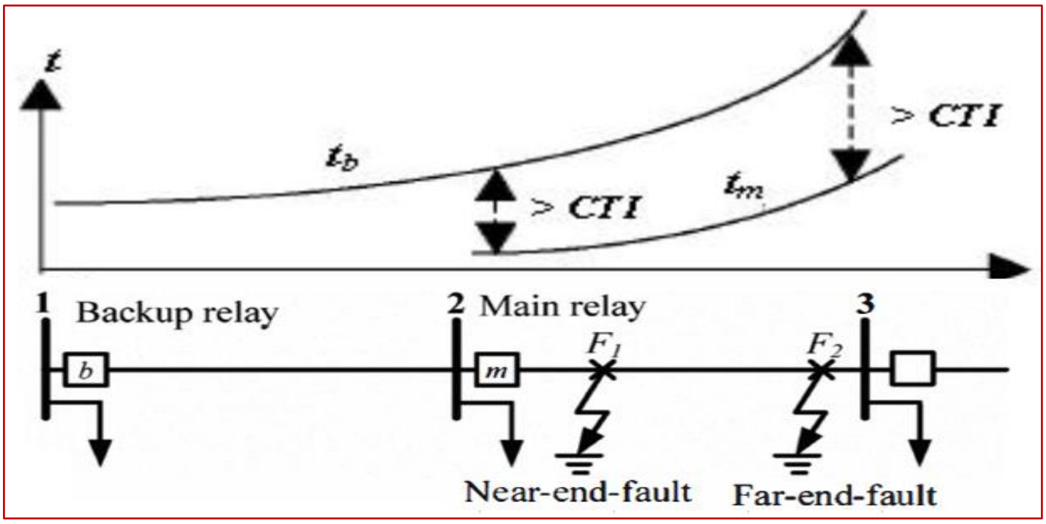


Figure 4.4 OCR Coordination Constraints (Koochaki & et al, 2008)

CTI is the Coordination Time Interval for Main and Backup relays

F1 and *F2* are short circuit faults at near and far end of the main relay

Constraint for the coordination of OCR_m and OCR_b are derived from equations 1 and 2:

$$\Delta tmb = tb(F1) - tm(F1) - CTI > 0 \qquad 4.5$$

$$\Delta tmb = tb(F2) - tm(F2) - CTI > 0 \qquad 4.6$$

The *OF* is expressed in the equation:

$$OF = a_1\Sigma\,(t_i)^2 + a_2\Sigma\,(\Delta t_{mb} - \beta_2(\Delta t_{mb} - |\Delta t_{mb}|))^2 \qquad 4.7$$

where:

- Δtmb = Operating difference for each relay pair ($tb - tm - CTI$)
- ti = The operating time for relay i for a fault (F1) close to the CB
- CTI = 0.4secs (estimated) and
- a_1 and a_2 are the weighting control
- β_2 is the new weighting control to correct the miscoordination.

The operating time of the backup relay (t_b) is the summation of operating time of the primary relay (t_m), the retardation time (t_r), the CB operating time (t_{CB}) and the additional safety margin (t_{sm}). The characteristic of a relay depends on the type of relay, as indicated in Table 4.1

Table 4.1 Parameters of different types of Characteristic curves (IEC 60255)

Relay Characteristics	**Characteristic symbol**	**x**	**y**
Normally Inverse	NI	0.14	0.02
Very Inverse	VI	13.5	1.0
Extremely Inverse	EI	80.0	2
Long Time Inverse	LI	120	1.0

- Standard Inverse (SI) having operating time T = $TSM \times \frac{0.14}{(PSM)^{0.02}-1}$
- Very Inverse (VI) having operating time T = $TSM \times \frac{13.5}{(PSM)^{1}-1}$
- Extremely Inverse (EI) having operating time T = $TSM \times \frac{80}{(PSM)^{2}-1}$
- Long-time Inverse (LI) having operating time T = $TSM \times \frac{120}{(PSM)^{1}-1}$

From the above equations it could be deduced that the unknown variable is the time setting multiplier (TSM), as the plug setting for a particular relay is fixed. The generalised characteristic equation becomes t = [c] × TSM where:

c = $\frac{x}{(PSM)^{y}-1}$ and

x = the numerator as given in Table 4.1

y = the exponential of the PSM

Minimizing the operating time T is the objective function OF i.e.

$$minOF = \sum_{i=1}^{n} c_i \times TMS_i \qquad 4.8$$

$$minOF = \sum_{i=1}^{n} T_i \qquad 4.9$$

where c_i = is the specific characteristic of the relay i. and

t_i = minimum operating time of the relay i

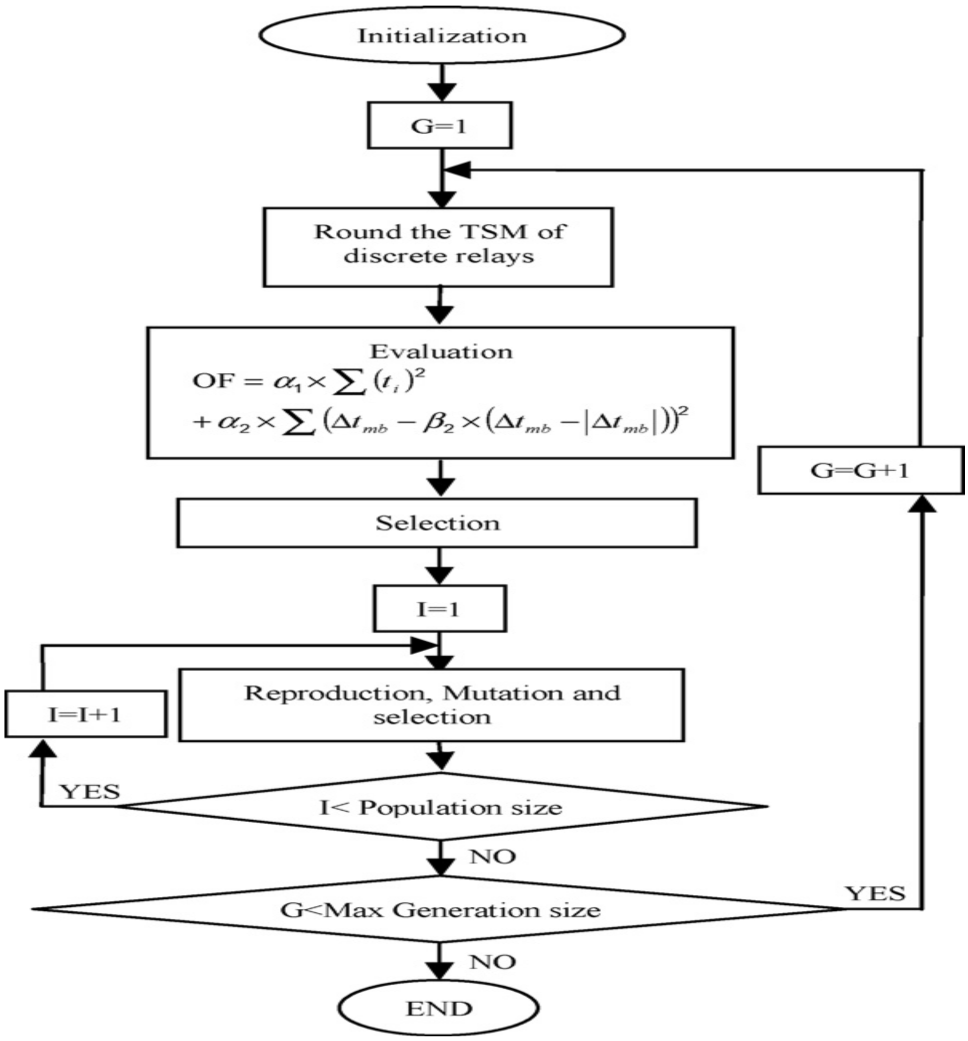


Figure 4.5 Flow diagram of GA application to relay coordination (Asadi & et al, 2008)

The *OF* is expressed in the equation:

$$OF = \alpha_1 \Sigma (t_i)^2 + \alpha_2 \Sigma (\Delta t_{mb} - \beta_2(\Delta t_{mb} - |\Delta t_{mb}|))^2 \quad 4.10$$

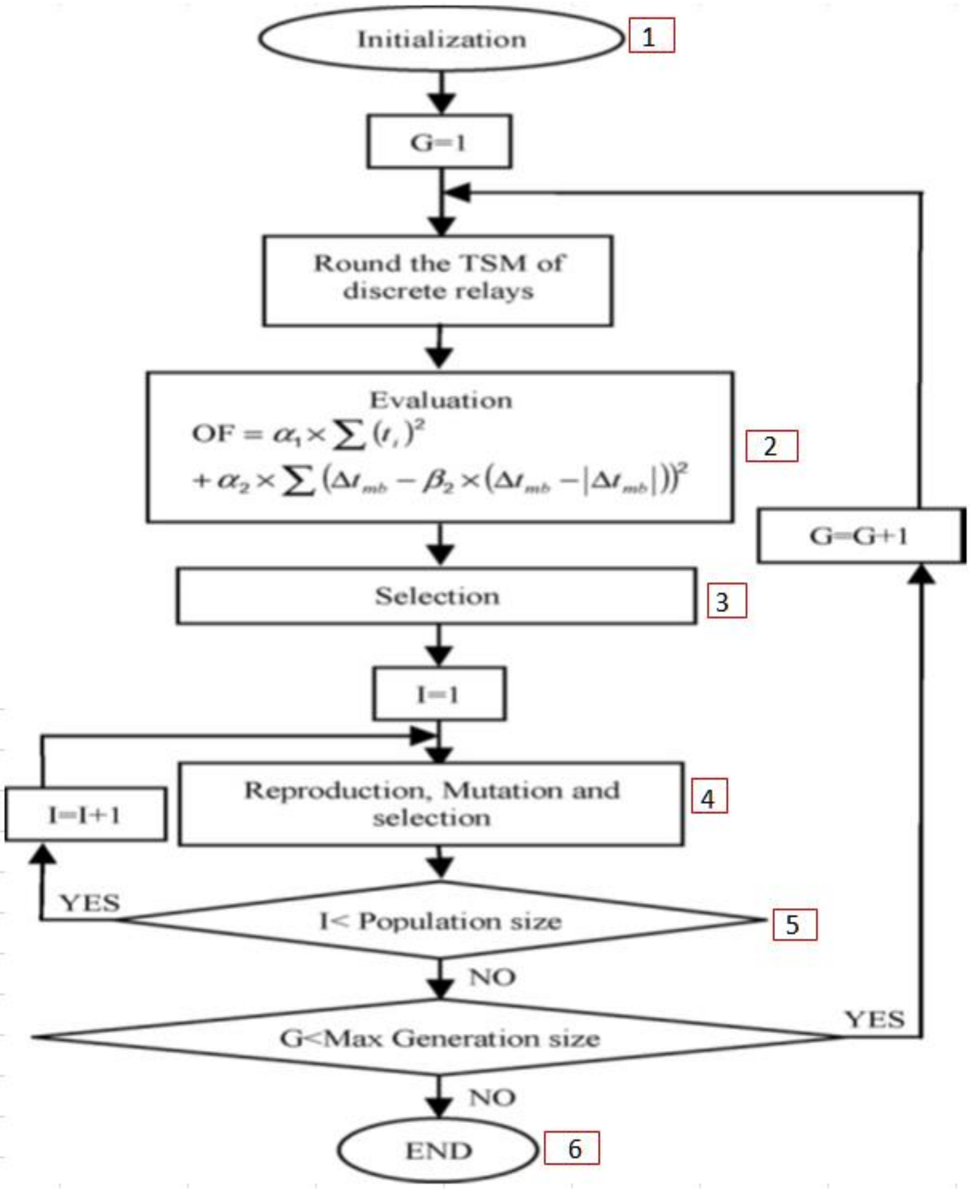


Figure 4.5 Flow diagram of GA application (Razavi, F; & et al;, 2008)

The flow chat diagram of the GA in Figure 4.6 as applied to relay coordination is the described as follows:

1. The input or initialization of the chromosomes named 'parents'
2. The evaluation of the parents
3. The selection of the parents
4. The reproduction and mutation of the 'children'
5. The new selection from the children and parents
6. The end of the process

Table 4.2 PSM and TSM Figures- (a) Without and (b) With DGs

Without DGs (a)	Pickup (I_P)	Isc (kA)	PSM	'C' for each location	t (secs)
1) Seven-Up	26.09	ISCQ = 51.9	2595	CQ = 0.822	0.30
2) Coca-Cola	3.28	ISCO = 7.9	395	CO = 1.1024	8.30
3) G-Imam 11kV	9.84	ISCP = 17.7	442.5	CP = 1.0802	1.53
4) ITC	32.8	ISCL = 34.4	860	CL = 0.9681	0.93
5) A. Dam12	19.68	ISCJ = 30.7	767.5	CJ = 0.9852	1.00
6) A. Dam14	19.68	ISCI = 29.4	735	CI = 0.9922	0.83

With DGs (b)	PSM	TSM	Pickup (I_P)	I_{SC} (kA)	t (secs)
1) Seven-Up	168.89	0.1	756	51.9	218.86
2) Coca-Cola	29.26	0.1	13.8	7.9	58.63
3) G-Imam 11kV	3.65	0.146	89	17.7	19.48
4) ITC	6.07	0.123	100	34.4	23.13
5) A. Dam12	5.85	0.122	93	30.7	22.80
6) A. Dam14	11.33	0.146	46	29.4	31.88

4.5 Report on GA Figures

Applying GA to the relay coordination was not the ideal scenario for the following reasons: The relationship for effective coordination between two relays should be that the value of the $PSM = \frac{Isc}{Ip}$ should be < 20, was not fulfilled in the table 4.2a which is for the case without DGs. From table 4.2a and 4.2b, the relay operating times could be seen that they were too high, when considering the discrimination interval, this situation would lead to miscoordination of the primary and backup relays.

Discrimination time interval of the coordination margin between primary and backup relays which should be the summation of (relay operating time) + (coordination time interval, not applicable to load end relay) + (overshoot time for electromechanical relays only), would still make times to be higher than the figures in the above table both for the two tables.

When multi-objective GA/EA (evolutionary algorithm) is used, the results were only an approximation. Each time the algorithm was run, a bit different approximation was returned. Stochastic algorithms in general can have difficulty in obeying equality constraints.

GA can be applied to solve problems that are not well suited for standard optimisation algorithms, including problems which objective function is discontinuous, non-differentiable, stochastic or highly nonlinear. In the relay coordination, although there are so many parameters however in the radial distribution system (from the protection point of view) the problem is linear and linear programming techniques can be applied. For example, if a downstream relay does not respond to a fault, the backup relay within the protection zone response to the fault. It could be very complicated with renewable energy system integrated at the distribution level; however, the problem is still linear.

GA could be justified for a ring distribution system but this is outside the scope of this thesis.

The Leaf-Node Algorithm was the alternative chosen for setting the coordination of the OCRs of the radial distribution system.

Figure 4.5   Proposed Leaf – Node Algorithm

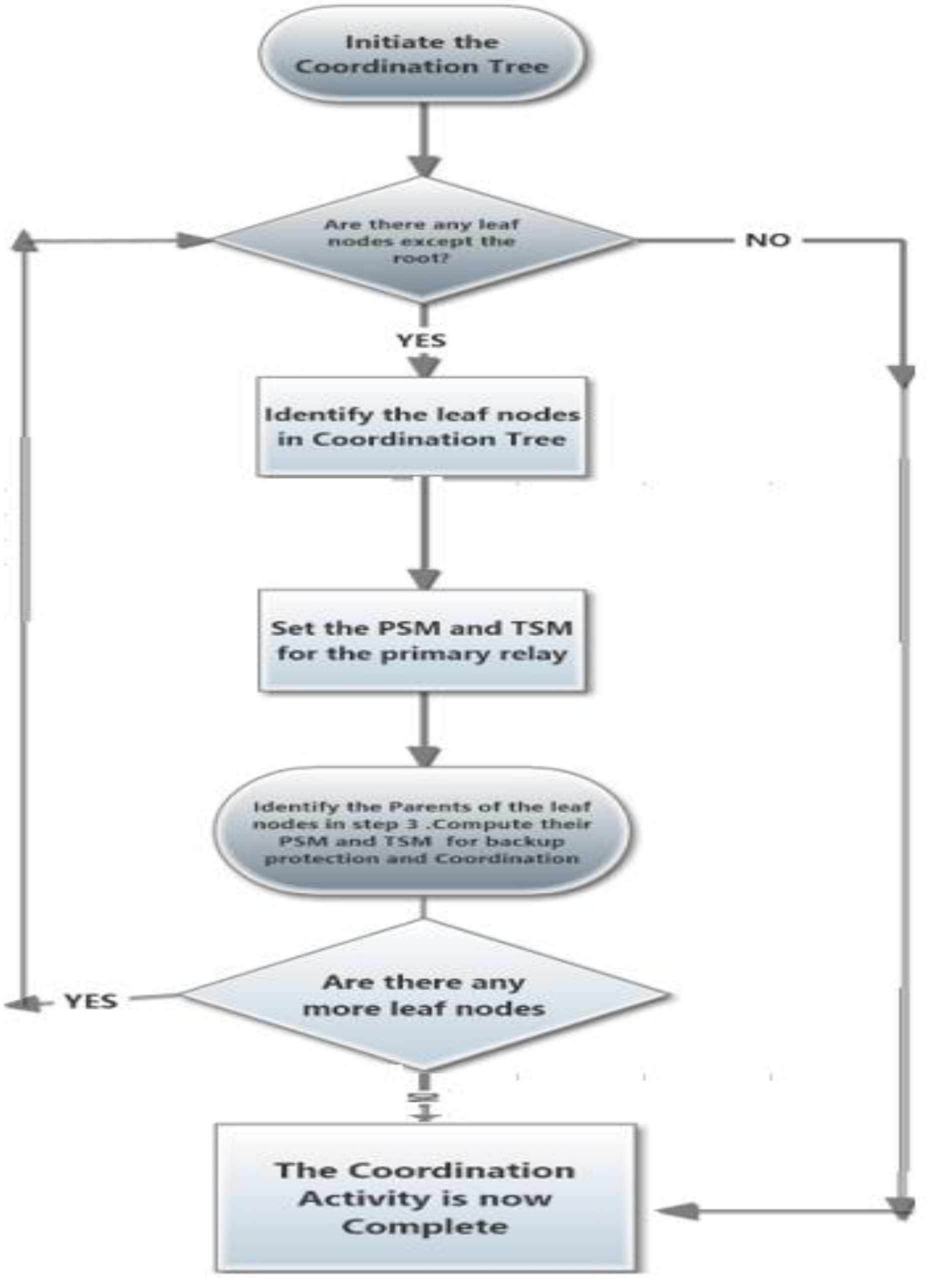


Figure 4.6   Proposed Leaf-Node Algorithm for Setting and Coordination of OCRs in a Radial System

Leaf-Node Algorithm was used instead of the GA which yielded better results. Starting the coordination from ‘Leaf Node’ relays to ‘Child’ relays, to ‘Parent’ relays and then finally to the source or ‘Root’ node relays, the PSM and TSM were calculated for each relay. The root node (parent relay) had no parent while the leaf-node had no child, as indicated in Figure 4.7.

All relays had dual roles of primary and backup protection to perform except the terminal node (Leaf-Node), which was not having backup duties.

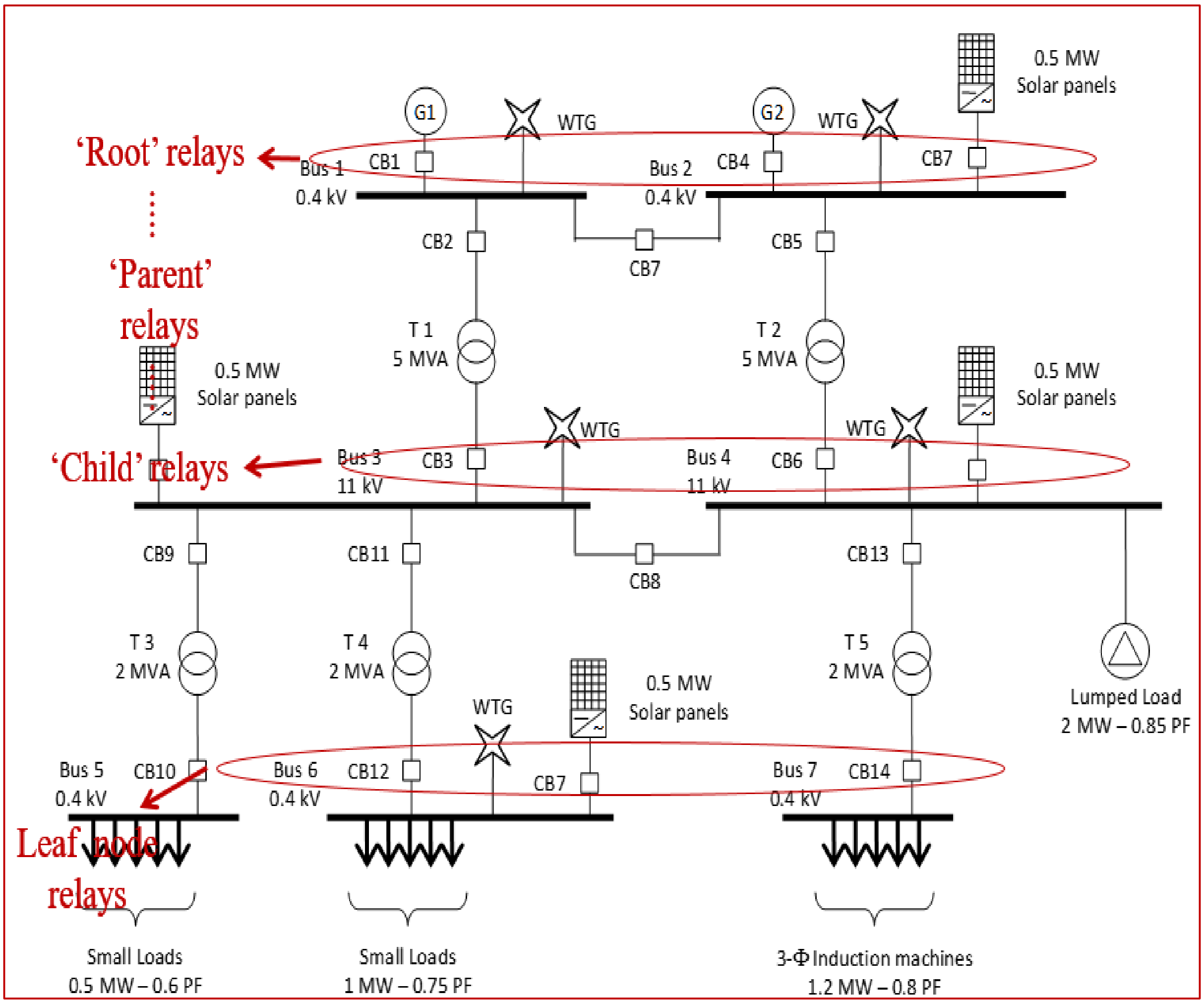


Figure 4.6 The Leaf-Node Algorithm as applied to Radial Distribution System

4.7 Summary

The OCRs are the main protection instruments for radial distribution systems, but are only used as backup protection at HV and EHV.

The mal-operation of the primary relay is the major cause of unnecessary outages of the adjacent equipment. The backup protection is of importance in the event of the primary relay failure. GA, being a form of artificial intelligence system could be used to solve directional coordination problem of backup protection problem for obtaining optimal co-ordination to give minimum discrimination time.

The two types of currents in any distribution system are the pickup currents (I_P), which is function of the load current (I_L), and the short-circuit current (I_{SC}), which should be greater than $1.5I_P$. The relationship between the load currents, fault currents, and the pickup currents ($2/3I_{fmin} > Ip > 1.25I_{Lmax}$) must be obeyed all the time or OCR protection would become ineffective when this relationship fails. The first and main objective function of the relay coordination, was to reduce to the minimum the summation of all the operating times (t) of all the relays in the system, the second objective was to prevent mal-operation of the relays.

OCR have current setting multipliers (plug setting and time setting), the PSM ranging from 50% to 200% in steps of 25%, while the earth relay ranges from 10% to 70% in steps of 10%.

The PSM, TSM and the CTI are the main parameters that could determine the minimum operating times of the relays. The relay characteristics, which depends on the type of relay is the other criterion, whether microprocessor relays or the electromechanical relays. These multipliers, (PSM and TSM) could be discrete or continuous. Ip was fixed, because it is the source of non-linearity, but it could not lead to minimizing the objective function.

When multi-objective GA/EA (evolutionary algorithm) is used, the results were only an approximation. Each time the algorithm was run, a bit different approximation was returned. Stochastic algorithms in general can have difficulty in obeying equality constraints.

GA could be justified for a ring distribution system but this is outside the scope of this thesis. The Leaf-Node Algorithm was the alternative chosen for setting the coordination of the OCRs of the radial distribution system.

Chapter 5

Simulations of the Case Study Distribution System

5.1 Introduction

The optimal penetration of distributed generators, (DG) especially the PV, WTG and Hydro that are connected with the renewable energy sources (RES), were the considered cases in this thesis. The types, locations and sizes of these RES were analysed in order to find optimal penetration in the distribution networks. All of these operate at different power factors. Almost all distribution networks are radial in nature rather than mesh except in densely populated cities, even the ring networks are usually radially operated with permanent open points. The simulations were connected with testing at the busbars for:

- The network current losses
- The voltage profile
- The short circuit level (SCL) at the busbars in the in-feed for
    - Different loadings
    - conditions

The important considerations in this thesis were:

1. Commercial considerations and
2. Technical consideration

The commercial considerations included;

- Cost of DG
- Installation costs compared with the conventional generations
- Operating costs
- Expected revenue
- Value of reduction in network losses from the installation work

The technical considerations include:

1. Thermal rating adequacy
2. Fault level calculations
3. Network current losses
4. Voltage profile
5. Load flow and harmonic analysis
6. Short circuit level (SCL)

The results of the short circuit (SC) study were used to confirm minimum equipment continuous interrupting and withstand ratings, to make sure that pickup currents were within equipment continuous current ratings and that clearing times were within their rated sc duration times.

If more than 25% of the loading in any circuit is non-linear, harmonic analysis and modelling becomes important for analysis. Harmonic modelling is a method of calculating harmonic distortion levels and potential resonances when all circuit data are known. International Standards have been stipulated for the distribution circuits.

High penetration of RES in the distribution system, otherwise called hybrid Renewable Energy Distributed Sources (HREDS) in the distribution system could be regarded as micro-grid where the load demand matches as or less than the local generated power. Of importance is the design of the appropriate control techniques embedded into the power converter control unit. Appropriate control strategy is a challenge to overcome all the power quality and stability issues in order to supply reliable steady power. Some of the challenges include protection coordination, power factor control, phase sequence, power fluctuation, frequency and voltage deviation and power fluctuation (and reverse power) in the RES and the load demand. The high penetration of HRED in the distribution system has led to the formation of microgrid. Microgrid is a cellular structured part of a larger distribution system, having distribution energy resources (DER), loads, storage and its system of relays. Microgrid is not unidirectional in power flow as it could be part of a larger grid or islanded as an autonomously independent small grid. At what percentage would the penetration of DGs make this part of the distribution system become microgrid? Since microgrid is a set of distribution system that are connected to the grid and can operate in the islanding mode intentionally or un-intentionally, how will the same set of relays operate in the two different scenarios under fault conditions? The majority of protection schemes used in power systems depend of the level short-circuit (SC) current capabilities. The installation of inverter-based DG's contribution to (SC) current level or other abnormal conditions is very small, for example 1pu, this is as a result of the controller limiters. But the synchronous generators (SG), or even induction generators (IG), have greater effects on SC current level. The introduction of high level DGs turns the normal radial distribution system to multidirectional current systems, and so the directional OCR are to be used in order to optimally set them for proper coordination of main and backup sets. Under islanding conditions, the islanded inverter based DGs would not have such high fault currents for relay coordination, therefore, the relay operation could become very slow or may not even operate at all. The setting of the relays may have to be lowered to be able to coordinate effectively, and the case becomes worse if SGs are in the island, as these would supply high current which could lead to mis-coordination. Such SGs would need a way to limit their fault currents by fault current limiters (FCLs), which would operate under fault conditions only. (Choudhary, Mohanty, & Singh, 2014)

5.2 Case Study Simulation Procedure

There are five basic steps to be taken to properly analyze the overcurrent coordination study, as indicated in Table 5.1. Three zone types were created in this simulation procedure. (Smith, 2006)

Table 5.1 Division into Zones of Protection

Zones	Division criteria for each protection zone	Remarks
1	All the directly-connected-loads' OCRs are set	Operating time fixed for 0.4secs
2	All buses (Nodes) are marked for this zone	Include both same voltage/transformation level
3	All the voltage-change transformation regions	Step-up/step-down transformers
4	Steps 3 and 4 are repeated for the whole circuit	
5	Summary table is made for the whole process	

The selected distribution circuit for the study of protection coordination of OCRs were investigated. The high penetration of DG to the distribution system usually prevent fault detection by the protective devices when they are within their protection zones, leading to miscoordination between the protective devices. The effect of the DG on the protection coordination depends on the DG type, size and location in the circuit, the directly connected synchronous type having profound effect more than the inverter interfaced type. The load flow analysis of the case study, an actual distribution circuit having PV, SG and WTG was carried out as shown in Figure 5.1.

5.2.1 System Description and Simulation Setup

In Figure 5.1, a section of the existing Ilorin industrial distribution feeder was shown in which there are three radial feeders from the 132/33 kV transmission substation (T.S), but only one feeder was simulated. The loading of the simulated feeder (Coca cola 33 kV network) was 25 MVA, with a total of 14 buses (one swing and 13 load buses. The feeders are energised by the utility through a transformer T1 of 60 MVA, 132/33 kV, 3,500 MVAsc and X/R ratio = 34. Seven DGs are connected at different locations at the seven industrial establishment distribution boards of the network. (green polygons). The yellow circles represent the installed capacitors.

The simulation procedures were conducted as follows:

The load flow analysis (LFA) were first conducted to determine the appropriate CTs for different relays. This was carried out to prevent saturation of undersized relays, thus causing mal-operation and mis-coordination.

The short-circuit analysis (SCA) was then conducted for proper ratings of all the equipment in the system (CBs, bus-bars, transformers, etc.)

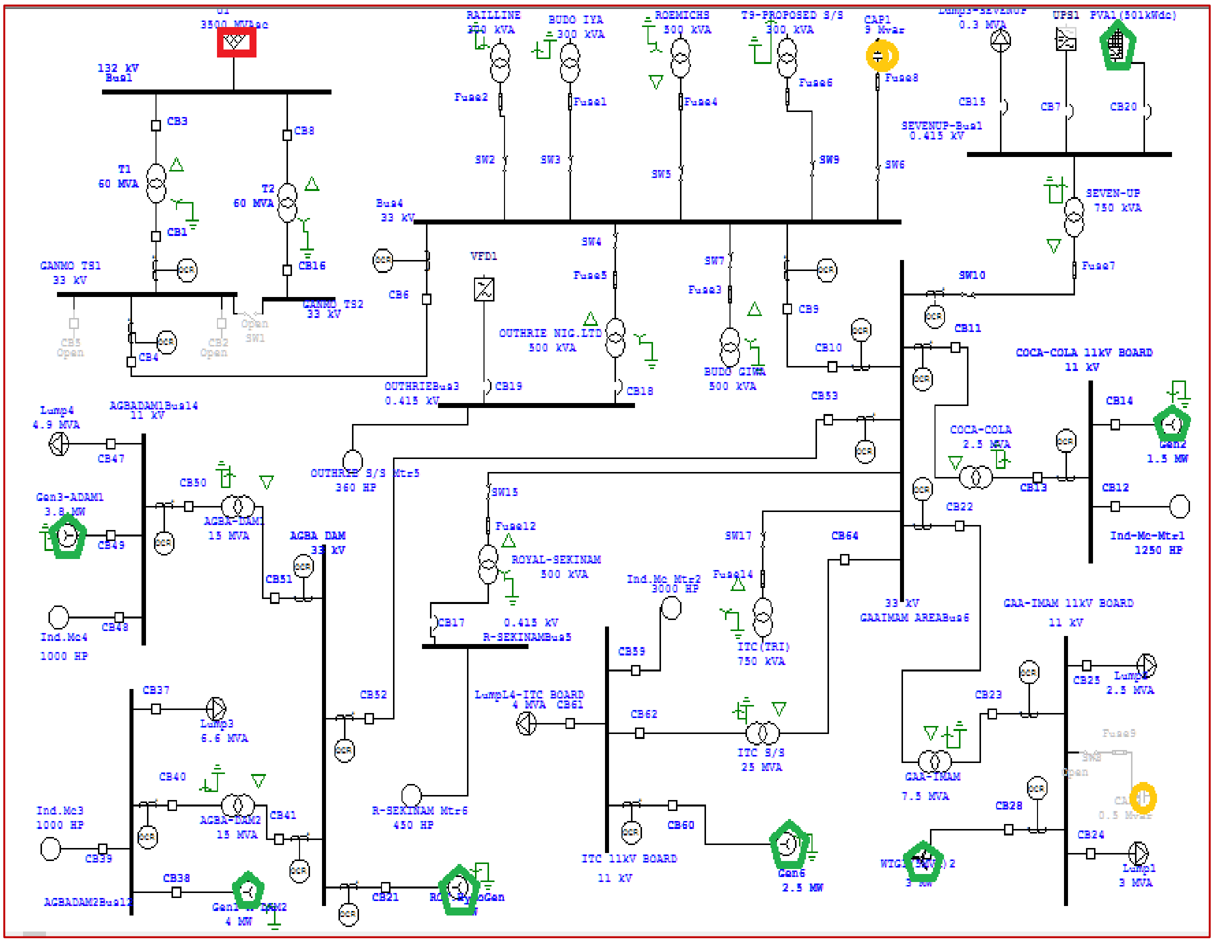


Figure 5.1 Case Study Distribution of Coca-Cola 33 kV Circuit (LFA)

The summary of the DG network was as shown in table 5.2 which formed the Coca-Cola 33 kV case study. The feeder load without DGs was 25.03 MVA, and DG contribution was 15.11 MVA, which was over 60% of the feeder load. From simulation studies carried out, it was observed that six relays (R1-R6) are required for this short radial network. The total length of the feeder is 11.37 km and the impedance of the 150 mm² ACSR conductor was 0.1574 + j0.1466 Ω/km. The operating zone of each relay was identified in which the relays should be capable enough to operate on the occurrence of different types of fault. Each relay should be capable of operating for close-end and far-end faults (three-phase and single-line-to-ground faults).

Table 5.2 Summary of the DG types in the Coca-Cola network

DG	Type	Bus Voltage (kV)	Generated MW	Generated Mvar	%PF
Ganmo TS (swing)	Transmission Station	33	24.01 without DGs	7.07	95.9
AgbaDam1 bus 14	Syn. Gen.	11	3.50	1.50	91.9
AgbaDam2 bus 12	Syn. Gen.	11	3.50	0.90	96.8
AgbaDam Main	Syn. Gen. RoF Hydro	33	1.80	0.90	95
Coca-Cola Board	Syn. Gen.	11	1.00	2.00	98.1
Gaa-Imam Board	Syn. Gen.	11	2.70	-0.427	-98.8
ITC Board	Syn. Gen.	11	2.00	0.657	95.0
Seven-Up	PV	0.415 PV	0.438	0.00	100
Total			14.938	3.730	

A short-circuit analysis was then performed at buses. Directional OCRs were used for the protection of distribution network, and this was the only mode of protection in distribution feeders when DGs were connected. The distribution networks lost their radial nature due to presence of DG which changed the magnitude as well as direction of fault current and this could lead to miscoordination of directional overcurrent relays. (Kalage & Ghewghwe, 2015)

The presence of the DGs have turned the radial network from being radial, therefore, each fault has now got two primary relays, one from each side and having at least two backup relays. All the relays have become directional relays having their tripping directions away from the concerned bus CB, as indicated in Figure 4.1

The protection coordination among the OCRs was classified into three set of studies:

1. Distribution network without DG.
2. DG integrated network in grid connected mode and
3. DG integrated network in islanded mode of operation

The correct coordination operation of the relays in the distribution network without the addition of the DGs was first investigated after selecting the right size of CT based on the maximum full load current it was to handle with overload margin. Some authorities put the overload margin to be 1.25 I_{FLA}. Wrongful (lower) primary CT rating can lead to saturation of the CT coils leading to mal-operation.

Then the effect of adding of DGs were investigated in steps of less than 20% and then above 60% were also simulated. Finally, the effect adding about 100% of connected load was investigated. The simulations of the different case-studies were conducted in ETAP software. The short-circuit current in each section after application of a fault (bolted three phase fault) at a specific location of the network, was obtained through fault flow analysis, and were saved in separate file. ETAP was used to check the magnitude of the fault current against the characteristic of the relay, the inverse definite minimum time (IDMT) OCR. This type of relay is normally used in the distribution networks, which was supposed to clear the fault current for different operating conditions. The coordination of two separate relays under different fault conditions and different operating scenarios were also checked.

5.2.2 Study Procedure with ETAP12.6

The following procedures were followed as indicated below:

1. The 33kV distribution network selected was simulated for load flow analysis (LFA) without the inclusion of the DGs.
2. The LFA was again conducted with the inclusion of the DGs.
3. The short circuit analysis (SCA) for nine different selected buses were carried out without the inclusion of the DGs, (the swing and the 8 DG buses)
4. The SCA was now conducted with inclusion of the DGs at the same locations. The DG buses were seven synchronous generators and one electronically connected DG, (PV)
5. Comparison of the current seen each the relay against its assumed time current characteristics using ETAP was analysed.
6. These steps were repeated severally.

Table 5.3 The swing bus and the seven DG buses that were short circuited

1	The 33kV swing bus, Ganmo TS	5	ITC Board (11 kV)
2	Seven-Up bus1 (0.415 kV)	6	Agba-Dam Main substation (33 kV).
3	Coca-Cola Board (11 kV)	7	Agba-Dam Area Bus12 (11 kV).
4	Gaa-Imam Board (11 kV)	8	Agba-Dam Area Bus14 (11 kV).

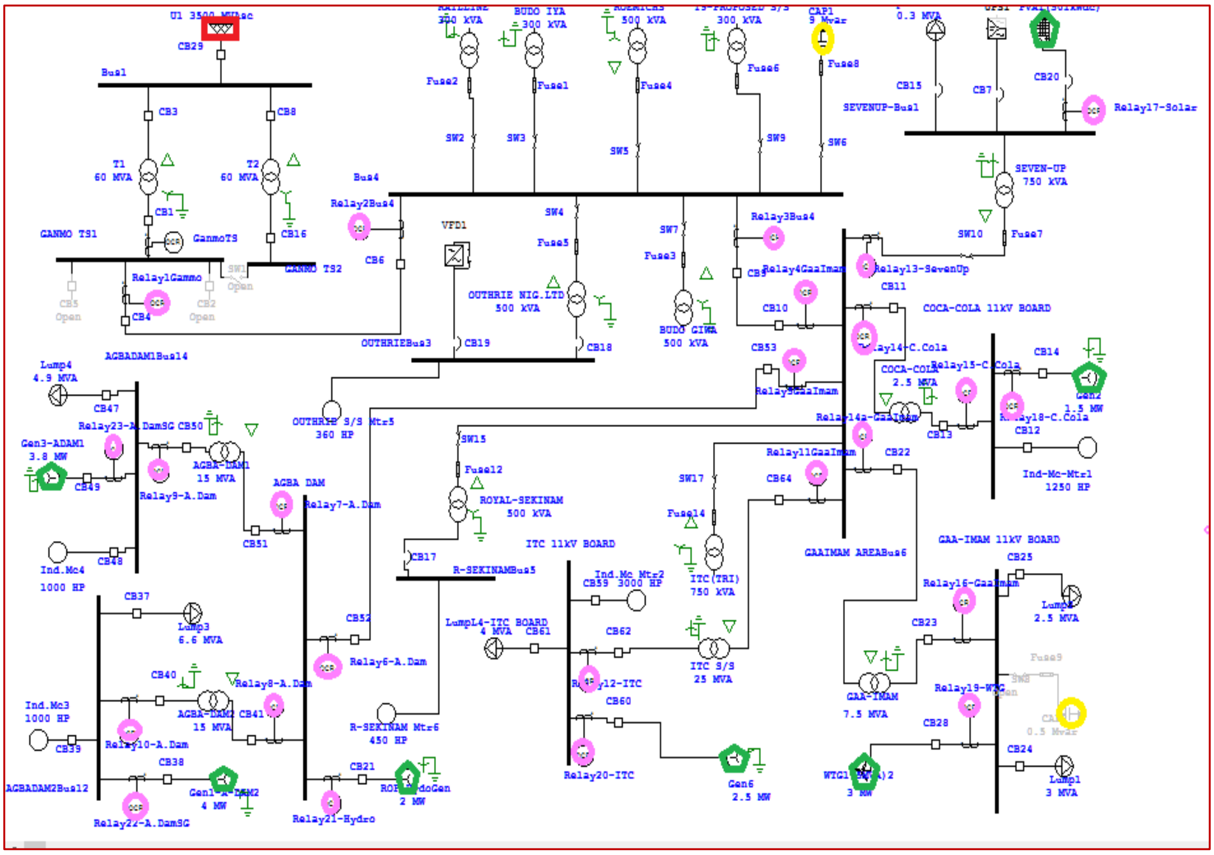


Figure 5.2 Study case circuit showing all the relays for coordination.

Figure 5.2 is the circuit diagram of all the relays mapped out for coordination including the relevant buses where the DGs are installed at different voltage levels. Relay coordination has to do with operating time to avoid the problems of blinding of protection, false and unnecessary sympathetic tripping, reclosure/fuse miscoordination, failed auto reclosure and other forms of miscoordination. The operating time of overcurrent relays is inversely proportional to the short circuit current passing through primary side of the CT of the relay. The magnitude of the pickup current and the operating time are the two important variables in relay coordination. When fault happened, the level of fault current of the network without DG changes which made the operating time of the OCRs to change.

5.3 Relay Coordination Settings

The fault current on the secondary of a distribution voltage transformer, for the purpose of selecting the correct overcurrent protective devices that can interrupt the available fault current is I_{fmax} as in equation 5.1. This is the interrupting rating of the current of the CB installed in the secondary of the transformer, but feeder breakers should include the estimated motor contribution too, and if the actual connected motors are not known, then assumption could be made for the contribution to be 4 x FLA of the transformer. A quick calculation for the Maximum Fault Current at the transformer secondary terminals is:

$$I_{fmax} = FLA \;/\; \%PU\ Z = \frac{FLA}{\%Z}\ x\,\frac{100}{1} \qquad 5.1$$

This is based on the infinite source method at the primary of the incoming transformer to the microgrid. The I_{fmax} is the short circuit current I_{SC}

The type of the relays usually installed in the distribution system is mainly inverse definite minimum time (IDMT) relays because of the radial nature of the circuits, since there is only one source of supply and the current flow is unidirectional. With the introduction of the DGs, and the current flow becomes multidirectional, the directional relays have to be installed in order to have the correct backup of all primary relays.

Relay setting must be readjusted in order to minimize the operating time of the relays to avoid mal-operation. While minimizing the operating time of the relays, care should be taken to see that coordination between the relays is still maintained by the optimization of the time setting multiplier (TSM).

Standard Inverse (SI) relay characteristic is governed by the following time of operation equation given below:

$$t = TSM \times \frac{0.14}{(PSM)^{0.02} - 1} \qquad 5.2$$

where $PSM = \frac{Isc}{Ip}$ 5.3

TMS (the time setting) and I_p (the current settings of the relay) are the two parameters involved in the operating characteristics of the relay. The *Isc* which was the fault current flowing in the primary of the CT was known and the pickup current setting Ip which was predetermined by the CT ratio and the plug setting was calculated. As the pickup currents of the relays were predetermined from the system requirements, equation 5.2 became as equation 5.5. It could be noted that PSM is constant for a relay with a typical characteristic, therefore, operating time t was expressed as $t = C(TSM)$, and so the operating of a specific relay became a function of TSM. The C for each relay is also a function of plug setting multiplier (PSM) which is calculated for different fault location as C is expressed as:

$$C = \frac{0.14}{(PSM)^{0.02} - 1} \qquad 5.4$$

$$t = C \times TSM \qquad 5.5$$

5.3.1 Relay Coordination Elements and the Respective Settings

The coordination elements are Overcurrent relay (OCR) consisting of:

- Time overcurrent TOC (51) and
- Instantaneous relay IOC (50)

These two important coordination settings for each relay in stage 51 are: (a) Pickup setting (PSM) and (b) Time Dial setting (TSM)., while stage 50 settings are: (a) Pickup (b) Delay (sec).

Guidelines for setting the phase overcurrent relay (OCR_{51}) co-ordinations, according to the Leaf-Node algorithm were followed:

- The starting point for relay co-ordinations is from the load end, the leaf-node = 0.4 sec)
- Coordination Time Interval (CTI) for series element was 0.05 sec for discrimination
- CTI for non-series element was 0.3 sec
- The plug setting of upstream relays = the plug setting of downstream relays

Guidelines for setting the Instantaneous relays (OCR_{50}) are as follows:

- Near-end fault setting have a discrimination time-delay of 0.3 sec with the thermal curve of their backup relay in order to prevent reaching I_{fmax}
- Instantaneous current settings for transformer primary relays should avoid inrush currents in setting the discrimination time, but should not be close to near-end fault values
- Backup relays must be able to trip with a definite time delay, so that faults at the lower end of the circuit does not cause unnecessary tripping, without discrimination.
- Primary relays at a voltage level should trip instantaneously, but the backup at another voltage level should trip thermally
- Instantaneous time delay of 0.05 sec is needed between the relays on both sides of the transformer at the lowest side.
- The instantaneous time delay between primary and its backup relays should be between 0.15 sec and 0.2 sec, the lower figure of 0.15 sec is for critical clearing time only. (IEEE Power & Energy Society, 2001)

The Coca Cola 33 kV feeder uses a combination of digital impedance relays, electromechanical impedance relays and electromechanical overcurrent relays. Most of the case-study relay characteristic is a combined inverse definite minimum time (IDMT)/Instantaneous type. The instantaneous part is fast in clearance-time for primary protection at high current, but the time delay required to coordinate with backup relays is provided by the IDMT part.

5.4. Simulation Results and Analysis

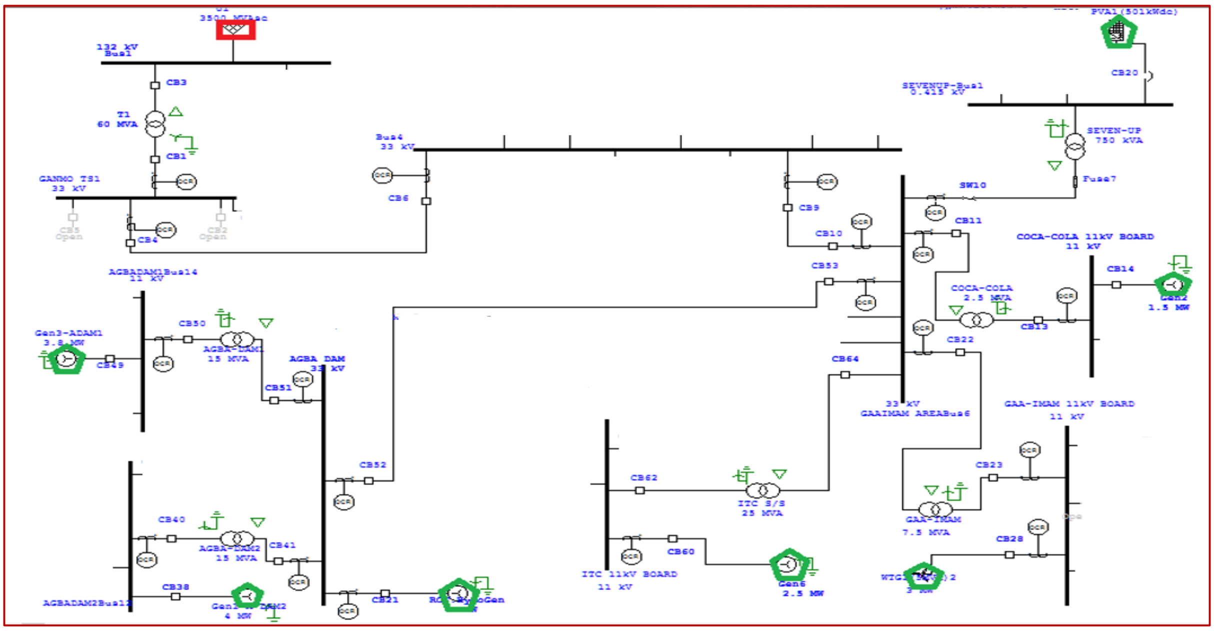


Figure 5.3 The seven buses having DGs that need short circuit analysis

The nine buses in Figure 5.3 are at three different voltage levels (33, 11, 0.415) kV levels. The SC levels for the initial symmetrical RMS values and the peak values of the circuit are listed below in Table 5.3

with C = $\dfrac{0.14}{(PSM)^{0.02}-1}$, it is expressed as $C_A = \dfrac{0.14}{(\frac{IF,A}{IP,A})^{0.02}-1}$

- Where $I_{F,A}$ is the fault current at relay A and
- $I_{P,A}$ is the pickup current at relay A with $I_{P,A} = 1.25\ L_{Amax}$ and
- L_{Amax} is the maximum load current at relay A

The operating time t of relay A is expressed as

$$t_A = C_A \times TSM_A \quad 5.5$$

To calculate the IDMT overcurrent relay setting (51/50) at point P_A

- Feeder load current = 438 A;
- Fault currents are (min 11.6 kA, max 29.3 kA);
- CT detail 500/5; Relay curve selected (Normal Inverse Type)
- Current setting is 100%
- The minimum time setting time at the bus t_A was estimated to be 700 ms,
- The minimum CTI was estimated to be 0.25 sec

Table 5.4 SC Levels for the Different Simulated Buses

Relay	Name of bus	I_{SC} Levels excluding DGs (kA)		I_{SC} Levels including DGs (kA)	
		Initial sym. RMS value	Peak value	Initial sym. RMS value	Peak value
A	33 kV swing bus Ganmo TS	9.30	30.05	9.67	32.64
M	Seven-Up bus1 (0.415 kV)	21.90	51.60	22.36	51.87
O	Coca-Cola Board (11 kV)	2.19	6.50	2.75	7.93
P	Gaa-Imam Board (11 kV)	4.08	16.80	4.51	17.77
L	ITC Board (11 kV)	9.55	31.65	10.71	34.44
J	Agba-Dam Area bus12 (11 kV)	7.78	26.74	9.35	30.68
I	Agba-Dam Area bus14 (11 kV)	7.78	25.64	9.27	29.40
H	Agba-Dam (33 kV)	9.16	29.32	9.65	32.56

5.4.1 Calculations of the Values of PSM and TSM without DGs

Table 5.5 Values of the PSM and TSM of primary 'leaf-node' relays

Nos	Pickup (A)	Isc (kA)	PSM	'C' for each location	TSM
M	4.0	$I_{SCM} = 24.3$	6.07	$C_M = 0.822$	0.19
O	48.8	$I_{SCO} = 2.4$	395	$C_O = 1.1024$	1.88
P	127.5	$I_{SCP} = 6.2$	442.5	$C_P = 1.0802$	0.18
L	147.5	$I_{SCL} = 12.5$	860	$C_L = 0.9681$	0.18
J	168.8	$I_{SCJ} = 10.4$	767.5	$C_J = 0.9852$	0.15
I	130.0	$I_{SCI} = 10.0$	735	$C_I = 0.9922$	0.15
H	168.8	$I_{SCH} = 9.16$	0.54	$C_H = 0.99$	0.26

From Table 5.4, most of the PSMs were over 20, then either 20 would be taken as their values or another relay would have to be considered, for example, Extremely Inverse type would be needed. The relay must be underrated and saturated, they should be changed. The TSM was calculated since the values of (t) at each location must be equal or greater than 0.25 secs, (0.3 sec for electromechanical relays), the minimum coordination time interval (CTI) between the primary relay and any backup.

There are 24 relays (A – X) to be analysed for the pickup current and fault current in the study case as listed are in Table 5.4.

Table 5.6 The relays of TOC (51), the TSM and Pickup current without DG

Relay	Relay name	TSM	I_{FLA} (A)	Pickup $I_{primary}$	Relay	Relay name	TSM	I_{FLA} (A)	Pickup $I_{primary}$
A	Relay1 Ganmo 33kV	0.1	438	547.5	M	Relay13 Seven-Up	0.185	3.2	4.0
B	Relay2 Bus4	0.197	438	547.5	N	Relay14 C-Cola	0.322	39	48.8
C	Relay3 Bus4	0.310	486	607.5	O	Relay15 C-Cola	0.192	39	48.8
D	Relay4 GaaIma m	0.277	486	607.5	P	Relay16 GaaIma m	0.186	102	127.5
E	Relay5 GaaIma m	0.253	239	298.8	Q	Relay17 Solar	0.193	-	-
F	Relay6 A-Dam	0.231	239	298.8	R	Relay18 C-Cola	0.307	-	-
G	Relay7 A-Dam	0.197	104	130.0	S	Relay19 WTG	0.325	-	-
H	Relay8 A-Dam	0.261	135	168.8	T	Relay20 ITC	0.231	-	-
I	Relay9 A-Dam	0.150	104	130.0	U	Relay21 Hydro	0.119	-	-
J	Relay10 A-Dam	0.151	135	168,8	V	Relay22 A-Dam (S/Gen)	0.253	-	-
K	Relay11 GaaIma m	0.352	118	147.5	X	Relay23 A-Dam (S/Gen)	0.197	-	-
L	Relay12 ITC	0.185	118	147.5	Y	Relay14a GaaIma m	0.307	102	127.5

The instantaneous overcurrent (IOC) relay setting (Table 5.5) is given delay 0.25 (sec) in order to discriminate the relay tripping. Relay A does not need instantaneous setting. The relays are all directional relays after the high penetration of the DGs, as indicated in Figure 5.3, which makes the backup relays to be specific.

Table 5.7 The C.T. Ratings and their Corresponding Plug Setting Ratio

Relay	Relay name	C.T. Ratio	Plug Setting Ratio	Relay	Relay name	C.T. Ratio	Plug Setting Ratio
A	Relay1 Ganmo 33kV	500/5	0.01	M	Relay13 Seven-Up	100/5	0.05
B	Relay2 Bus4	500/5	0.01	N	Relay14 C-Cola	300/5	0.017
C	Relay3 Bus4	500/5	0.01	O	Relay15 C-Cola	100/5	0.05
D	Relay4 GaaImam	500/5	0.01	P	Relay16 GaaImam	200/5	0.025
E	Relay5 GaaImam	300/5	0.017	Q	Relay17 Solar	200/5	0.025
F	Relay6 A-Dam	200/5	0.025	R	Relay18 C-Cola	100/5	0.05
G	Relay7 A-Dam	200/5	0.025	S	Relay19 WTG	200/5	0.025
H	Relay8 A-Dam	200/5	0.025	T	Relay20 ITC	200/5	0.025
I	Relay9 A-Dam	200/5	0.025	U	Relay21 Hydro	100/5	0.05
J	Relay10 A-Dam	200/5	0.025	V	Relay22 A-Dam (S/Gen)	300/5	0.017
K	Relay11 GaaImam	200/5	0.025	X	Relay23 A-Dam (S/Gen)	500/5	0.01
L	Relay12 ITC	200/5	0.025				

5.4.2 Calculation of Values of PSM and TSM with DGs included

Table 5.8 The relays of TOC (51), the TSM and Pickup current including DG

Relay	Relay name	TSM	I_{FLA} (A)	Pickup $I_{primary}$	Relay	Relay name	TSM	I_{FLA} (A)	Pickup $I_{primary}$
A	Relay1 Ganmo 33kV	0.1	162	202.5	M	Relay13 Seven-Up	0.143	4.3	5.4
B	Relay2 Bus4	0.181	162	202.5	N	Relay14 C-Cola	0.294	11	13.8
C	Relay3 Bus4	0.197	236	295	O	Relay15 C-Cola	0.1	11	13.8
D	Relay4 GaaIma m	0.255	236	295	P	Relay16 GaaIma m	0.146	71	89
E	Relay5 GaaIma m	0.210	78	98	Q	Relay17 Solar	0.1	605	756
F	Relay6 A-Dam	0.211	78	98	R	Relay18 C-Cola	0.299	53	66.3
G	Relay7 A-Dam	0.167	37	47	S	Relay19 WTG	0.1	143	179
H	Relay8 A-Dam	0.231	74	93	T	Relay20 ITC	0.1	109	136
I	Relay9 A-Dam	0.146	37	46.3	U	Relay21 Hydro	0.1	35	44
J	Relay10 A-Dam	0.122	74	93	V	Relay22 A-Dam (S/Gen)	0.1	189	236
K	Relay11 GaaIma m	0.307	80	100	X	Relay23 A-Dam (S/Gen)	0.1	197	246
L	Relay12	0.123	80	100	Y	Relay14a	0.289	71	89

	ITC					GaaIma m			

The pickup current was set at 1.25 x I_{FLA} which is the overload limit, and the current setting was maintained as 100%

With C = $\frac{0.14}{(PSM)^{0.02} - 1}$ the calculated C for each location is as in table 5.9

Therefore, time of operation t = C × TSM and if TSM = 1, then t = C

The I_{SC} and pickup current Ip then determine the value of C

If the actual time t at the load end is set to be 0.4sec, the actual TSM can then be calculated from the above equation.

Table 5.9 Calculated values of PSM and TSM of Leaf-Node relays without DG

Nos	Pickup I_{kA}	Isc (kA)	PSM	'C' for each location	TSM
M	4.0	I_{SCM}= 24.3	6.08	C_Q = 1.04	0.18
O	48.8	I_{SCO} = 2.4	0.05	C_O = 0.94	1.18
P	127.5	I_{SCP} = 6.2	0.05	C_P = 0.94	0.18
L	147.5	I_{SCL} = 12.5	0.09	C_L = 0.95	0.18
J	168.8	I_{SCJ} = 10.4	0.06	C_J = 0.96	0.15
I	130	I_{SCI} = 10.0	0.75	C_I = 0.99	0.15
H	168.8	I_{SCH} = 9.16	0.54	C_H = 0.99	0.26

5.4.3 Setting of the OCR Co-ordination Guidelines

The following guidelines were of importance in the setting of the OCR relays:

- OCRs were coordinated from the leaf-node till root-node as directed in Figure 4.7. The root-nodes had no parent because they were source (swing), and all leaf-nodes had no children to backup.
- Coordinating Time Interval (CTI) would either be 0.05 sec for series elements or 0.3 sec for non-series element
- Leaf-nodes should fulfil its responsibility without CTI, while the root-node had no instantaneous time setting.
- An instantaneous time delay of 0.2 sec existed between primary and backup relay (but could be reduced to 0.15 sec in critical cases).
- All terminals (leaf-node) relays' TSMs were set to the higher discrete value and the I_{fmax} was used instead of I_{fmin} in all calculations, since they do not backup any node.
- All the DG relay tripping times were set to be 0.05 sec, in order to trip instantaneously when a near fault took place, so as not to contribute to the fault current.

The Appendix A3 was used to identify the different categories of the case-study distribution circuit relays, as indicated in the table below to identify the leaf-nodes, generator relays and the series element relays. The root-node was the source 'A' (the swing).

Table 5.10 The Different Categories of the Case-Study OCRs

List of DG Relays	List of Leaf-Node Relays	List or Series Element Relays
Q	P	P & Y
R	O	J & H
S	M	I & G
T	L	L &K
U	J	D & C
V	I	B & A
X		N & O

The type of relay characteristics used for this system were IDMT relays

The summary of the Plug setting (Ip), Time Setting Multiplier (TSM) and Operating Time (s) settings is given in Tables 5.11a and 5.11b below.

Table 5.11a Summary of Ip, TSM, and Operating Time (s) DGs included.

Relay ID	Relay nos	CT Ratio	Plug Setting A (Ip)	TSM	Operating time (s)	Relay ID	Relay nos	CT Ratio	Plug Setting A (Ip)	TSM	Operating time (s)
A	1	500/5	202.5	0.1	0.52	M	13	100/5	5.40	0.185	0.33
B	2	500/5	202.5	0.197	0.47	N	14	300/5	13.8	0.322	0.30
C	3	500/5	295.0	0.310	0.42	O	15	100/5	13.8	0.192	0.25
D	4	500/5	295.0	0.277	0.38	P	16	200/5	89.0	0.186	0.25
E	5	300/5	98.0	0.253	0.35	Y	40	200/5	89.0	0.307	0.30
F	6	200/5	98.0	0.231	0.30	R	18	100/5	66.3	0.307	0.05
G	7	200/5	47.0	0.197	0.20	S	19	200/5	179.0	0.325	0.05
H	8	200/5	93.0	0.261	0.28	T	20	200/5	136.0	0.231	0.05
I	9	200/5	46.3	0.150	0.15	U	21	100/5	44.0	0.119	0.05
J	10	200/5	93.0	0.151	0.23	V	22	300/5	236.0	0.253	0.05
K	11	200/5	100.0	0.352	0.22	X	23	500/5	246.0	0.197	0.05

L	12	200/5	100.0	0.18	0.17	Q	17	200/5	756.0	0.193	0.05

The first two columns 'relay ID' and 'Relay numbers' are as in table 5.8. Relay A is the root node (parent node) which has no backup (parent), it only backups other relays, while the Relays A and B are series elements.

The operating time of all the leaf-node relays (P, O, M, L, J, I, H) were set as the minimum operating time, since they do not backup any other relays, and I_{fmax} was in calculating their PSMs

The operating time of all the DG relays (Q, R, S, T, U, V, X) were set to be 0.05 sec, as they are to trip instantaneously, contributing no fault currents.

Table 5.11b Summary of Ip, TSM, and Operating Time (s) without DG

Relay ID	Relay nos	CT Ratio	Plug Setting A (Ip)	TSM	Operating time (s)	Relay ID	Relay nos	CT Ratio	Plug Setting A (Ip)	TSM	Operating time (s)
A	1	500/5	547.5	0.350	0.78	M	13	100/5	4.00	0.185	0.30
B	2	500/5	547.5	0.248	0.56	N	14	300/5	48.80	0.322	0.32
C	3	500/5	607.5	0.310	0.51	O	15	100/5	48.80	0.192	0.27
D	4	500/5	607.5	0.277	0.45	P	16	200/5	127.5	0.186	0.28
E	5	300/5	298.8	0.253	0.39	Y	40	200/5	127.5	0.307	0.33
F	6	200/5	298.8	0.231	0.33	R	18	100/5	-	-	-
G	7	200/5	130.0	0.197	0.24	S	19	200/5	-	-	-
H	8	200/5	168.8	0.261	0.31	T	20	200/5	-	-	-
I	9	200/5	130.0	0.150	0.19	U	21	100/5	-	-	-
J	10	200/5	168.8	0.151	0.26	V	22	300/5	-	-	-
K	11	200/5	147.5	0.352	0.29	X	23	500/5	-	-	-
L	12	200/5	147.5	0.185	0.25	Q	17	200/5	-	-	-

The DG relays (Q, X, V, U, T, S, and R) were none existing at the 'without DG' locations as shown table 5.11b.

5.5 Summary

After the connection of the DGs, total losses reduced from 113 + j2.274 (2.277 MVA), without DG to 0.037 +j0.564 (0.648 MVA) which is at 65% of the feeder load, i.e. a reduction of 1.629 MVA. The reduction in the reactive power losses of 1.713 MVAr is remarkable, but the reduction in active power losses of 0.076 MW is not so much. The remarkable reduction in reactive power was as a result of the connected DGs were synchronous type, that generated more reactive power than active power. The WTG absorbs reactive power, rather than generate active power.

When the contribution of the DG was made to be 100% of feeder load, it was noticed that: Total apparent losses further reduced to 0.028 + j0.334 (0.335 KVA).

The branch losses have further reduced to 335.38 KVA {$\sqrt{(28.1^2 + 334.2^2)}$}, for the nearly 100% level contribution, because more power was supplied by the local distributed generators which would have caused transmission losses if such power had come from the grid.

The connection of DGs amounted to transmission capacity relieve as well as distribution capacity relief since there was a reduction of <u>14.4 MW</u> (23.9 – 9.5), and <u>5.8 MVAR</u> (6.5 – 0.7) when the DGs were included in the simulation.

This reduction amounted to (24.77 – 9.53) MVA i.e. 15.24 MVA which was = 61.53%, which was supplied by the DGs.

The low voltages at the previous 11 kV buses were rectified by the penetration of the DGs. The loss reduction was as a result of localised generation which was removed from the transmission grid losses if the load had been supplied by the grid.

Table 5.12 Summary of the Total Distribution Losses in the Network

% of DG Contribution of feeder load	Total Distribution Losses in the network (KVA)
Without DGs	2,277
With 65% of feeder load	648
With approximately 100% of feeder load	335

The ITC 11 Kv synchronous generator became over-excited as a result of the generator's capacity increase from 2.5 MVA to 7 MW.

When multi-objective GA/EA (evolutionary algorithm) is used, the results were only an approximation. Each time the algorithm was run, a bit different approximation was returned. Stochastic algorithms in general can have difficulty in obeying equality constraints.

GA could be justified for a ring distribution system but this was outside the scope of this thesis. The Leaf-Node Algorithm was the alternative chosen for setting the coordination of the OCRs of the radial distribution system.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Comparing the simulated relay setting figures with on-site figures at the Utility Industrial site did show some marked discrepancies for the following reasons:

- The CB ratings in most of the substations were of the same standard and underrated for the new short-circuit level. The loading at source without DGs was 25 MVA, 109.5 A, the short-circuit rating without DGs was 11.9 kA. At 60% of the feeder load penetration, the SC rating became 12.9 kA.
- There were no appreciable changes in the circuit configuration at 20% penetration.
- At 100% DG contribution, the ITC industrial substation became 'voltage control' which could be swing control like the grid, as the simulation in ETAP has shown.
- With DGs contributing nearly 100% of feeder load, the voltages at ITC 11 KV and the Coca Cola 11 KV boards, had caused overvoltages at these buses, which could cause miscoordination of the respective OCR relays.

6.2 Recorded Anomalies of the Case-Study

- There were changes in the transformer sizes in some of the distribution substations which were not updated in the schematic drawings and other documents.
- Illegal line extensions were not reported; the recorded data could not be relied upon.
- Most of the equipment have aged and obsolete but are still in service, their original technical data are not useful for calculations. The on-site offices

must improve on the updating culture of the record keeping of changes. It is suggested that the relay coordination studies should be performed twice a year regarding relay setting in developing countries.

- Almost all the installed relays have CTs with lower ratings, from the records kept by the Utility. They are all electromechanical relays having '100/1' as their CT ratings. These relays were installed over 50 years ago, but the feeder load had increased by over 300%. The CTs were oversaturated, which led to frequent unnecessary tripping, blinding of protection, false and unnecessary sympathetic tripping, reclosure/fuse miscoordination, failed auto reclosure and other forms of miscoordination.
- Most of the case-study relay characteristic was a combined inverse definite minimum time (IDMT)/Instantaneous type. The instantaneous part was fast in clearance-time for primary protection at high current, but the time delay required to coordinate with backup relays was not provided by the IDMT part. All the relays were of the IDMT types, with only time delay discrimination, there were no indications of backup, thus any type of fault could trip the primary-leaf-node and the root node simultaneously.
- Before any DGs (the existing industry's standby generators) would be connected the relays need re-calibration, while some need changing completely.

6.3 Recommendations for Future Work

- The retrofitting of the existing dual constructed radial distribution lines of (11 & 0.415) kV could be done by converting it to hybrid distribution energy resources (HDER) of DC-AC systems. The high tension would be DC, while the low voltage would be AC at 415 volts, especially at high penetration of more than 50%.
- Any penetration above 100% should be Utility owned and located at the source distribution injection substation. This would remove the problem of reconductoring and other problems that might come up.
- Such dual constructions should become microgrids with identified point of common coupling (PCC) to the grid.
- Field research on grids with high DG penetration should be intensified, as laboratory simulations could not show the real conditions in every detail. Investigation of high penetration of DGs with varying contribution of short-circuit currents need more field research studies.
- Both the Utility and the independent power producers (IPP) must be actively involved in site installations of new extensions, as the IPP are more interested in the active power transfer because there is no remuneration for reactive power compensation and other ancillary services that the DGs are supposed to render are not paid for by the utility.
- Pre-standardization of safety and protection rules and regulations should be addressed by international standards' regulating bodies, as there are no existing standards internationally, for hybrid DC-AC distribution systems.

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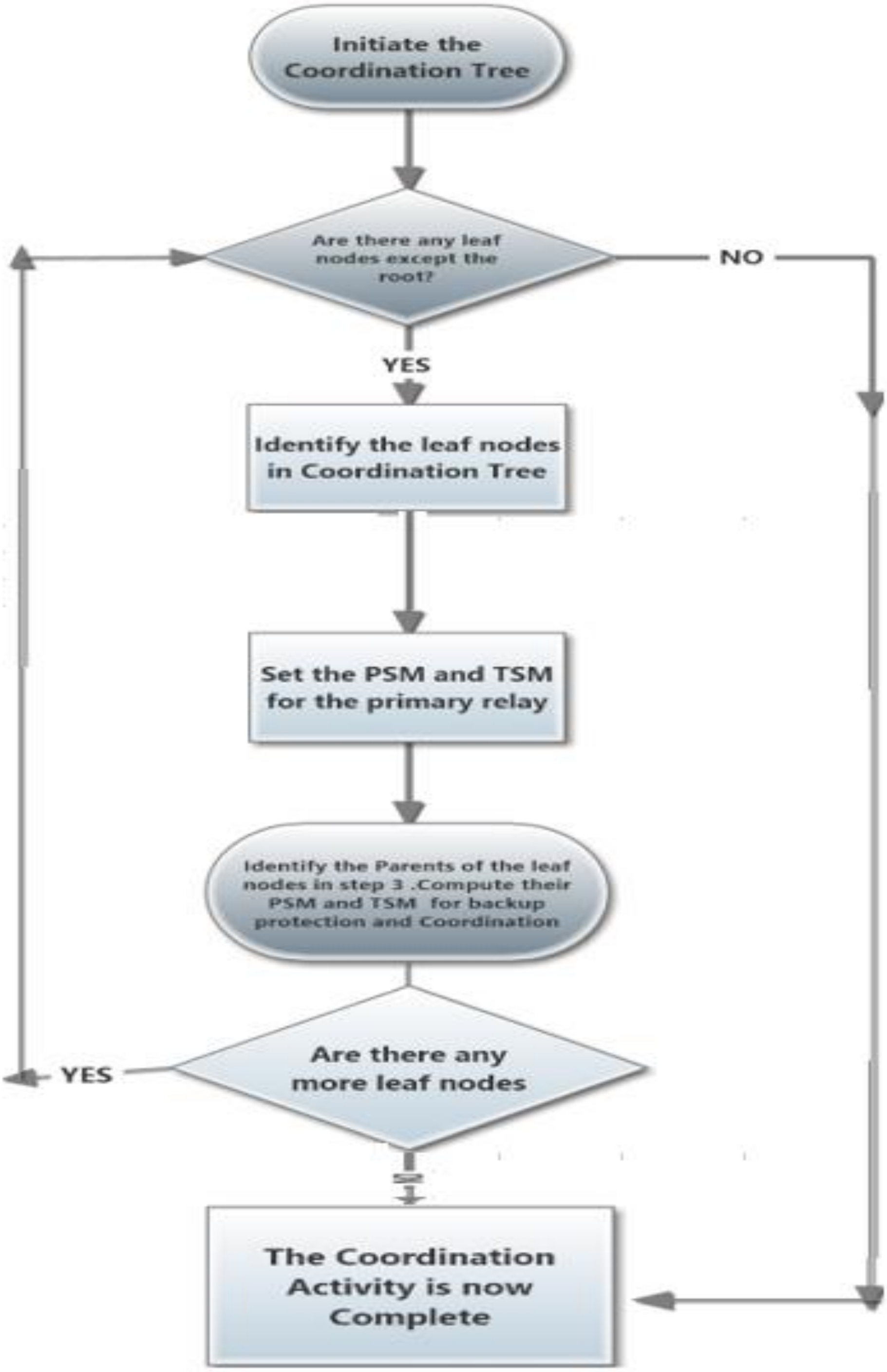
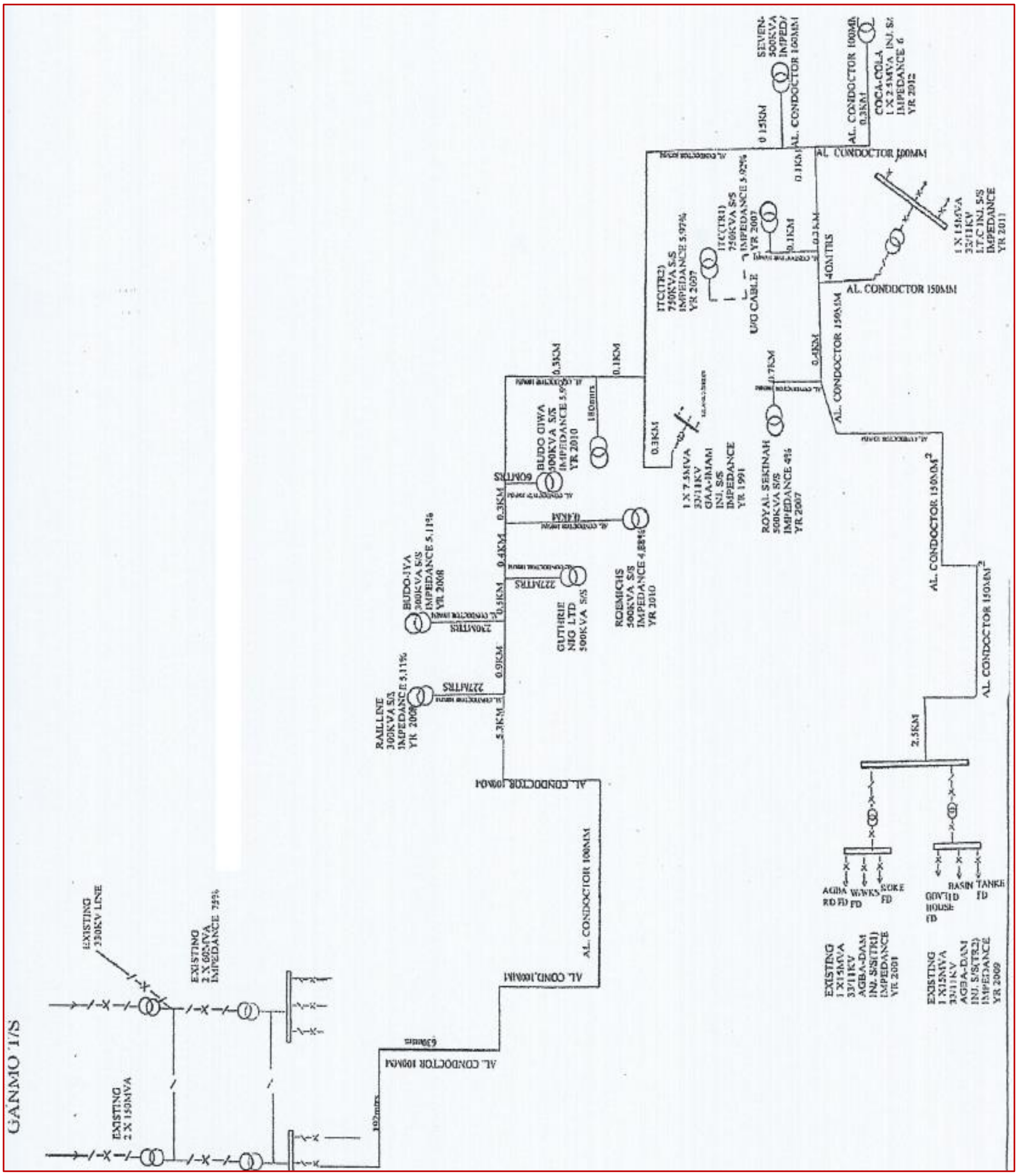
APPENDIX

APPENDIX A1 Figure of Proposed Algorithm for Setting and Coordination of OCRs in a Radial System



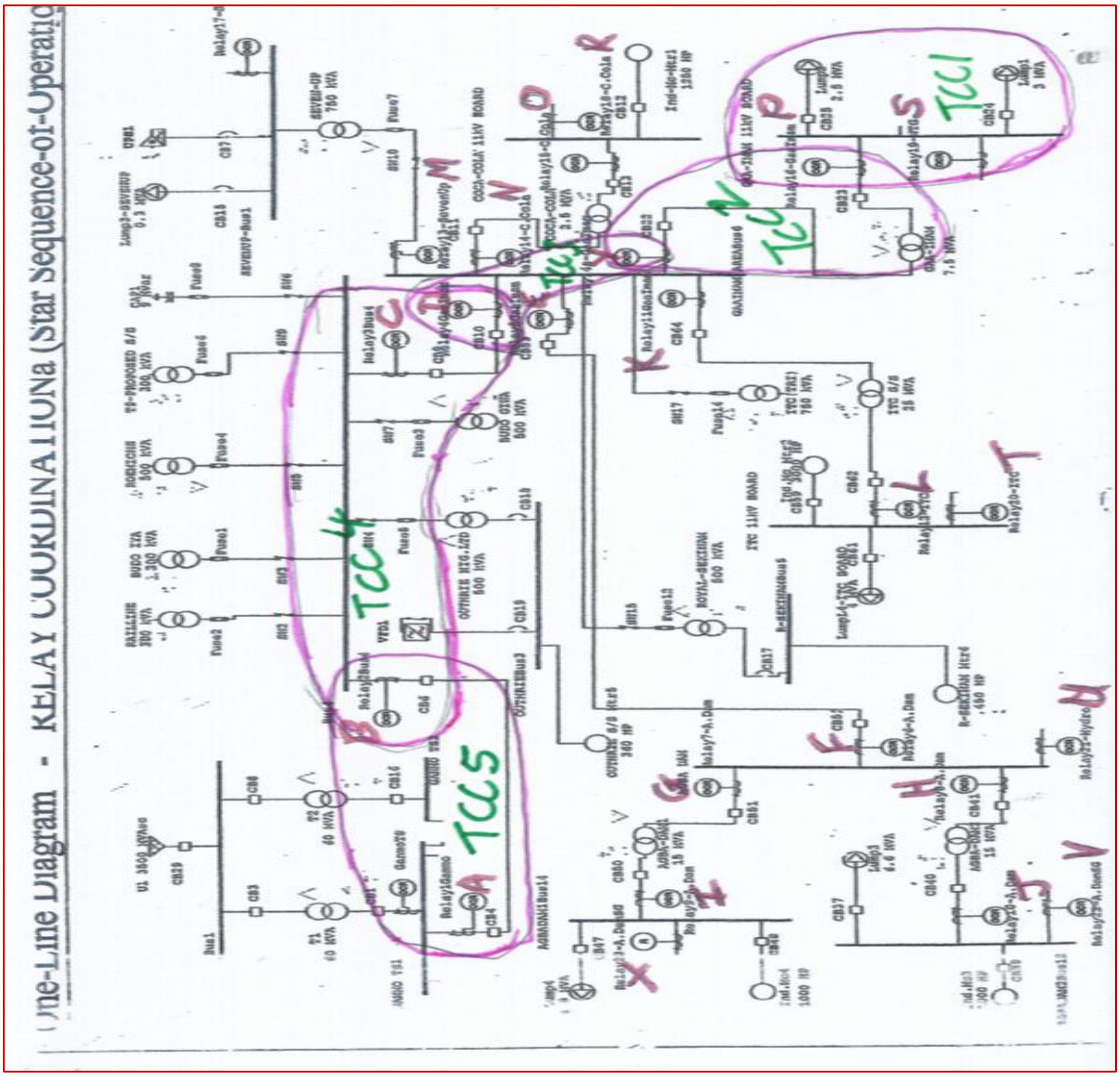
Starting the coordination from 'Leaf Node' relays to 'Child' relays, to 'Parent' relays and then finally to the source or 'Root' node relays, the PSM and TSM were calculated for each relay. The root node (parent relay) had no parent while the leaf-node had no child.

APPENDIX A2 Figure of Existing Industrial 33kV CocaCola Distribution Circuit in Nigeria



The original schematic circuit diagram of the Industrial feeder showing the 132/33 KV grid injection substation, having three 33 KV circuits, one of which was chosen as the Case Study (Coca-Cola Industrial feeder). It is a short radial distribution line of 11.37kms.

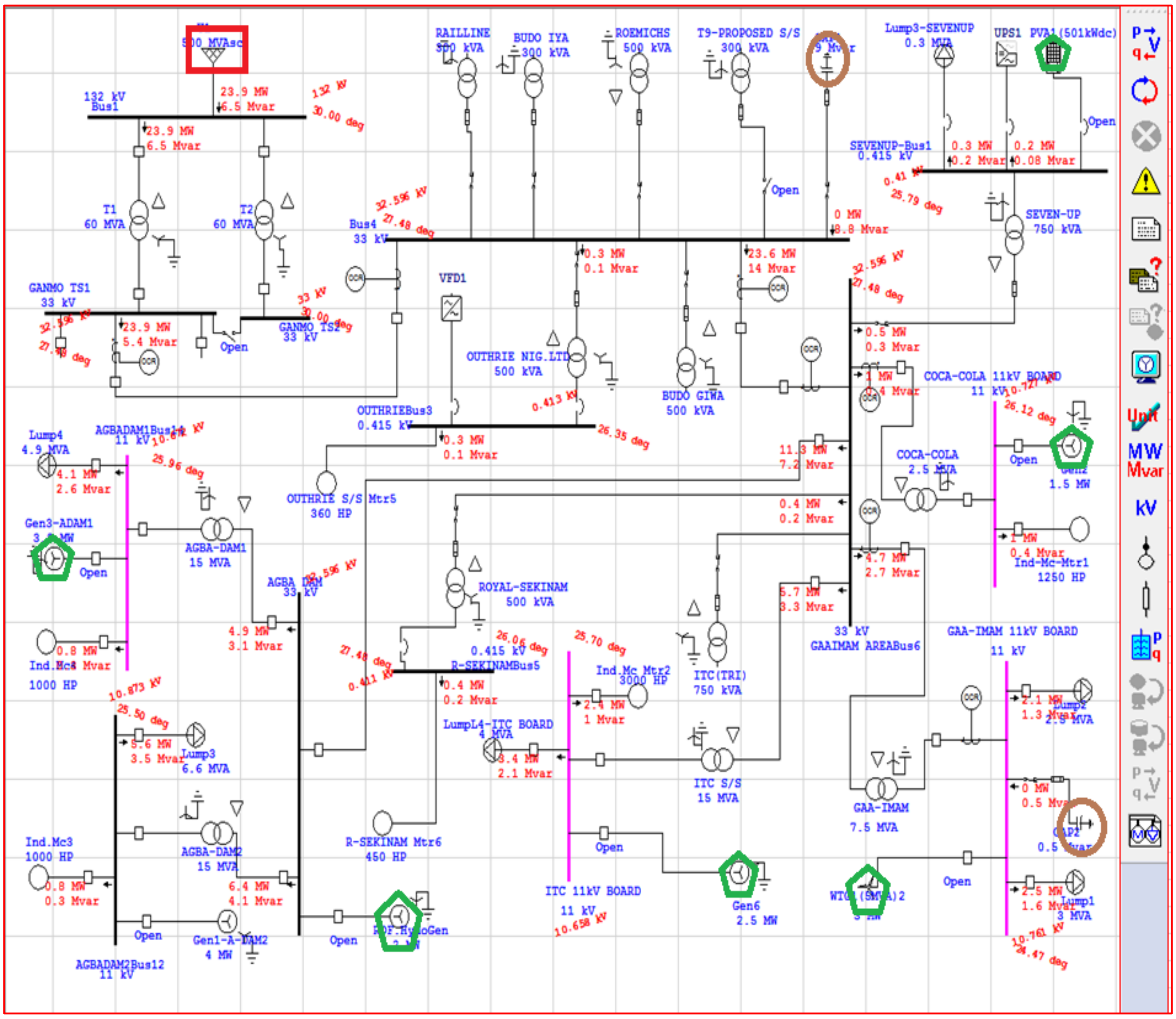
APPENDIX A3. Figure of The Zones of the Relay Coordination



The operating zone of each relay (TCC) was identified in which the relay should be capable enough to operate on the occurrence of different types of faults. Each relay should be capable of operating for close-end and far-end faults (three-phase and single-line-to-ground faults). Each node represented a relay; these relays have primary and backup duties to perform. The swing or source node was named 'root node', (TCC5) while the terminal nodes represented the leaf-node

(TCC1). All relays had dual roles of primary and backup protection to perform except the terminal node (Leaf-Node), which was not having backup duties.

APPENDIX A4 Figure of LFA of Existing 33 kV Coca-Cola Industrial Feeder without DGs

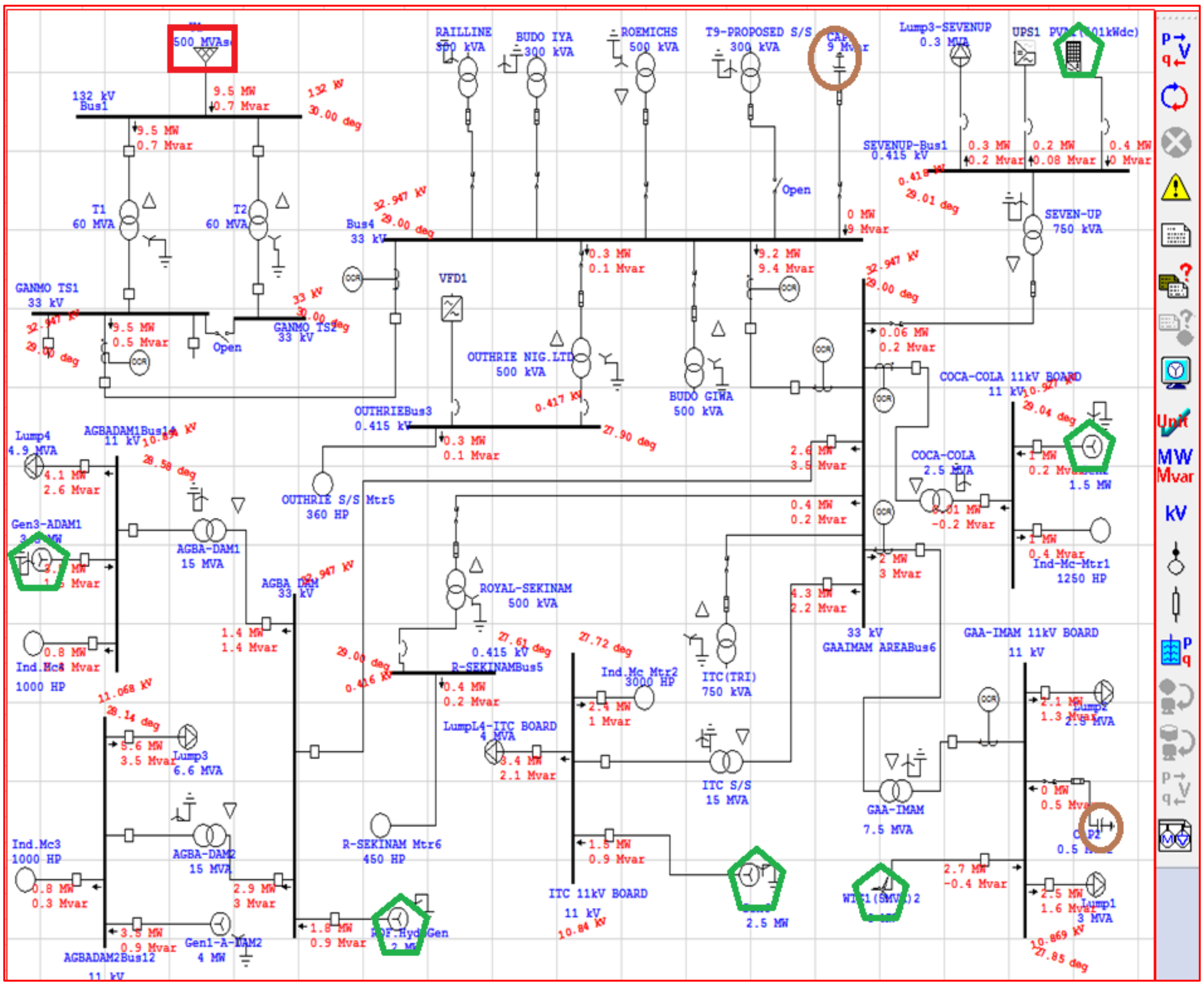


The swing or infinite bus was indicated in red square colour, the green polygons indicated the locations of the existing and proposed DGs, and the existing capacitors are in brown circles.

The load flow analysis (LFA) for analysis after the conversion of the original circuit to ETAP software is shown above. The LFA analysis quickly pointed out that the following 11 kV buses had low voltages: Coca-Cola, Gaa-Imam, ITC, and

Agba-Dam which is the farthest substation from source (indicated in pink). This was the reason why all of them had standby generators initially.

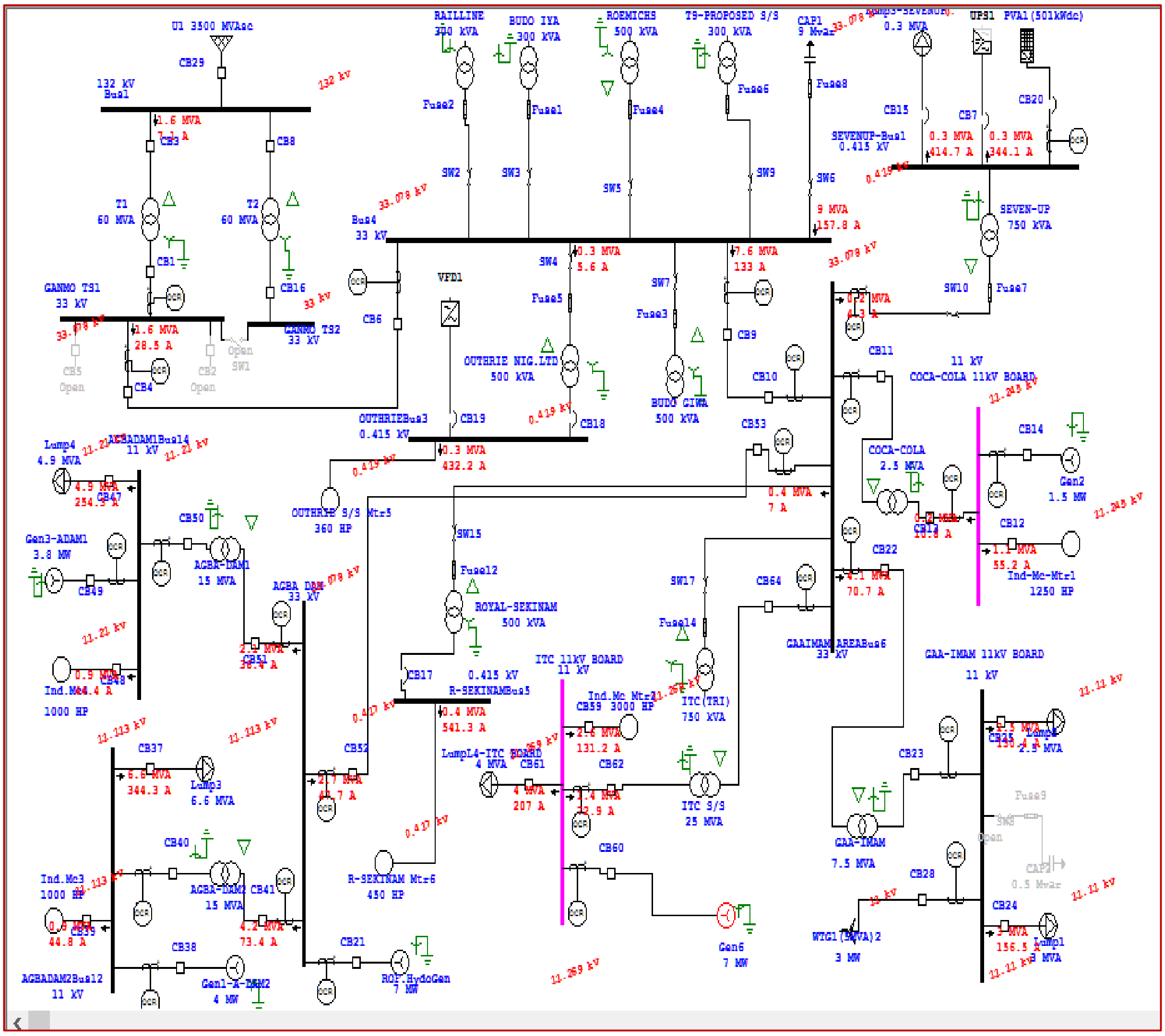
APPENDIX A5 Figure of LFA of Existing 33 kV Coca-Cola Industrial Feeder including DGs



The penetration of more than 65% DGs amounted to transmission capacity relieve in the form of distribution capacity relief since there was a reduction of <u>14.4 MW</u> (23.9 – 9.5), and <u>5.8 MVAR</u> (6.5 – 0.7) when the DGs were included in the simulation. This reduction amounted to (24.77 – 9.53) MVA i.e. 15.24 MVA which was = 61.53%, which was supplied by the DGs.

The low voltages at the previous 11 kV buses were rectified by the penetration of the DGs. The loss reduction was as a result of localised generation which was removed from the transmission grid losses if the load had been supplied by the grid.

APPENDIX A6 Figure of LFA-Case Study with more than 100% DG Capacity of Feeder Load



With DGs contributing nearly 100% of feeder load, the voltages at ITC 11 KV and the Coca-Cola 11 KV boards, had caused overvoltages at these buses, which could cause miscoordination at the respective OCR relays

Name of Bus	Bus Voltage (without penetration) KV	Bus Voltage (at 65% penetration) KV	Bus Voltage (at 100% penetration) KV
Coca-Cola 11 KV	10.27	10.97	11.24
ITC 11 KV	10.658	10.84	11.27

APPENDIX B1 Table of LFA-Case Study with nearly 100% DG Capacity of Feeder Load

	MW	Mvar	MVA	% PF
Source (Swing Buses):	1.423	-1.428	2.016	70.59 Leading
Source (Non-Swing Buses):	22.638	6.360	23.514	96.27 Lagging
Total Demand:	24.061	4.932	24.561	97.96 Lagging
Total Motor Load:	20.335	11.353	23.290	87.31 Lagging
Total Static Load:	3.697	-6.755	7.700	48.01 Leading
Total Constant I Load:	0.000	0.000	0.000	
Total Generic Load:	0.000	0.000	0.000	
Apparent Losses:	0.028	0.334		
System Mismatch:	0.000	0.000		

When nearly 100% of the feeder load was supplied by the DGs, in the simulations, the result was that the source (swing Bus), generated negative VARs. was (-1.428 MVARs) which indicated reverse power swing, while the non-swing source buses, i.e. the contribution of the DGs was 23.514 MVA and total load demand was 24.561 MVA.

APPENDIX B2 Table of Branch Losses of Case Study with nearly 100% DG Capacity of Feeder Load

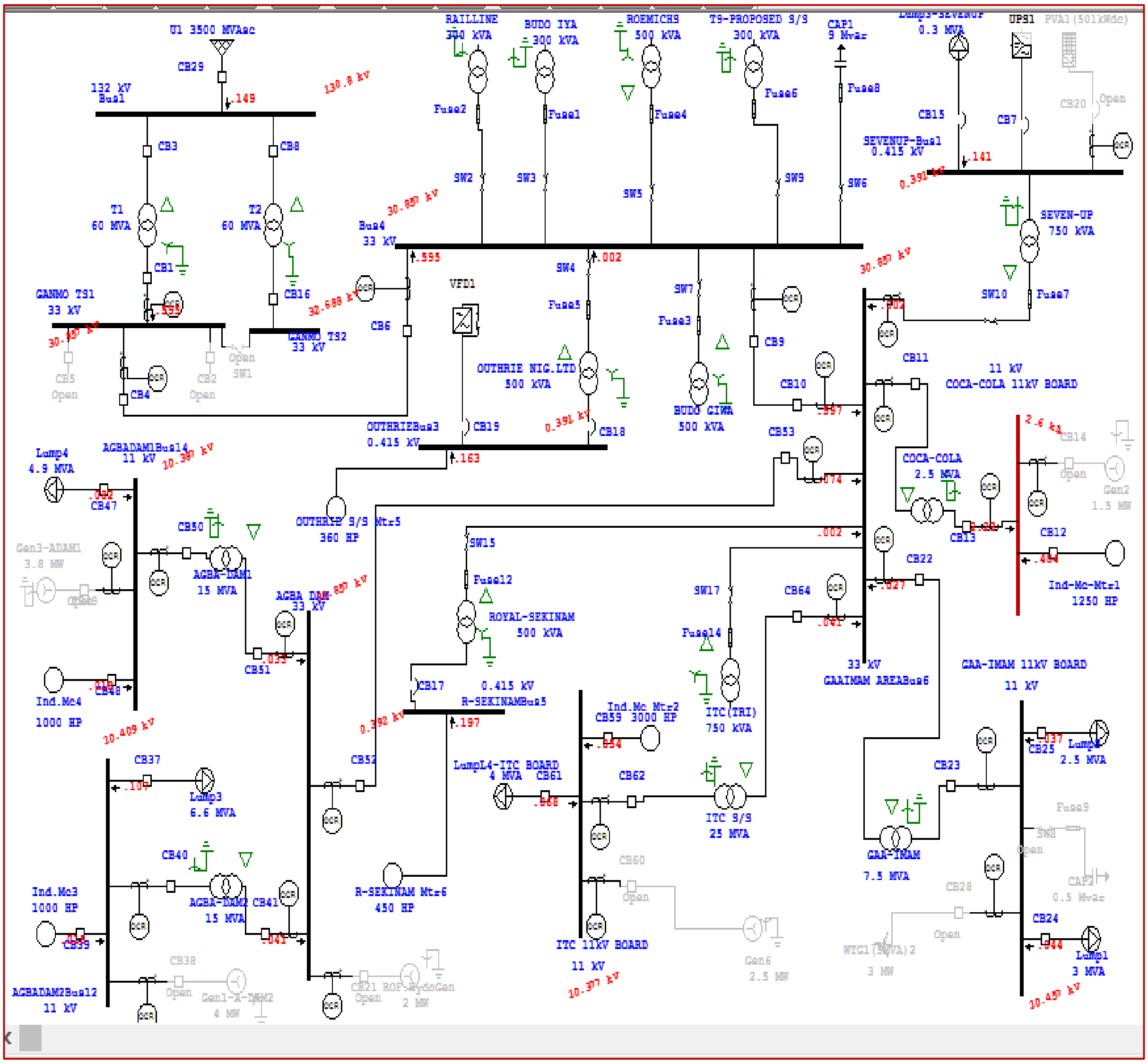
CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
AGBA-DAM1	1.496	1.455	-1.494	-1.432	1.2	23.1	100.3	101.9	1.67
AGBA-DAM2	2.935	3.016	-2.930	-2.922	5.0	93.8	100.3	101.0	0.79
T1	1.423	-1.428	-1.423	1.435	0.2	7.4	100.0	100.3	0.25
T2	0.000	0.000	0.000	0.000			100.0	100.0	0.00
OUTHRIE NIG.LTD	0.291	0.131	-0.289	-0.123	2.5	7.7	100.3	101.0	0.77
COCA-COLA	0.005	-0.210	-0.005	0.211	0.1	1.1	99.8	100.3	0.50
GAA-IMAM	-1.994	-3.337	2.008	3.518	13.9	181.2	101.0	100.3	0.76
ITC S/S	-0.724	0.676	0.724	-0.672	0.2	3.9	100.3	100.0	0.25
ROYAL-SEKINAM	0.364	0.165	-0.360	-0.153	3.9	12.1	100.3	100.6	0.33
SEVEN-UP	0.057	0.239	-0.056	-0.235	1.0	3.9	100.3	101.1	0.83
					28.1	334.2			

After the connection of the 60% DGs, total apparent losses reduced from 113 + j2.274 (2.277 MVA. without DG) to 0.037 +j0.564 (0.648 MVA), at 60% contribution by DGs of the feeder load, i.e. a reduction of 1.629 MVA.

The branch losses have further reduction of 335.38 kVA {$\sqrt{(28.1^2 + 334.2^2)}$}, for the nearly 100% level contribution, because more power was supplied by the local generators which would have caused transmission losses if such power had come from the grid.

% of DG Contribution of feeder load	Total Distribution Losses in the network (kVA)
Without DGs	2,277
With 65% of feeder load	648
With approximately 100% of feeder load	335

RAPPENDIX B3 Figure of SCA – Coca-Cola Board (11 kV) Excluding DGs



The short-circuit current at each bus, after application of a fault (bolted three phase fault) at a specific location of the network, was obtained through fault flow analysis, and were saved in separate file. The bolted three phase fault is regarded as the worst fault in which all the three phases are shorted together. The single phase to earth fault could be worse than the three phase fault only under grounded transformer conditions. The Coca-Cola 11 kV bus was shorted in the above appendix B3 using the ETAP software simulation.

APPENDIX B4 SCA Table – Coca-Cola Board (11 kV) Report Excluding DGs

SHORT-CIRCUIT REPORT

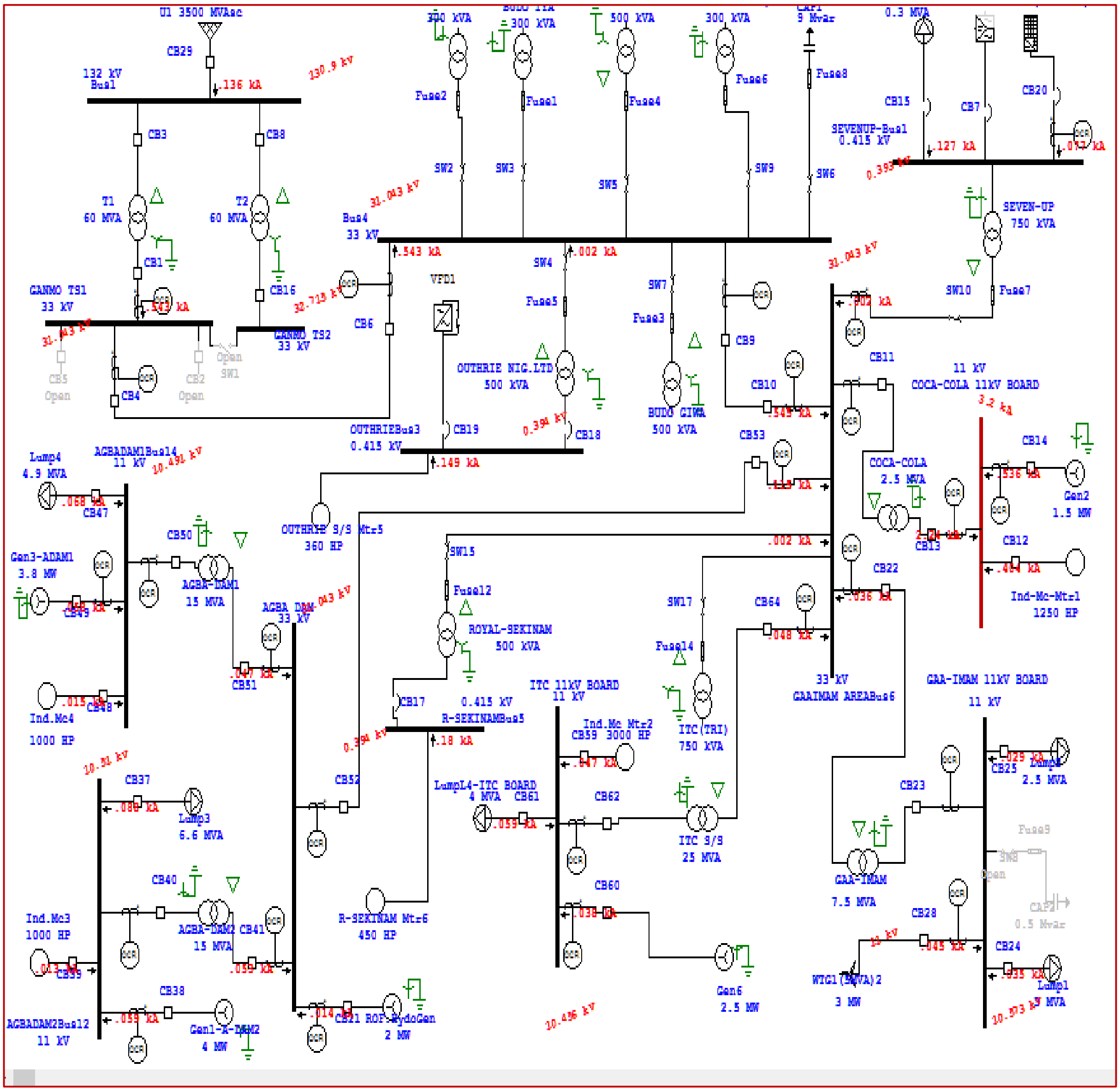
3-Phase fault at bus: **COCA-COLA 11kV BOARD**

Nominal kV	= 11.000	
Voltage c Factor	= 1.10	(User-Defined)
Peak Value	= 6.495	kA Method C
Steady State	= 2.194	kA rms

Contribution		Voltage & Initial Symmetrical Current (rms)				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
COCA-COLA 11kV BOARD	Total	0.00	0.265	-2.620	9.9	2.633
GAAIMAM AREABus6	COCA-COLA 11kV BOARD	93.51	0.206	-2.220	10.8	2.230
Ind-Mc-Mtr1	COCA-COLA 11kV BOARD	100.00	0.059	-0.399	6.8	0.404
AGBA DAM	GAAIMAM AREABus6	93.51	0.008	-0.073	8.8	0.074
GANMO TS1	Bus4	93.51	0.051	-0.593	11.5	0.595
Bus4	GAAIMAM AREABus6	93.51	0.052	-0.595	11.5	0.597

The readings showed a total bolted short current at the Coca Cola 11 kV bus has a magnitude of 2.633 kA. The I_{SCmax} = 6.495kA, while the I_{SCmin} = 2.194 kA without DGs

APPENDIX B5 SCA Figure – Coca-Cola Board (11 kV) Including DGs



The bolted short circuit fault currents, with the DGs. The Coca-Cola 11 kV bus was shorted in the above appendix B5 with the ETAP software simulation.

APPENDIX B6 SCA Table – Coca-Cola Board (11 kV) Including DGs

SHORT-CIRCUIT REPORT

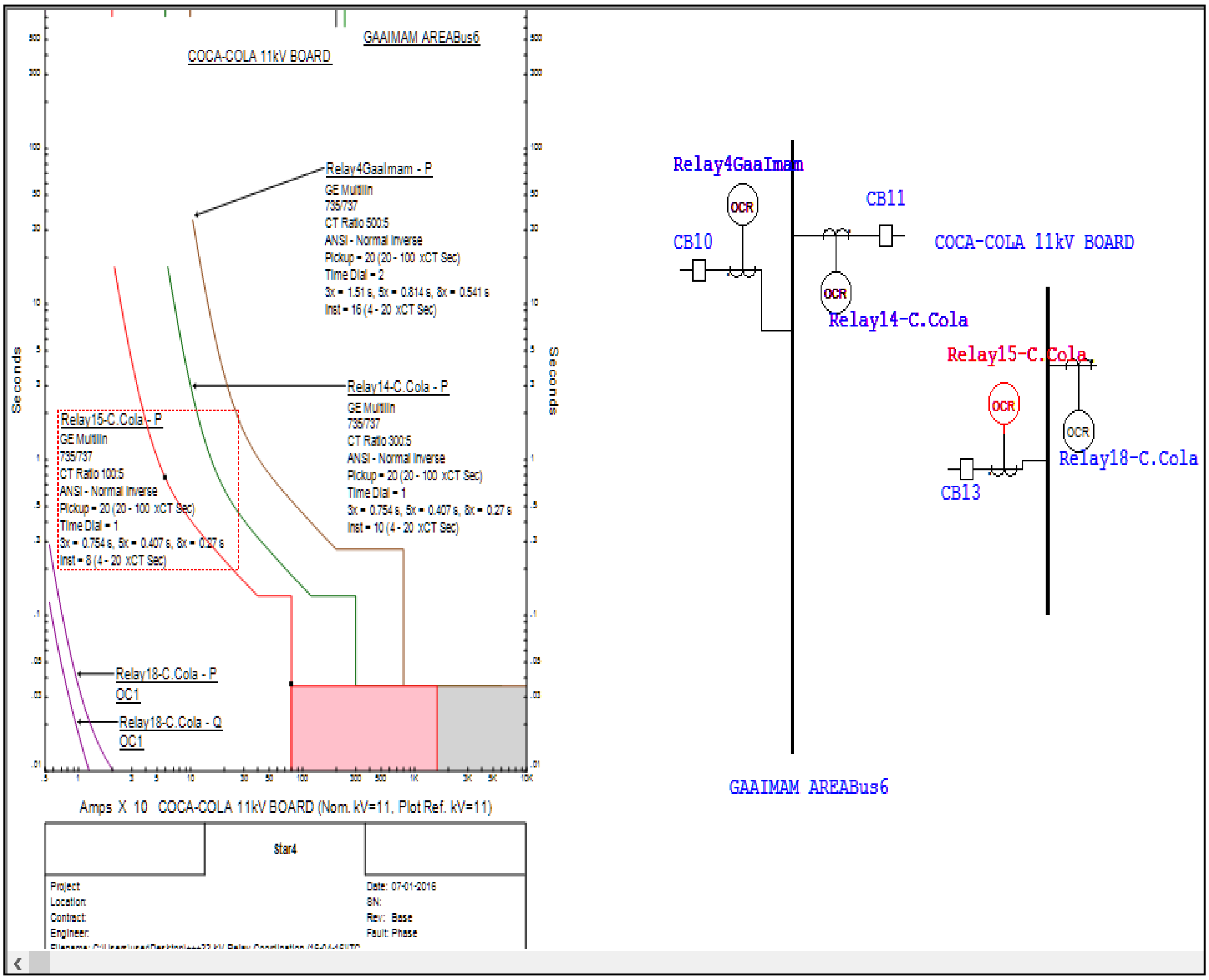
3-Phase fault at bus: **COCA-COLA 11kV BOARD**

Nominal kV	= 11.000	
Voltage c Factor	= 1.10	(User-Defined)
Peak Value	= 7.931	kA Method C
Steady State	= 2.751	kA rms

Contribution		Voltage & Initial Symmetrical Current (rms)				
From Bus ID	To Bus ID	% V From Bus	kA Real	kA Imaginary	X/R Ratio	kA Magnitude
COCA-COLA 11kV BOARD	Total	0.00	0.295	-3.168	10.7	3.181
GAAIMAM AREABus6	COCA-COLA 11kV BOARD	94.07	0.208	-2.233	10.8	2.243
Gen2	COCA-COLA 11kV BOARD	100.00	0.028	-0.535	19.0	0.536
Ind-Mc-Mtr1	COCA-COLA 11kV BOARD	100.00	0.059	-0.399	6.8	0.404
AGBA DAM	GAAIMAM AREABus6	94.07	0.010	-0.114	11.5	0.115
GANMO TS1	Bus4	94.07	0.045	-0.542	11.9	0.543
Bus4	GAAIMAM AREABus6	94.07	0.046	-0.543	11.9	0.545

The readings showed a total bolted short current at the Coca-Cola 11 kV bus has a magnitude of 3.181 kA. The I_{SCmax} = 7.931 kA, while the I_{SCmin} = 2.751 kA including DGs

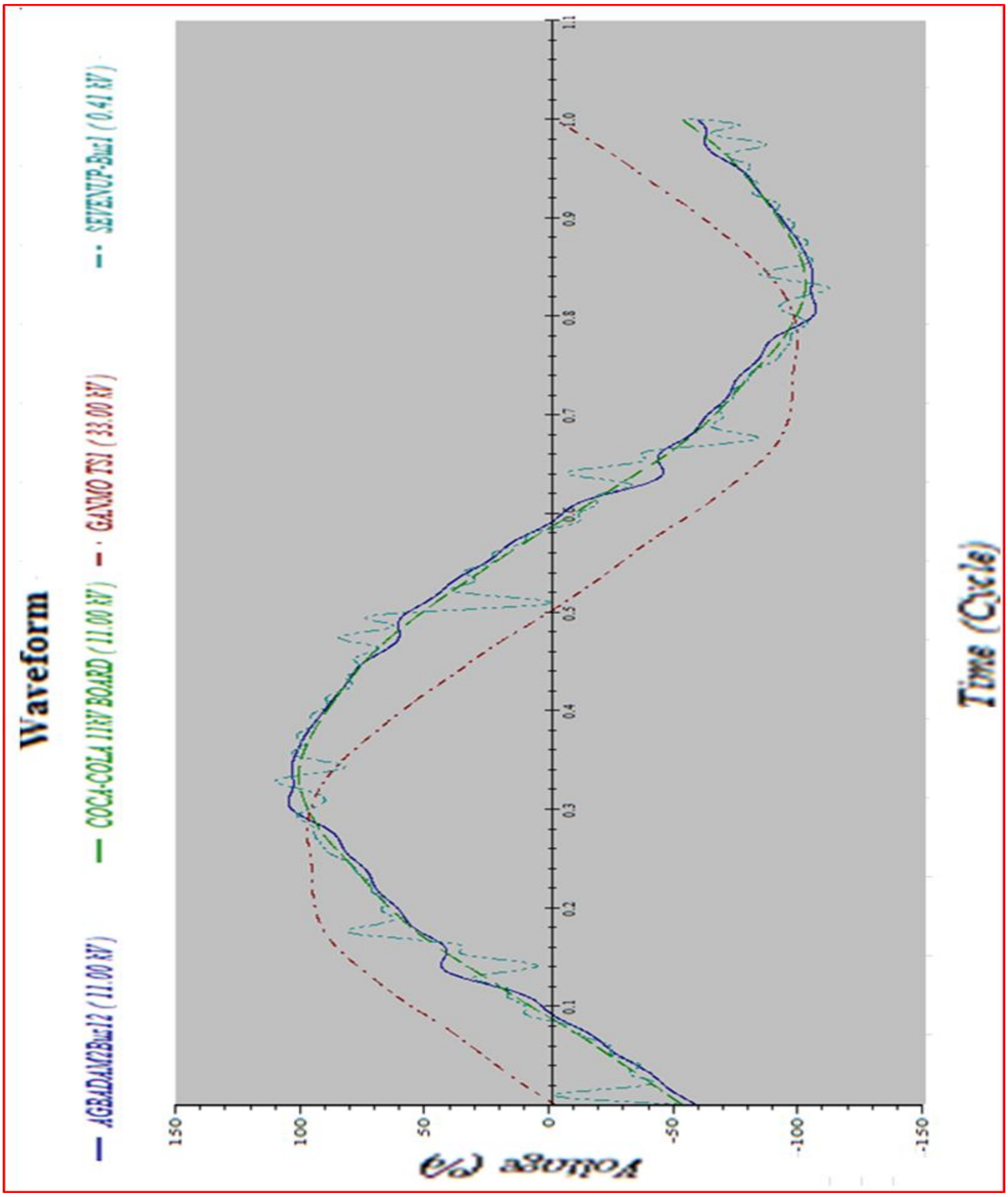
APPENDIX C1 Figure: Sequence of Operation of Leaf-Node of Coca-Cola S/S.



The intersection between TCC curves of the protection devices is the main reason for loss of coordination. There would be loss of coordination for feeders having crossings on TCC curves of main and backup protection devices. There would be mis-coordination at a particular level of short circuit current if the TCC curves cross.

The downstream protection curve of the Coca-Cola branch, i.e. the leaf-node relay, relay 15, while relay 14 backs up relay 15, and relay 4 is the second backup for relay 14. Relay 18, was the generator relay at the Coca-Cola factory.

APPENDIX C2 Waveform of the DG Buses showing the Level of Distortions



The waveform of the PV at the 7UP-bus (0.415 kV), in green (-.-.-.), had shown that the power electronic inverter contributed worse harmonic distortions than the other DG waveforms, which could lead to miscoordination of the relay there.