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Relay Coordination in Distributed Power System Network Using Renewable Energy

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***Abstract*— The integration of renewable energy sources into power distribution networks presents significant challenges for relay coordination, essential for protecting the network from faults and ensuring reliable operation. This paper provides an in-depth analysis of relay coordination principles under fault conditions in a distributed power system using ETAP software. Key analyses, including load flow, short circuit, and fault analysis, were conducted to evaluate the reliability of the developed model. Utilising the Newton-Raphson algorithm, the ETAP software adjusts relay settings in real-time to ensure optimal performance. The study's findings demonstrate the model's effectiveness in maintaining network stability and reliability amidst the dynamic nature of renewable energy sources, highlighting the critical importance of advanced relay coordination strategies in modern power systems.**

***Keywords*—protection relay, relay coordination, distribution power system network, ETAP software, Renewable Energy Sources, short circuit analysis, load flow analysis**

I. Introduction

Relay Coordination is one of the critical aspects for maintaining the reliability and stability of the distributed system network[2]. In recent eras, the energy landscape worldwide has undergone major changes because more attention is being given to environmental sustainability and reducing our reliance on limited energy sources. This has led to a growing interest in renewable energy sources such as wind and solar power. Distributed systems involve generating electricity from many small-scale and often spread-out sources, like household solar panels, and wind turbines. In traditional power systems, collaboration is fairly straightforward, as the generation is stable, and fault currents can be reliably prognosticated Unlike traditional centralized power generation, renewable energy sources are known for their intermittent and variable nature[3,4]. Protective relays serve as the first line of defence against faults and disturbances in the network, acting swiftly to isolate faulty sections and prevent cascading failures that could lead to widespread outages. In traditional centralized power systems, relay coordination primarily focuses on optimizing protection schemes for the interconnected grid. However, the dynamic nature of distributed power systems demands a paradigm shift towards decentralized relay coordination strategies that account for the diverse characteristics and operating con- ditions of distributed energy resources[4]. Integrating relay coordination with renewable energy sources causes lots of challenges. Renewable energy sources such as solar energy, and wind produce power depending on the weather conditions and times of the day. Moreover, these resources also allow the bidirectional flow of power from consumers to the grid during power generation. Fluctuations in generation patterns lead to dynamic fault currents, complicating the design and implementation of collaboration schemes. To address these complexities and ensure sustainable energy development, the integration of a proper industrial model is essential. In this study/experiment, an industrial model has been proposed and developed with renewable energy sources that can maintain the reliability and stability of the network in the ETAP software. This study mainly focuses on the relay coordination of components in distributed systems with renewable energy sources, but the main requirement is relay coordination between the components when there is any fault in the network. The prepared model has undergone load flow analysis, short circuit analysis and relay coordination when a fault is induced. The load flow analysis method is performed to determine the state of the equipment present in the network to ensure their operational limit is not exceeding[5]. Short circuit analysis is used to determine the magnitude of short circuit current, the system can produce and compare that magnitude withthe interrupting rating of the overcurrent protective devicesby fault analysis it is determined that the model can protectthe network when a fault is induced in the network. The ETAP Software uses Newton Raphson Algorithm to adjust the relay setting according to the real time information and perform relay coordination in the network. Many architectural models can be used to study relay coordination but as this model involves the usage of renewable energy sources, it is importantto consider a ring power system model. Therefore, the star view of the industrial model in the distributed network shows the proper coordination of the model. It is very importantthat the model successfully gives the result during load flow analysis, giving voltage magnitude and phase angles, short circuit analysis and when a fault is induced in the bus relay coordination between the components in the network.

Recent research on relay coordination in distributed power systems using renewable energy sources has focused on addressing notable demonstrations to overcome the challenges

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posed by the integration of renewable energy into the power grid. The most common approach to overcome the challenges is to use simulation software to test the performance of protective relays under different fault scenarios. This testing involves creating a range of fault scenarios based on the system configuration and types of faults that could occur,simulating these faults to analyse the coordination of the protective relays, and verifying their operation through primary and secondary injection testing. The results of these tests are then documented and used to adjust the relay settings to ensure optimal relay coordination. A new formulation for the coordination of directional overcurrent relays in interconnected networks, which aimed to improve the efficiency and effectiveness of relay coordination in such systems is proposed by Adelnia et al. In 2015. Another illustration is given by Singhet al. in 2020, who developed an optimum coordination of over current relays using the CMA-ES algorithm, which isa type of evolutionary algorithm. This research demonstrated the potential of using advanced algorithms to optimize the coordination of over current relays in power systems with distributed generation. In this study, the model successfully gives the result during load flow analysis, giving voltage magnitude and phase angles, short circuit analysis and when a fault is induced in the bus relay coordination between the components in the network. The prepared model completed all the above-mentioned analyses and gave results, which marks the successful completion of the model. Additionally, the Time Current Coordination Analysis on ETAP explains the nature of current when there is a fault and the principle of relay in this model.

II. Methodology

In this study, a 10-bus circuit industrial ring model is designed in the ETAP Software to demonstrate relay coordination. The load flow, short circuit current and fault analysis performed in the ETAP software demonstrate the reliability and stability of the model to detect faults and protect the net- work. Additionally, the Time Current Coordination Analysis on ETAP is also performed to determine the nature of the current when there is a fault and the principle of relay in this model. The 10-bus industrial model consists of, a power grid of 33 KV with two static lamp loads of 2 MVA each withtwo induction motors whose ratings are 1000 KW each along with two synchronous generators of 33 kV each and two wind turbines of 6.6 KV each. Also, step-down transformers are:

$$T_1, T_{13}, T_{18} = 50mVA, 33/11kV$$
$$T_{11}, T_7, T_{15} = 25mVA, 11/6.6kV$$
$$T_{10}, T_6 = 2.5mVA, 6.6/0.416kV$$

Load flow analysis is performed after modelling in the ETAP software to determine the state of the equipment present in the network to ensure their operational limit isnot exceeding. The load inflow analysis gives the current, voltage and Power inflow of lines, machines, motors, circuit breakers, motors, and other devices. Using the load flow study, we can decide the draw setting of the relay. At the time of designing a new system, or analysing the system, factors such as voltage drop, load capacity, power factor constraints, steady-state stability limits, motor valve settings, and creator excitation situations need to be considered[5]. Next, Shortcircuit analysis is performed to determine the magnitude ofthe short circuit current, the system can produce and compare that magnitude with the interrupting rating of the over current protective devices (OCPD)[6]. The fault analysis in the ETAP software explains any disturbances or electrical faults in the electrical network. This helps to understand how the model,or the electrical network behaves during abnormal conditions and how much it causes impact on the network. During fault analysis, the location of the fault in the network is first identified and then the fault current that is obtained during fault condition is calculated[4]. ETAP also gives data regardingthe current and voltage drops during fault conditions and also shows the abnormal flow of current in some parts of the network. Fault analysis in ETAP gives the appropriate setting details about protective devices and relays. As a first step, all these details are studied with an initial model to successfully implement the model and perform the analysis. Finally, the results of the analysis performed in the ETAP software are studied to understand the performance and reliability of the model during fault conditions.

III. ETAP Software

To implement the model that will show the relay coordination in the distributed network enriched with renewable energy sources, it is very important to understand the software and its operation. To prepare the model ETAP 21.0.2 version is used and using basic ETAP software knowledge a basic model is prepared first then the initial model undergoes load flow analysis, fault analysis and relay coordination to understand how in the ETAP the relay coordination is taking place and which algorithm it is following. From this analysis, it is studied that ETAP software uses the Newton-Raphson method to perform relay coordination in the distributed Network.

ETAP Software follows the Newton-Raphson algorithm to perform relay coordination between the components. In this study, the model was designed with 10 buses. So, to elucidate the Newton-Raphson algorithm utilized in ETAP software for relay coordination, we begin by considering a simplified scenario involving two buses. Let x1 and x2 represent the variables associated with the functions f1 and f2, respectively, such that:

$$f_1(x_1, x_2) = C_1 \quad (1)$$
$$f_2(x_1, x_2) = C_2 \quad (2)$$

Where C1 and C2 are constants. Let $x_1(0)$ and $x_2(0)$ be the initial estimates of solutions to "(1)" and "(2)" and let $\Delta x_1(0)$ and $\Delta x_2(0)$ be the values by which the initial estimates differ from the correct solutions. That is,

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$$f_1(x_1(0) + \Delta x_1(0), x_2(0) + \Delta x_2(0)) = C_1 \quad (3)$$

$$f_2(x_1(0) + \Delta x_1(0), x_2(0) + \Delta x_2(0)) = C_2 \quad (4)$$

Simplifying this equation, we get

$$x_1(1) = x_1(0) + \Delta x_1(0) \quad (5)$$

$$x_2(1) = x_2(0) + \Delta x_2(0) \quad (6)$$

IV. Load Flow Analysis

For electrical systems, load flow studies are crucial, as they determine the sizes of capacitors, transformers, and current-limiting reactors (CLR) based on system needs. Load Flow analysis provides data on current, voltage, and about various components like lines, machines, and motors. With this information, we can change the relay parameters for effective protection. Whether designing a new system or assessing an existing one, factors such as voltage drop, load capacity, power factor constraints, stability limits, motor settings, and generator conditions must be considered to ensure optimal system performance and reliability[5]. From the designed model shown in Fig.1. the voltage magnitude and phase angles are determined by performing load flow analysis which gives an understanding of any modification required to enhance the standing of the overcurrent protective device (OCPD). The short-circuit analysis in ETAP provides a comprehensive view of the system's short-circuit behaviour and an understanding of managing fault currents effectively [6]. Formulae of Short Circuit Analysis.

$$\%\,reactance\ at\ base\ kVA = \frac{Base\ kVA}{Rated\ kVA} \times \%\,reactance\ at\ rated\ kVA$$

$$Short - circuit\ \ kVA = \text{Base kVA} \times \frac{100}{\%X}$$

LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
Bus8	6.600	99.504	-3.0	0.000	0.000	9.901	0.000	Bus12	1.968	0.086	173.2	99.9	
								Bus10	-11.869	-0.086	1043.5	100.0	
* Bus9	33.000	100.000	0.0	12.326	1.427	0.000	0.000	Bus10	12.326	1.427	217.1	99.3	
Bus10	11.000	99.724	-1.1	0.000	0.000	1.864	0.769	Bus9	-12.318	-1.180	651.3	99.5	
								Bus8	11.886	0.484	626.1	99.9	
								Bus16	11.886	0.484	626.1	99.9	
								Bus17	-12.318	-1.180	651.3	99.5	
								Bus18	-1.000	0.624	62.0	-84.8	
Bus12	0.416	99.003	-5.5	0.000	0.000	1.960	0.000	Bus8	-1.960	0.000	2748.0	100.0	
Bus15	0.416	99.003	-5.5	0.000	0.000	1.960	0.000	Bus16	-1.960	0.000	2748.0	100.0	
Bus16	6.600	99.504	-3.0	0.000	0.000	9.901	0.000	Bus15	1.968	0.086	173.2	99.9	
								Bus10	-11.869	-0.086	1043.5	100.0	
* Bus17	33.000	100.000	0.0	12.326	1.427	0.000	0.000	Bus10	12.326	1.427	217.1	99.3	
Bus18	6.600	99.562	-1.0	1.000	-0.620	0.000	0.000	Bus10	1.000	-0.620	103.4	-85.0	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

\# Indicates a bus with a load mismatch of more than 0.1 MVA

Fig. 2. Load Flow Analysis Report

SHORT- CIRCUIT REPORT

Fault at bus: **Bus16**

Prefault voltage = 6.600 kV = 100.00 % of nominal bus kV (6.600 kV)
= 100.00 % of base kV (6.600 kV)

Contribution		3-Phase Fault		Line-To-Ground Fault					Positive & Zero Sequence Impedances Looking into "From Bus"			
From Bus ID	To Bus ID	% V From Bus	kA Symm. rms	% Voltage at From Bus Va	Vb	Vc	kA Symm. rms Ia	3I0	% Impedance on 100 MVA base R1	X1	R0	X0
Bus16	Total	0.00	16.259	0.00	95.62	87.04	19.560	19.560	1.18E+001	5.25E+001	1.18E+000	2.80E+001
Bus15	Bus16	0.00	0.000	50.25	55.20	99.19	0.000	0.000				
Bus10	Bus16	52.04	16.259	78.63	99.19	67.94	19.560	19.560 *	1.18E+001	5.25E+001	1.18E+000	2.80E+001
Bus9	Bus10	60.10	3.691	99.86	84.63	68.87	2.501	0.000 *	8.52E+001	4.87E+001		
Bus8	Bus10	52.04	0.000	62.61	95.62	87.04	0.000	0.000				
Bus17	Bus10	62.28	3.538	96.32	89.35	70.83	2.476	0.000 *	7.98E+001	6.41E+001		
Bus18	Bus10	53.01	0.195	63.37	95.67	87.28	0.132	0.000	1.43E+003	1.18E+003		
Bus20	Bus10	62.28	3.538	96.32	89.35	70.83	2.476	0.000 *	7.98E+001	6.41E+001		
Bus22	Bus10	53.01	0.195	63.37	95.67	87.28	0.132	0.000	1.43E+003	1.18E+003		
Mtr4	Bus10	100.00	0.122	100.00	100.00	100.00	0.082	0.000	8.84E+001	2.14E+003		
Mtr3	Bus10	100.00	0.195	100.00	100.00	100.00	0.132	0.000	4.96E+001	1.33E+003		
U1	Bus9	100.00	1.230	100.00	100.00	100.00	0.476	0.000	6.63E+001	6.63E+000	6.63E+001	6.63E+000
Bus12	Bus8	52.04	0.000	67.94	78.63	99.19	0.000	0.000				
Gen1	Bus17	100.00	1.179	100.00	100.00	100.00	0.483	0.000	3.03E+000	5.76E+001	3.03E+000	2.12E+001
WTG1	Bus18	100.00	0.325	100.00	100.00	100.00	0.256	0.000	4.86E+001	1.31E+003		
Gen3	Bus20	100.00	1.179	100.00	100.00	100.00	0.483	0.000	3.03E+000	5.76E+001	3.03E+000	2.12E+001
WTG3	Bus22	100.00	0.325	100.00	100.00	100.00	0.256	0.000	4.86E+001	1.31E+003		

\# Indicates fault current contribution is from three-winding transformers

* Indicates a zero sequence fault current contribution (3I0) from a grounded Delta- Y transformer

Fig. 3. Short Circuit Analysis Report

V. Relay Coordination

Relay Coordination in a distributed electrical network is about ensuring selective and coordinated protection. Selective protection means that when a fault occurs, only the nearest relay should act, isolating the faulty section without affecting the rest of the network. This principle is crucial for maintain- ing the reliability of electrical power. To achieve this, relays

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are configured with specific settings based on fault current and time characteristics. These settings ensure that each relay responds appropriately to faults based on its location and fault severity, preventing unnecessary disruptions to the entire network. Relay Coordination aims to balance quick fault detection and isolation while minimizing disruptions to optimize the overall reliability and performance of the electrical distribution system[2,4]. Time / PSM Curve, Plug Setting,Time Setting, Fault Current, and Current Transformer Ratio are the parameters required to calculate the relay operating time][1].

Relay coordination involves selecting appropriate plug and time multiplier settings based on maximum fault currents at relay locations. The fault current is converted into the relay coil current by using the current transformer ratio. The plug setting multiplier (PSM) is calculated by expressing the relay current as a multiple of the current setting. Graphical coordination checks are then conducted to ensure proper sequencing of protective devices. Maintaining specific time intervals between coordination curves is crucial, particularly for inverse time overcurrent relays. These relays determine the actual operating time for a given fault current by multiplying the operating time of the relay, obtained from the PSM based on the relay's current setting and the actual current measured during a fault with a time setting multiplier and are commonly used for effective coordination. Operating characteristics are typically represented graphically, showing the plug setting multiplier along the X-axis and operating time along the Y-axis[1]. Formulae of relay coordination.

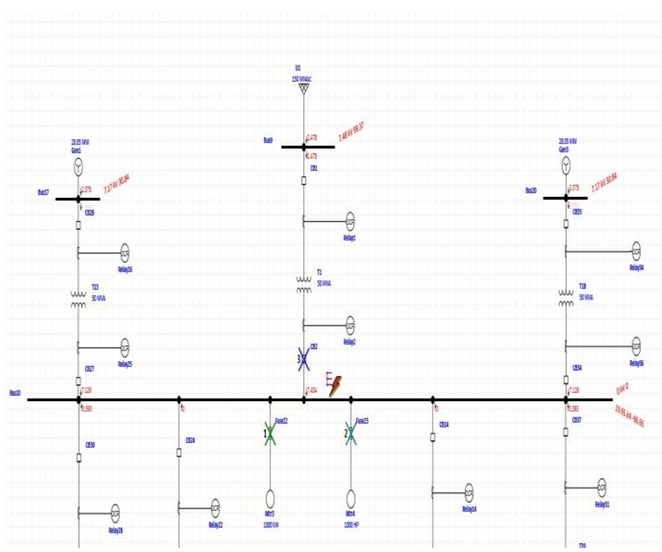

Fig. 4. Sequence of operations between Circuit Breaker and Relay during fault conditions

Sequence-of-Operation Event Summary Report

Symmetrical 3-Phase Fault between Fuse19 and Load13. Adjacent to Bus15.

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
13.6	Fuse19	50.753	<10.0	<13.6	
18.7	Relay19	50.753	18.7		Phase - OC1 - 50
19.0	Relay20	3.199	19.0		Phase - OC1 - 50
68.7	CB41		50.0		Tripped by Relay19 Phase - OC1 - 50
69.0	CB22		50.0		Tripped by Relay20 Phase - OC1 - 50
69.0	CB23		50.0		Tripped by Relay20 Phase - OC1 - 50
158	Fuse22	0.038	79.1	158	
587	Fuse23	0.024	204	587	

Fig. 5. Operating Time of Relay

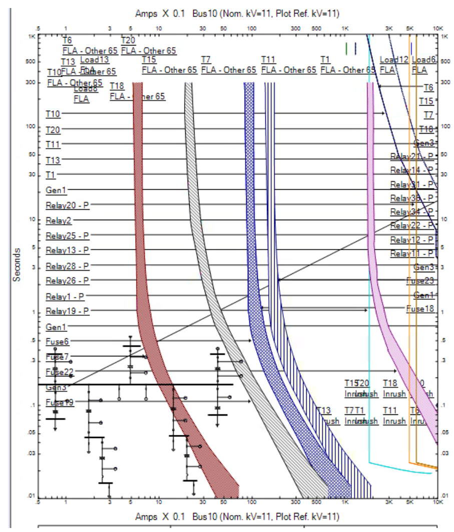

Fig. 6. Relay Coordination

$$FPC = \frac{voltage\ between\ healthy\ and\ fault\ phase}{normal\ phase\ voltage}$$

$$plug\ setting = \frac{desired\ pickup\ current}{CTR}$$

$$primary\ operation\ current = CTR \times ps$$

$$plug\ setting\ multiplier = \frac{FI}{actual\ POC}$$

Where $FPC = First\ pole\ clear$

$POC = primary\ operation\ current$

$CTR = current\ transformer\ ratio$

$ps = plug\ setting$

VI. Results and Discussion

In this study, a 10-bus circuit industrial ring model was designed using ETAP software to evaluate relay coordination in a distributed power system incorporating renewable energy sources. The model underwent three critical analyses: Load Flow Analysis, Short Circuit Analysis, and Fault Analysis, to ensure the system's reliability and stability under various conditions.

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These are some of the findings from this study:

- The load flow analysis provided detailed information on voltage magnitudes and phase angles across different buses. This data is crucial for understanding the steady-state operation of the network and for setting the relay parameters effectively. The results indicated that the network maintained stable voltage levels and power flows, essential for reliable operation.
- The short circuit analysis revealed the maximum fault currents the system could produce. These values were compared against the interrupting ratings of the overcurrent protective devices (OCPD). The analysis confirmed that the protective devices could handle the fault currents without compromising the network's safety. This step is vital to ensure that the relays operate correctly and isolate faulty sections promptly.
- Fault analysis provided insights into the locations of faults and the corresponding fault currents. The ETAP software effectively identified fault conditions and calculated the resulting current and voltage drops. The analysis showed that the network could isolate faults efficiently, minimizing the impact on the overall system. This capability is crucial for maintaining stability and preventing cascading failures.
- The relay coordination study focused on configuring relays with appropriate settings based on fault currents and time characteristics. The Time Current Coordination Analysis illustrated how relays responded to fault conditions, ensuring that only the nearest relay acted to isolate the fault. This selective protection mechanism is essential for minimizing disruptions and maintaining the network's reliability. The use of the Newton-Raphson algorithm in ETAP to adjust relay settings in real-time proved effective in optimizing relay coordination.

VII. CONCLUSIONS

The integration of renewable energy sources into distributed power systems presents unique challenges for relay coordination due to the intermittent and variable nature of these energy sources. This paper successfully demonstrated the use of ETAP software to model a 10-bus industrial ring network and perform comprehensive analyses to address these challenges. Some of the key outcomes include:

- Effective Relay Coordination: The model ensured that relays operated selectively and efficiently, isolating faults without causing unnecessary disruptions to the network.
- Reliable Fault Isolation: The system's ability to detect and isolate faults promptly was validated through load flow, short circuit, and fault analyses.
- Stability and Reliability: The designed model maintained stable voltage levels and power flows, demonstrating its reliability under various operating conditions.

The following points summarise the omplications of this research:

- The paper highlights the importance of advanced relay coordination strategies in modern power systems, particularly those incorporating renewable energy sources.
- The findings underscore the critical role of simulation tools like ETAP in designing and evaluating protection schemes for distributed networks.
- Future research can explore the application of more sophisticated algorithms and models to further enhance relay coordination and network stability.

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