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Overcurrent Relay for Generation Distribution Utilization

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Abstract: Distributed Generation (DG) is the production of electricity from a variety of renewable energy sources that is closer to the customer and load. The addition of distributed generation sources to the distribution networks alters the characteristics of distribution system and has an influence on its protection coordination. Relay protection plays a critical function in protecting a power system from various problems. Relay protection coordination reduces relay operating time and avoids relay failure. As a result, a fault analysis of the distribution network with and without distributed generation installation is required to determine the effects of installing DG at the radial system on overcurrent relay protection. The software programmed ETAP version 19.0 was used to represent an actual distribution system in this research paper. The consequences on the overcurrent protection relay were discovered as a result of the analysis. Simultaneously, the presence of an overcurrent relay following the installation of DG may no longer be dependable. As a result, it is critical to assess the effects of DG installation in order to verify that the protective zone can be properly protected.

Keywords: Distributed Generation, Fault Current Analysis, Overcurrent Relay.

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1. INTRODUCTION

The rapid development of new technologies in today's period has sparked engineer's curiosity in building distribution generation (DG) from renewable sources with great efficiency. The ever-present oil problem has piqued the interest of electrical power experts in developing high efficiency distributed generation (DG) from renewable sources. Therefore, the approaches of DG have encouraged environmental sustainability and pollution free living. The installation of distributed generation, on the other hand, would have a variety of effects on the performance of a distribution network system. It may render the existing protection mechanism ineffective. Short circuit levels escalate to the point that the selectivity of the relay is impaired when the DG units are connected to the distribution system, resulting in miss-operations. [1].

In general, fault occurrences occur in all power systems, which may be caused by open circuits, short circuits, unbalanced situations and other undesired conditions. Majority fault occurrences come from the strike of lightning on overhead lines and it is called as transient faults as it is temporary faults. As a result, it's critical to guarantee that the protection zone can be protected again and that equipment doesn't suffer damage or downtime as a result of the protection system's failure to work. This protection coordination also can reduce the maintenance cost, behavior of systems operational is becoming more reliable and distribution networks becoming more secure.

2.1 LITERATURE REVIEW

2.1.1 Introduction

This paper will concentrate on broad understanding of the Distributed Generation (DG) and overcurrent relay protection technology that will be employed in the project. This chapter will go through the Distributed Generation system and the idea of overcurrent relay protection utilizing Inverse Definite Minimum Time (IDMT), relay coordination, and IDMT relay setting determination.

2.1.2 IDMT Overcurrent Relay Protection

The primary function of an overcurrent relay in a power system is to detect fault current and quickly isolate the problematic region from the healthy system. It serves as backup protection in power systems because to its great dependability, selectivity, and low cost and effectiveness. Another feature of the IDMT overcurrent relay is that it may be graded over a broad variety of currents and running periods [2]. Furthermore, owing to its inversely proportional to current operating duration, it has quick fault clearing times, which means that the greater the fault current, the shorter the operating time.

Figure 1 depicts the relay characteristics of an IDMT overcurrent relay. The compromise feature allows for speedy operation as fault levels decline along a transmission line, but the definite time factor produces very rapid tripping at high fault levels, leading in a loss of selectivity.

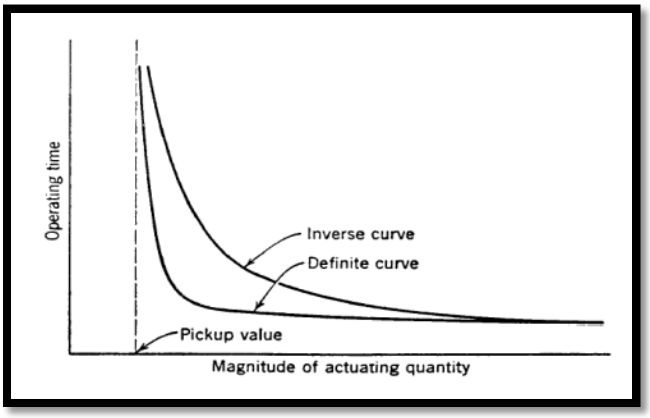

Figure 1. Relay Characteristic of IDMT Overcurrent Relay

2.1.3 Characteristics of IDMT Overcurrent Relay

Figure 2 shows the structure of an Overcurrent Relay. It operates on the induction principle, with the moving system consisting of aluminum discs mounted on a fixed vertical shaft and rotating on two jeweled bearings between the poles of an electromagnet and a damping magnet. The electromagnetic windings have eight tapping which are connected to a plug setting bridge, which enables the number of turns to be changed to provide the desired current setting. The induction effect generates the secondary winding and wrapped over the middle of the upper magnet as well as the two limbs of the lower magnet. Using this method, the leakage flux from the higher magnet entering the disc was shifted into phase with the flux entering the disc from the lower magnet [2].

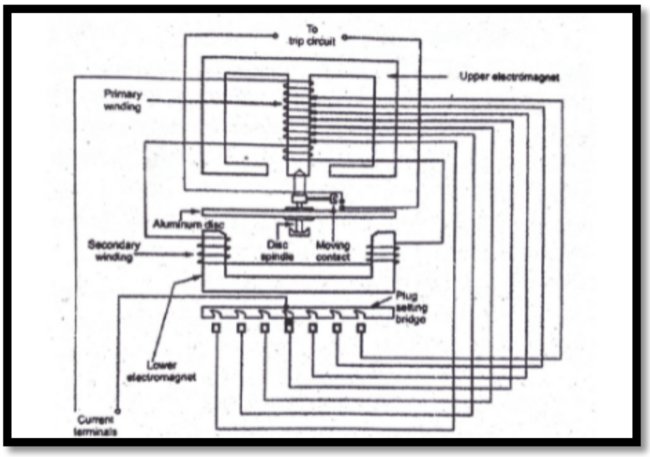

Figure 2. Structure of an Overcurrent Relay

The speed of rotation of the disc is set to the present setting (torque), and as the load current increases, the speed of rotation of the disc increases, reducing the operating time. A saturated upper magnet is used to establish the relay's specified minimum time characteristics. When the current reaches a particular amount, this assures that there is no additional rise in flux, and any subsequent increase in current will not influence the relay functioning. The current time characteristic is flattened as a consequence, and the relay is known as an Inverse definite minimum time (I.D.M.T.) relay.

2.1.4 Overcurrent Relay Settings

The inverse proportional connection between the relay operating time and the function of current influences IDMT. The rotational speed of the disc is determined by the current flowing through the main inductor coil, which also determines the time required to shut the IDMT relay contacts. As a result, there are two critical factors to consider while configuring this relay:

- Plug Setting
- Time Multiplier Setting

2.1.4.1 Plug Setting (PS)

It is described as the number of amperes turns that may be modified utilizing taps on the relay's coil. The plug setting may be either directly in amperes or indirectly in the range of 50% to 200 percent of the rated current in 25% increments [3]. This formula may be used to calculate the value of the plug setting:

$$PS > \frac{Iload \ x \ 100}{CT \ Ratio} \quad (1)$$

In Figure 3, IDMT curves are used when the amount of time which should pass at given current, before initiating an action, usually the tripping of a circuit breaker. When the PS is changed, the relay characteristics in Figure 3 shift horizontally.

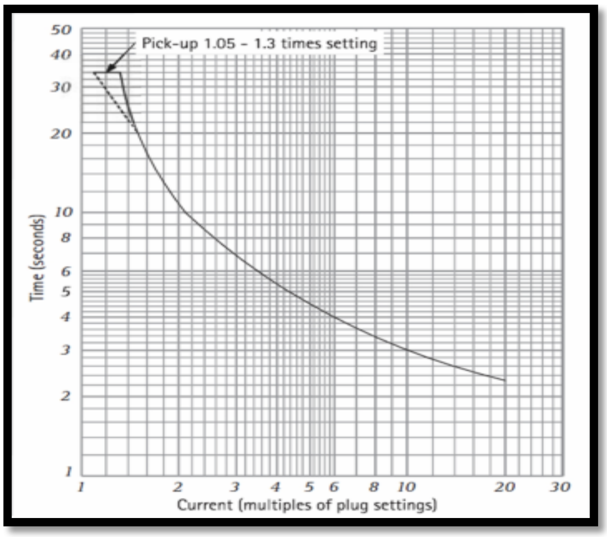

Figure 3. Standard IDMT Relay Characteristics

2.1.4.2 Time Multiplier Setting (TMS)

The time multiplier setting (TMS) parameter controls the distance traversed by the moving contacts before creating any connections for a specific plug setting (PS). The adjustment may be managed by changing the position of the disc backstop, which corresponds to the moving contact. The angle of the moving contact is exactly related to TMS. Most relay designs raise dial positions by 0.05 increments up to the maximum setting of 1.0 [4].

2.1.5 Equations to Determine the Settings of IDMT Relay

According to earlier study, there are two methods that may be used to calculate the parameters of an IDMT relay: mathematical methods and graphical methods. For this paper, we will concentrate on mathematical methods to identify the appropriate parameters.

Five basic equations which were used for calculation of relay settings [3]:

i. $$RSI = CT\ Ratio \times \frac{PS}{100} \quad (2)$$

ii. $$PSM = \frac{FC}{RSI} \quad (3)$$

iii. $$RCOT = \frac{0.14}{(PSM^{0.02} - 1)} \quad (4)$$

iv. $$ROT = RCOT \times TSM \quad (5)$$

v. $$RJOT = RNOT + DT \quad (6)$$

CT	-	Current Transformer
FC	-	Fault Current
DT	-	Discrimination Time Interval
PSM	-	Relay Plug Setting Multiplier
RSI	-	Relay Setting Current
RCOT	-	Relay Characteristic Operating Time
TMS	-	Time Multiplier Setting
ROT	-	Real Relay Operating Time

2.1.6 Power Concepts

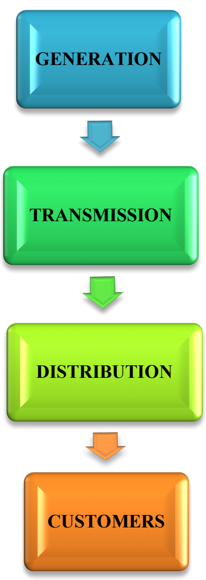

Figure 4. Power System Flow Charts

According to power system flow charts, it shows that most power systems generation having into account the following consideration:

- Electricity is created in massive power plants that are close to the energy source but far from the end customers.
- A huge passive distribution infrastructure comprising of high voltage (HV), medium voltage (MV), and low voltage (LV) networks serves customers.
- Distribution networks are designed to operate in a radial fashion. Electricity only flows in one direction: down from higher voltage levels to consumers through radial feeders.
- Before electricity reaches the end consumer, it must pass through three stages: generation, transmission, and distribution.

2.1.7 Distributed Generation

The term "distributed generation" refers to a tiny generator that generates power from a number of small sources [5]. The power consumption console is usually close to the distributed generation. At the distribution network, distributed generation serves a specific purpose for the power system. It may be used as a load demand provider for consumers, linked into the grid to supply energy to the rest of the electric power system, or utilized in an isolated mode. Distributed generating was installed in a particular location to fulfil the needs of individual consumers and to help the current power distribution system run more efficiently [6]. There are commonly some of distributed generation characteristics are [7]:

- Distributed generation ratings are typically low when compared to conventional power plants.
- Distributed generating is often privately owned.
- Distributed generating is not placed and delivered from a central location.

The majority of DG systems use renewable energy sources, which means lower fuel expenses. However, it produced a significant quantity of pollutants (CO and NOx); others are ecologically friendly but not cost-effective at the moment. Distributed generation may take many forms, including renewable and non-renewable energy sources. The technologies used in distribution generation include, but are not limited to: [8]

- Wind turbines.
- Photovoltaic.
- Induction generators.
- Micro turbines.

2.2 Research Methodology

2.2.1 Introduction

The literature study for this paper started with a focus on both distributed generation (DG) and the IDMT Overcurrent Relay. The fault current was examined both with and without the installation of DG. The project will be simulated using ETAP software to determine the fault current from each bus bar. Then, when the relays were put to the circuit, the ROT was calculated using the PSM and TMS.

2.2.2 Components of ETAP Software

Because multiple components from the simulator will be utilized to construct the circuit design, it is critical to understand each component's role in order to execute the analysis and simulation appropriately. The components listed below will be used:

i. Distributed Generation
ii. Power Grid
iii. Bus Bar
iv. Circuit Breaker

v. Transmission Line Cable
vi. Current Transformer
vii. Overcurrent Relay
viii. Load

2.2.3 Flow Chart Overall Project

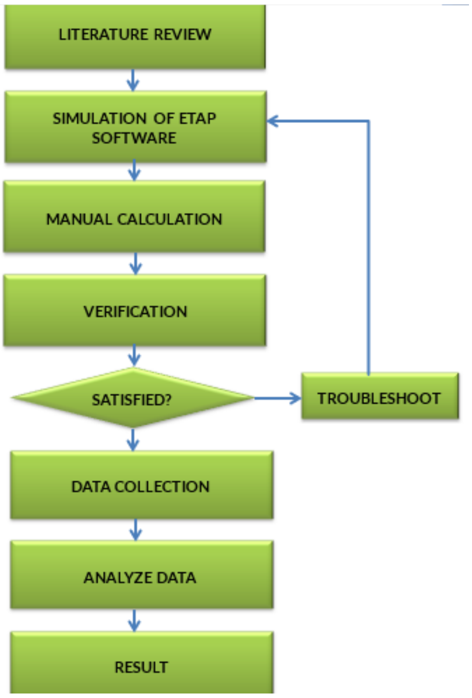

Figure 5. Overall Project Flow Chart

2.2.4 Flow Chart to Determine the IDMT Setting Relays

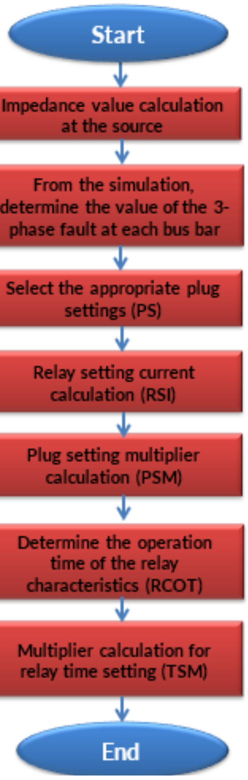

Figure 6. The IDMT Relay Settings are Determined Using a Flow Chart

2.2.5 Circuit Design for 4-Bus System

Figures 7, 8 and 9 consists of three different radial distribution networks: one without distributed generation and two with distributed generation of 5MVA at bus 2 and bus 4 respectively.

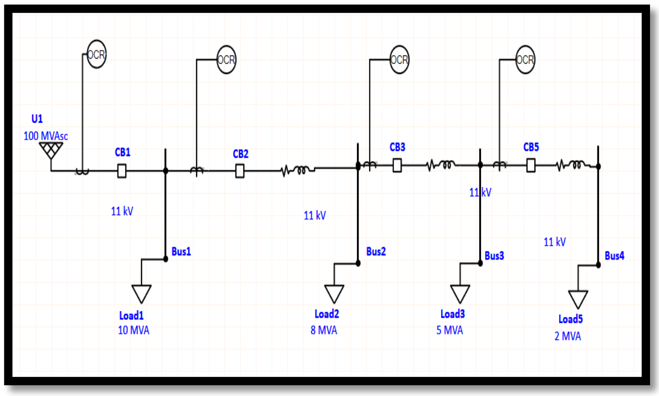

Figure 7: Circuit with no Distributed Generation Installation

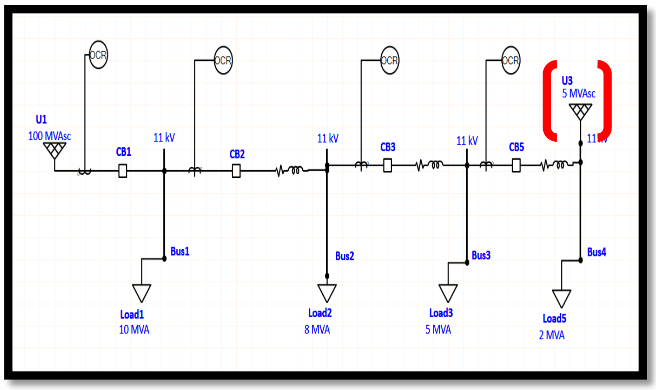

Figure 8. Circuit with Distributed Generation 5MVA Installation at Bus 4

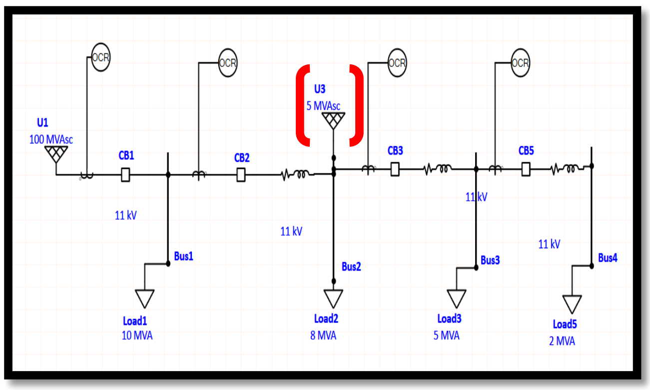

Figure 9. Circuit with Distributed Generation 5MVA Installation at Bus 2

2.2.6 Circuit Design for 14-Bus System

Figures 10, 11 and 12 consists of three different radial distribution networks: one without distributed generation and two with distributed generation of 5MVA and 8MVA at bus 8 and bus 3 respectively.

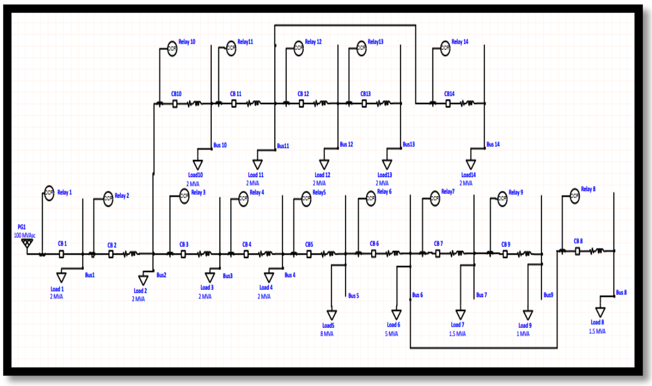

Figure 10. Circuit with no Distributed Generation Installation

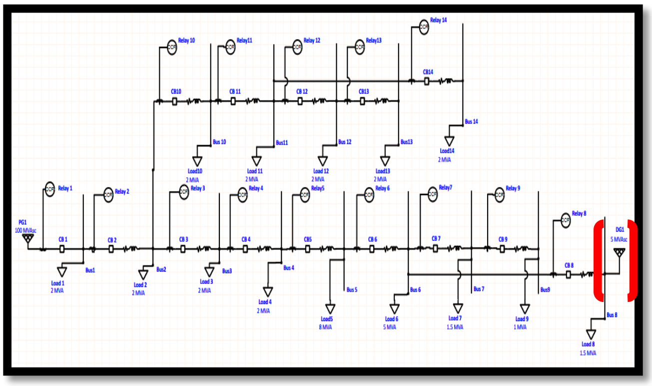

Figure 11: Circuit with Distributed Generation 5MVA Installation at Bus 8

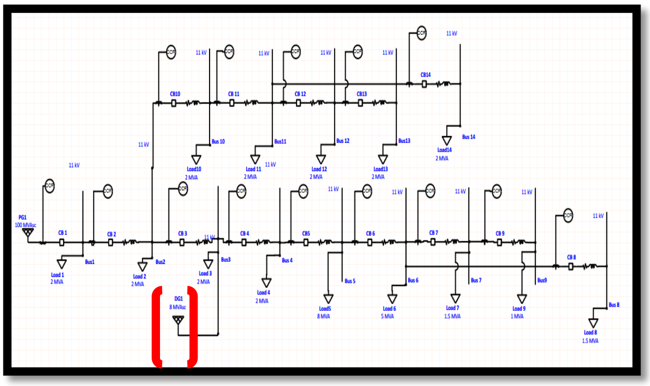

Figure 12: Circuit with Distributed Generation 8MVA Installation at Bus 3

2.2.7 Circuit Design for 31-Bus System

Figures 13, 14 and 15 consists of three different radial distribution networks: one without distributed generation and two with distributed generation of 10MVA at bus 8 and bus 3 respectively.

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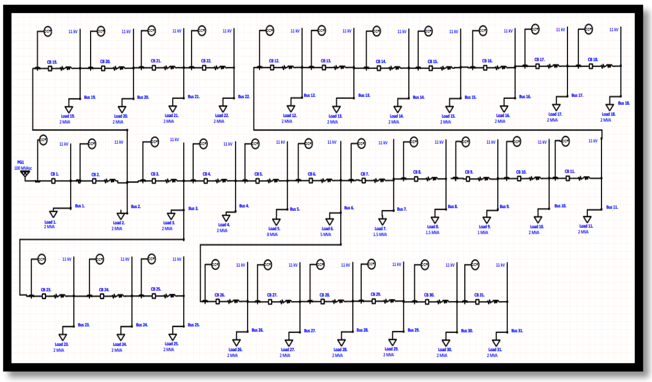

Figure 13. Circuit with no Distributed Generation Installation

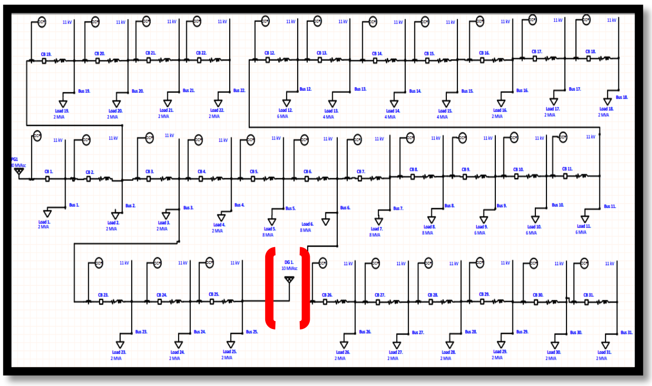

Figure 14. Circuit with Distributed Generation 10MVA Installation at Bus 25

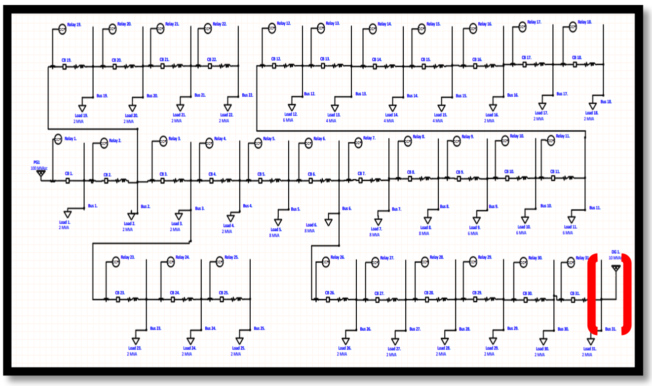

Figure 15: Circuit with Distributed Generation 10MVA Installation at Bus 31

2.3 Result & Analysis

2.3.1 Introduction

The circuit design will be given with the fault current validation using an ETAP simulator. The manual computations for PMS, RCOT, ROT, and TMS were then displayed. Following that, the data will be examined in terms of fault currents and ROT.

2.3.2 *Fault Current Simulated from ETAP Simulator*

Table 1. Result of Fault Current using ETAP Simulator for 4 bus bars

Bus Bar	**Fault Current (A)**				
	Without DG	With 5MVA at Bus 4	With 5MVA at Bus 2	With 8MVA at Bus 4	With 8MVA at Bus 2
1	5249	5488	5502	5609	5644
2	2608	2830	2836	2959	2975
3	2071	2288	2218	2418	2306
4	1456	1670	1532	1804	1575

Table 2. Result of Fault Current using ETAP Simulator for 14 bus bars

Bus Bar	**Fault Current (A)**				
	Without DG	With 5MVA at Bus 3	With 5MVA at Bus 8	With 8MVA at Bus 3	With 8MVA at Bus 8
1	5249	5497	5462	5633	5549
2	2739	2974	2953	3114	3056
3	2162	2389	2372	2529	2479
4	1508	1621	1715	1688	1829
5	1153	1220	1360	1259	1481
6	933	977	1140	1000	1268
7	783	813	927	831	1013
8	783	813	991	831	1127
9	674	697	780	709	841
10	1778	1880	1869	1938	1910
11	1307	1363	1356	1393	1377
12	1032	1066	1062	1085	1075
13	851	874	872	887	880
14	1032	1066	1062	1085	1075

Table 3. Result of Fault Current using ETAP Simulator for 31 bus bars

Bus Bar	**Fault Current (A)**				
	Without DG	With 10MVA at Bus 25	With 10MVA at Bus 31	With 8MVA at Bus 25	With 8MVA at Bus 31
1	5249	5616	5492	5564	5471
2	2739	3138	3020	3072	2989
3	2162	2565	2449	2495	2415
4	1508	1699	1807	1668	1768
5	1153	1263	1466	1246	1422
6	933	1004	1260	933	1211
7	783	832	1004	824	972
8	674	710	833	705	811
9	592	619	711	615	695
10	527	549	620	546	608
11	475	493	550	490	541
12	433	447	494	445	486
13	397	410	448	408	442
14	367	378	410	376	405
15	341	350	378	349	374
16	319	327	351	325	347
17	299	306	327	305	324
18	281	288	306	287	303
19	1778	1942	1892	1916	1880
20	1307	1394	1367	1381	1361
21	1032	1084	1068	1077	1065
22	851	887	876	822	873

23	1508	1922	1643	1845	1628
24	1153	1583	1231	1497	1223
25	933	1379	983	1285	978
26	783	832	1127	824	1072
27	674	710	1038	705	976
28	592	619	977	615	907
29	527	549	935	546	857
30	475	493	908	490	820
31	433	447	890	445	792

2.3.3 Relay Plug Settings Calculation for 4 Bus System

Table 4. Without Installation Distributed Generation for 4 bus-bars

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
1	5249	1250/5	100	1250	1178
2	2608	700/5	100	700	653
3	2070	400/5	100	400	298
4	1458	100/5	100	100	84

Table 5. Installation with DG (5MVA) at Bus 4 for 4 bus-bars

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
1	5488	1000/5	100	1000	840
2	2830	400/5	100	400	315
3	2288	400/5	100	400	320
4	1670	500/5	100	500	425

Table 6. Installation with DG (5MVA) at Bus 2 for 4 bus-bars

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
1	5502	1000/5	75	750	525
2	2836	800/5	100	800	772
3	2218	400/5	100	400	352
4	1532	100/5	100	100	99

2.3.4 Relay Plug Settings Calculation for 14 Bus System

Table 7. Without Installation Distributed Generation for 14 bus-bars

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
5	1153	500/5	100	500	448
6	933	300/5	100	300	225
7	783	100/5	75	75	62
9	674	100/5	25	25	24

Table 8. Installation with DG (8MVA) at Bus 8 for 14 bus-bars

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
5	1481	100/5	50	50	37
6	1268	400/5	100	400	300
7	1013	150/5	100	150	110
9	841	100/5	50	50	44

Table 9. Installation with DG (8MVA) at Bus 3 for 14 bus-bars

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
5	1259	700/5	100	700	615
6	1000	400/5	100	400	310
7	831	100/5	100	100	84
9	709	100/5	50	50	34

2.3.5 Relay Plug Settings Calculation for 31 Bus System

Table 10. Without Installation Distributed Generation for 31 bus-bars

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
6	933	550/5	100	550	508
7	783	300/5	100	300	287
8	674	250/5	100	250	208
9	592	200/5	100	200	148
10	527	150/5	100	150	112
11	475	100/5	100	100	83
12	433	100/5	100	100	60
13	397	50/5	100	50	41
14	367	50/5	75	37.5	30
15	341	50/5	25	12.5	21
16	319	50/5	25	12.5	12
17	299	50/5	25	12.5	8
18	281	50/5	25	12.5	4

Table 11. Installation with DG (10MVA) at Bus 25 for 31 bus-bars

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
6	1004	600/5	100	600	595
7	832	350/5	100	350	336
8	710	300/5	100	300	244
9	619	200/5	100	200	173
10	549	150/5	100	150	131
11	493	150/5	75	112.5	98
12	447	100/5	75	75	71
13	410	100/5	75	75	49
14	378	50/5	75	37.5	36
15	350	50/5	50	25	24
16	327	50/5	50	25	14
17	306	50/5	25	12.5	9
18	288	50/5	25	12.5	5

Table 12. Installation with DG (10MVA) at Bus 31 for 31 bus-bar

Bus Bar	If Max (A)	CT Ratio	PS	RSI (A)	Imax (A)
6	1260	400/5	100	400	297
7	1004	500/5	100	500	463
8	833	400/5	100	400	336
9	711	250/5	100	250	238
10	620	200/5	100	200	181
11	550	150/5	100	150	135
12	494	100/5	100	100	97
13	448	100/5	75	75	67
14	410	100/5	50	50	49
15	378	100/5	50	50	33
16	351	50/5	50	25	19
17	327	50/5	50	25	13
18	306	50/5	50	25	6

2.3.6 IDMT Relay Settings Calculation for 4 Bus System

Fault downstream of Relay 4,

Relay 4 can see 1456 A	Relay 3 can see 1456 A
$RSI = 100 \times \frac{100}{100} = \mathbf{100\ A}$	$RSI = 400 \times \frac{100}{100} = \mathbf{400\ A}$
$PSM = \frac{1458}{100} = \mathbf{14.58}$	$PSM = \frac{1458}{400} = \mathbf{3.645}$
$RCOT = \frac{0.14}{(14.58^{0.02} - 1)} = \mathbf{2.543s}$	$RCOT = \frac{0.14}{(3.645^{0.02} - 1)} = \mathbf{5.343s}$
$ROT = 2.543 \times 0.05 = \mathbf{0.127s}$ (Choose the lowest TSM is 0.05)	$ROT = 0.127 + 0.4 = \mathbf{0.527s}$ (Choose DT = 0.4)
(Choose the lowest TMS is 0.05)	$TMS = \frac{0.527}{5.343} = \mathbf{0.098\ s}$

Fault downstream of Relay 3,

Relay 3 can see 2070 A	Relay 2 can see 2070 A
$RSI = 400 \times \frac{100}{100} = \mathbf{400\ A}$	$RSI = 700 \times \frac{100}{100} = \mathbf{700\ A}$
$PSM = \frac{2070}{400} = \mathbf{5.175s}$	$PSM = \frac{2070}{700} = \mathbf{2.957}$
$RCOT = \frac{0.14}{(5.175^{0.02} - 1)} = \mathbf{4.188s}$	$RCOT = \frac{0.14}{(2.957^{0.02} - 1)} = \mathbf{6.386s}$
$ROT = 4.188 \times 0.098 = \mathbf{0.410s}$	$ROT = 0.410 + 0.4 = \mathbf{0.810s}$ (Choose DT = 0.4) $TMS = \frac{0.810}{6.386} = \mathbf{0.127s}$
$TMS = \mathbf{0.098\ s}$	

Fault downstream of Relay 2,

Relay 2 can see 2608 A	Relay 1 can see 2608 A
$RSI = 700 \times \frac{100}{100} = \mathbf{700\ A}$	$RSI = 1250 \times \frac{100}{100} = \mathbf{1250\ A}$
$PSM = \frac{2608}{700} = \mathbf{3.726}$	$PSM = \frac{2608}{1250} = \mathbf{2.086}$
$RCOT = \frac{0.14}{(3.726^{0.02} - 1)} = \mathbf{5.252s}$	$RCOT = \frac{0.14}{(2.086^{0.02} - 1)} = \mathbf{9.448s}$
$ROT = 5.252 \times 0.127 = \mathbf{0.667s}$	$ROT = 0.667 + 0.4 = \mathbf{1.067s}$ (Choose DT = 0.4) $TMS = \frac{1.067}{9.448} = \mathbf{0.113s}$
$TMS = \mathbf{0.127s}$	

Fault downstream of Relay 1,

Relay 1 can see 5249 A
$RSI = 1250 \times \frac{100}{100} = \mathbf{1250\ A}$
$PSM = \frac{5249}{1250} = 4.199$
$RCOT = \frac{0.14}{(4.199^{0.02} - 1)} = \mathbf{4.808s}$
$ROT = 4.808 \times 0.113 = \mathbf{0.543}$
$TMS = \mathbf{0.113s}$

Table 13. Relay Plug Settings Calculation without DG for 4 bus-bar

Fault Location		Relay 4	Relay 3	Relay 2	Relay 1
4	PSM	14.58	3.645		
	RCOT	2.543	5.343		
	TMS	0.05	0.098		
	ROT	0.127	0.527		
3	PSM		5.175	2.957	
	RCOT		4.188	6.386	
	TMS		0.098	0.127	

	ROT		0.410	0.810	
2	PSM			3.726	2.086
	RCOT			5.252	9.448
	TMS			0.127	0.113
	ROT			0.667	1.067
1	PSM				4.199
	RCOT				4.808
	TMS				0.113
	ROT				0.543

Table 14. Relay Plug Settings Calculation with DG (5MVA) at Bus 4 for 4 bus-bars

Fault Location		**Relay 4**	**Relay 3**	**Relay 2**	**Relay 1**
4	PSM	3.340	4.175		
	RCOT	5.735	4.828		
	TMS	0.05	0.142		
	ROT	0.287	0.687		
3	PSM		5.720	5.720	
	RCOT		3.944	3.944	
	TMS		0.142	0.243	
	ROT		0.560	0.960	
2	PSM			7.075	2.830
	RCOT			3.508	6.659
	TMS			0.243	0.188
	ROT			0.852	1.252
1	PSM				5.488
	RCOT				4.042
	TMS				0.188
	ROT				0.759

Table 15. Relay Plug Settings Calculation with DG (5MVA) at Bus 2 for 4 bus-bars

Fault Location		**Relay 4**	**Relay 3**	**Relay 2**	**Relay 1**
4	PSM	15.32	3.830		
	RCOT	2.496	5.143		
	TMS	0.05	0.102		
	ROT	0.125	0.525		
3	PSM		5.545	2.773	
	RCOT		4.017	6.795	
	TMS		0.102	0.119	
	ROT		0.409	0.809	
2	PSM			3.545	3.781
	RCOT			5.462	5.193
	TMS			0.119	0.202
	ROT			0.649	1.049
1	PSM				7.336
	RCOT				3.443
	TMS				0.202
	ROT				0.695

When a problem occurs, ROT is the minimum clearing time for the overcurrent relay to clear the defective portion. The fault location is isolated quickly enough when the fault occurs when ROT is modified in less than 1 second. The fault current is inversely related to the time to react, according to the IDMT overcurrent relay's characteristic. It indicates that the sooner the fault clears, the larger the fault current (ROT).

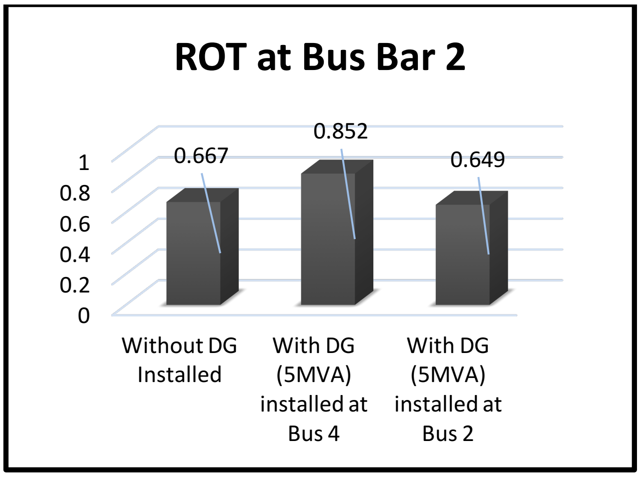

Figure 16. Comparisons of relay operating time at Bus 2 with and without installation DG of 5MVA

PSM range (0.01-10.00), this is because the PSM in relay 4 exceeds the range of the IDMT overcurrent relay. As a consequence, DGs with ratings more than 5MVA are no longer dependable and must be replaced, as must a larger variety of PSM. Another possibility is to install a DG with a maximum rating of 5MVA, ensuring that the IDMT is not overloaded.

When DG was put closer to bus bar 1, the fault current rose on a regular basis. The main power supply or substation is the most costly and crucial component of a radial system. As a result, the DG should be installed as far away from the main power supply and substation as feasible, so that the fault current at the bus bar near it is as modest as possible.

2.3.7 IDMT Relay Settings Calculation for 14 Bus System

Fault downstream of Relay 9,

Relay 9 can see 674 A	Relay 7 can see 674 A
$RSI = 100 \times \frac{25}{100} = \mathbf{25\ A}$	$RSI = 100 \times \frac{75}{100} = \mathbf{75\ A}$
$PSM = \frac{674}{25} = \mathbf{26.96}$	$PSM = \frac{674}{75} = \mathbf{8.987}$
$RCOT = \frac{0.14}{(26.96^{0.02} - 1)} = \mathbf{2.055s}$	$RCOT = \frac{0.14}{(8.987^{0.02} - 1)} = \mathbf{3.118s}$
$ROT = 2.055 \times 0.05 = \mathbf{0.103s}$ (Choose the lowest TSM is 0.05)	$ROT = 0.103 + 0.4 = \mathbf{0.503}$ (Choose DT = 0.4)
	$TMS = \frac{0.503}{3.118} = 0.161$

Fault downstream of Relay 7,

Relay 7 can see 783 A

$$RSI = 100 \times \frac{75}{100} = \mathbf{75\ A}$$

$$PSM = \frac{783}{75} = \mathbf{10.44}$$

$$RCOT = \frac{0.14}{(10.44^{0.02} - 1)} = \mathbf{2.91s}$$

$$ROT = 2.91 \times 0.161 = \mathbf{0.468s}$$

$$TMS = \mathbf{0.161s}$$

Relay 6 can see 783 A

$$RSI = 300 \times \frac{100}{100} = \mathbf{300\ A}$$

$$PSM = \frac{783}{300} = \mathbf{2.61}$$

$$RCOT = \frac{0.14}{(2.61^{0.02} - 1)} = \mathbf{7.227}$$

$$ROT = 0.468 + 0.4 = \mathbf{0.868s}$$

(Choose DT = 0.4)

$$TMS = \frac{0.868}{7.227} = \mathbf{0.12s}$$

Fault downstream of Relay 6,

Relay 6 can see 933 A

$$RSI = 300 \times \frac{100}{100} = \mathbf{300\ A}$$

$$PSM = \frac{933}{300} = \mathbf{3.11}$$

$$RCOT = \frac{0.14}{(3.11^{0.02} - 1)} = \mathbf{6.099s}$$

$$ROT = 6.099 \times 0.12 = \mathbf{0.732s}$$

$$TMS = \mathbf{0.12s}$$

Relay 5 can see 933 A

$$RSI = 500 \times \frac{100}{100} = \mathbf{500\ A}$$

$$PSM = \frac{933}{500} = \mathbf{1.866}$$

$$RCOT = \frac{0.14}{(1.866^{0.02} - 1)} = \mathbf{11.15s}$$

$$ROT = 0.732 + 0.4 = \mathbf{1.132s}$$

(Choose DT = 0.4)

$$TMS = \frac{1.132}{11.15} = \mathbf{0.102s}$$

Fault downstream of Relay 5,

Relay 5 can see 1153 A

$$RSI = 500 \times \frac{100}{100} = \mathbf{500\ A}$$

$$PSM = \frac{1153}{500} = \mathbf{2.306}$$

$$RCOT = \frac{0.14}{(2.306^{0.02} - 1)} = \mathbf{8.308s}$$

$$ROT = 8.308 \times 0.102 = \mathbf{0.847s}$$

$$TMS = \mathbf{0.102s}$$

Table 16. Relay Plug Settings Calculation without DG for 14 bus-bars

Fault Location		Relay 9	Relay 7	Relay 6	Relay 5
9	PSM	26.96	8.987		
	RCOT	2.055	3.118		
	TMS	0.05	0.161		
	ROT	0.103	0.503		
7	PSM		10.44	2.610	
	RCOT		2.91	7.227	
	TMS		0.161	0.120	
	ROT		0.468	0.868	
6	PSM			3.110	1.866
	RCOT			6.099	11.15
	TMS			0.120	0.102
	ROT			0.732	1.132
5	PSM				2.306
	RCOT				8.308
	TMS				0.102
	ROT				0.847

Table 17. Relay Plug Settings Calculation with DG (8MVA) at Bus 8 for 14 bus-bars

Fault Location		Relay 9	Relay 7	Relay 6	Relay 5
9	PSM	16.82	5.607		
	RCOT	2.411	3.991		
	TMS	0.05	0.131		
	ROT	0.121	0.521		
7	PSM		6.753	2.533	
	RCOT		3.595	7.464	
	TMS		0.131	0.117	
	ROT		0.471	0.871	
6	PSM			3.170	25.36
	RCOT			5.998	2.096
	TMS			0.117	0.526
	ROT			0.702	1.102
5	PSM				29.62
	RCOT				1.997
	TMS				0.526
	ROT				1.050

Table 18. Relay Plug Settings Calculation with DG (8MVA) at Bus 3 for 14 bus-bars

Fault Location		Relay 9	Relay 7	Relay 6	Relay 5
9	PSM	14.18	7.090		
	RCOT	2.570	3.504		
	TMS	0.05	0.151		
	ROT	0.129	0.529		
7	PSM		8.310	2.077	
	RCOT		3.236	9.504	
	TMS		0.151	0.093	
	ROT		0.488	0.888	
6	PSM			2.500	1.428
	RCOT			7.569	19.55
	TMS			0.093	0.056
	ROT			0.704	1.104
5	PSM				1.798
	RCOT				11.85
	TMS				0.056
	ROT				0.664

2.3.7.1 Over-Reaching of Downstream IDMT Relay

A case study where distributed generation 5MVA is introduced at Bus 3 may be utilized to show how distributed generation might cause a relay to over-reach. Figure below shows the relay operating time(s) versus bus-bars relay for case without DG and DG at Bus 3.

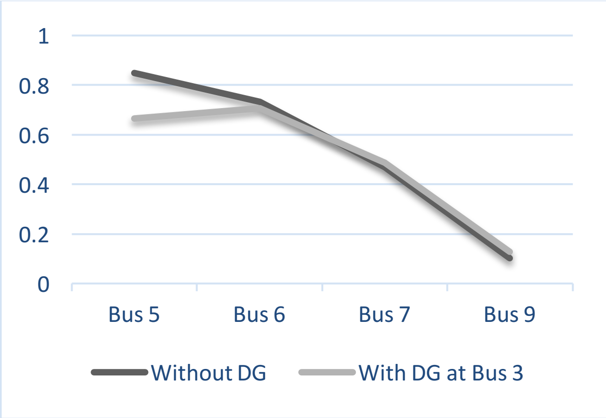

Figure 17. Relay Operating Time(s) versus busbar relay for case without DG and DG at Bus 3

According to figure above, the downstream IDMT relay operating time for the distribution system with DG connected at Bus 3 seems to function quicker (with shorter tripping time) than the distribution system without DG.

2.3.7.2 Under-Reaching of Upstream IDMT Relay

Distributed generation may cause previously appropriate relay settings to under-reach, depending on its location, capacity, and the strength of the network to which it is linked. A case study of a 5MVA DG connected to bus 8 of the radial distribution system is used to demonstrate this. Figure below shows the relay operating time (s) versus bus-bar relay for case without DG and DG at Bus 8.

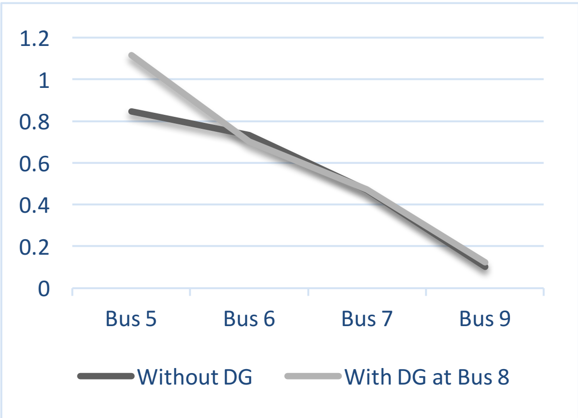

Figure 18: Relay Operating Time(s) versus busbar relay for case without DG and DG at Bus 8

According to figure above, for the situation with DG at Bus 8, relays 6, 7, and 9 have a quicker tripping time than the case without DG, as described in the preceding section discussing the over-reach phenomenon. However, relay 5, the upstream IDMT relay for the distribution system with DG coupled to Bus 8, seems to trip on a three-phase balanced fault at bus-bar 9 longer than without DG. Relay 5 should work quicker than its sibling, according to the trend, but the results show otherwise.

2.3.8 IDMT Relay Settings Calculation for 31 Bus System

Table 19. Relay Plug Settings Calculation without DG for 31 bus-bars

Fault Location		**Relay 18**	**Relay 17**	**Relay 16**	**Relay 15**
18	PSM	21	21		
	RCOT	2.229	2.229		
	TMS	0.05	0.229		
	ROT	0.111	0.511		
17	PSM		21	21	
	RCOT		2.229	2.229	
	TMS		0.229	0.409	
	ROT		0.511	0.911	
16	PSM			21	21
	RCOT			2.229	2.229
	TMS			0.408	0.587
	ROT			0.909	1.309
15	PSM				21
	RCOT				2.229
	TMS				0.487
	ROT				1.309

Table 20. Relay Plug Settings Calculation with DG (10MVA) at Bus 25 for 31 bus-bars

Fault Location		**Relay 18**	**Relay 17**	**Relay 16**	**Relay 15**
18	PSM	21	21		
	RCOT	2.229	2.229		
	TMS	0.05	0.229		
	ROT	0.111	0.511		
17	PSM		21	12.24	
	RCOT		2.229	2.725	
	TMS		0.229	0.334	
	ROT		0.511	0.911	
16	PSM			13.08	13.08
	RCOT			2.653	2.653
	TMS			0.334	0.485
	ROT			0.886	1.286
15	PSM				14
	RCOT				2.583
	TMS				0.485
	ROT				1.253

Table 21. Relay Plug Settings Calculation with DG (10MVA) at Bus 31 for 31 bus-bars

Fault Location		**Relay 18**	**Relay 17**	**Relay 16**	**Relay 15**
18	PSM	12.24	12.24		
	RCOT	2.725	2.725		
	TMS	0.05	0.197		
	ROT	0.136	0.536		
17	PSM		13.08	13.08	
	RCOT		2.653	2.653	
	TMS		0.197	0.348	
	ROT		0.523	0.923	
16	PSM			14.04	7.02
	RCOT			2.580	3.522
	TMS			0.348	0.369
	ROT			0.898	1.298
15	PSM				7.56
	RCOT				3.391
	TMS				0.369
	ROT				1.251

3. CONCLUSION

Overall, it can be said that this paper's objectives have been attained. The main protective mechanisms in a distribution system are overcurrent relays. Relays in the electrical system must be appropriately coordinated in order to offer both main and backup protection while also preventing malfunction, which could cause an unnecessarily long system outage. Therefore, it is crucial to do an analysis prior to installing the DG. After the installation of DG, the value of fault current at each bus bar were spiked. The position of DG also plays an important role in order to protect the power supply. They should be located as far as possible from power supply. Next, it is proved that when DG were installed, the relay will operate faster (ROT decreased) when fault current increased. Finally, I'd like to stress that a thorough analysis of the influence on the protection system before and after DG installation is necessary to decide if a protection system update is necessary.

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