Adaptive Protection of Micro-Grid

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Abstract

The present situation in the power system network is to realize more number of distributed energy sources. These increased distributed generators in the distribution network are causing specialized issues such as power quality, power energy balance, and protection, etc. However, the protection of micro-grid is most important. Local generation in a combination with a possible islanded activity can pose protection sensitivity and selectivity issues in case of fault clearing depend upon the relay settings. This paper focuses on novel adaptive microgrid protection systems using Numerical relay and advanced communication. The protection system is based on a centralized architecture where relay protection settings are modified centrally concerning a micro-grid operating condition.

Keywords -- *Distribution Generation, Fault Analysis, Micro-grid, P441 Numerical Relay*

I. INTRODUCTION

A microgrid is a gathering of interconnected loads and distributed energy resources within clearly defined electrical limits that act as a single controllable entity concerning the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode [1].

Distributed Generators (DGs) are small generating units installed near load centers at sub-transmission level to satisfy the customer's need. Their capacities change from kilowatts to Megawatts. A portion of the prevalently utilized DGs is wind turbines, microturbines, gas turbines, internal combustion engines, and photo-voltaic [3]. DGs have focal points such as an increase in the overall energy efficiency of the distribution network, enhanced system reliability, improved power quality, and security.

Micro-grid protection is needed to manage the impact caused by the traditional distribution system by integrating the micro-grid and meeting the requirement for protection brought by an islanded operation. The incorporation of various DGs and Energy Storage (ES) changes the fault characteristics of the distribution system and makes the variation of electrical variables very complicated in the case of a fault. The traditional protection principles and fault detection methods may fail to correctly locate the fault. Appropriate activity and protection strategies are the keys to the reliable activity of the DG system [2]. As the micro-grid is proposed for grid-connected activity and islanded operation, its protection and control are very complicated. There are two fundamental issues the micro-grid has to address concerning its protection. Initially, the determination of the time when it should be islanded from the main grid. Lastly, the provision of a properly coordinated and reliable protection system so that it can reliably trip in the event of a fault within it.

Numerical relays are otherwise called Intelligent Electronic Devices (IED) that is utilized for a wide variety of applications like transformer protection, transmission line protection, bay control, feeder protection, etc. The GE MiCOM series of numerical relays are gaining importance due to their user-friendliness and free software and for relay settings [14]. These relays are used in the power system industry for the protection of transmission lines up to 400kV. The P441 relay can protect the line using various schemes like over-current, over-voltage, earth fault protection, distance protection, and synchro check. The P441 relay is used to implement an over current protection scheme for Distribution lines. Over current protection has been an important protection scheme for distribution protection against short circuit faults.

The organization of this paper is as follows: Section II outlines the protection issues of micro-grid, Section III explains the Adaptive protection of micro-grid, Section IV explains the Simulation results, and followed by conclusion and references.

II. PROTECTION ISSUES OF MICRO-GRID

Protection is the most crucial challenge for MGs because it refers to both modes of operation. Fault current magnitude in a system depends on the MG operation mode and changes considerably between grid connected and autonomous operations. Therefore, MGs require a protection scheme to prevent faults, such as short circuits, which may harm components and consumer equipment. Protective relays have to be installed in power systems to detect abnormal conditions automatically and initiate circuit breakers to isolate faults. Protection schemes that change relay settings online to ensure that the MG system is protected have been proposed. When the fault current is below the load current, some relays may not trip, while others react to a fault with a time delay. The potential unnoticed fault current could spread out into the system and damage equipment. Expansion of the traditional over current protection techniques is relevant [5].

Protection issues of micro-grid, when it is grid connected mode and islanded mode of operation are as follows:

A. Events or Faults during Grid Connected Mode

For a fault within the micro-grid, the response of line or feeder protection must be to disconnect the faulty portion from the rest of the system as quickly as possible and how it is done depends on the features and complexity of the micro-grid and the protection strategy is used. There may be some non-fault cases that are resulting in low voltages at PCC like voltage unbalance and non-fault open phases which are difficult to be detected and it may create hazards for sensitive loads, micro-sources, etc [6]. Therefore, some protection mechanisms must be developed to avoid such situations.

B. Events or Faults during Islanded Mode

The nature of the problem is different in islanded mode than the grid connected mode. In grid connected mode, the fault currents of higher magnitude (10-50 times the full load current) are available from the utility grid for activating conventional OC protection devices. For the islanded mode of micro-grid, the fault current is five times the full load current. The conventional OC protection devices are usually set at (2-10 times the full load current) [7]. Hence, due to this drastic reduction in fault level, the time-current coordination of OC protective devices is distributed, the high set instantaneous OC devices and extremely inverse characteristics OC devices like fuses are most likely to be affected.

III. ADAPTIVE PROTECTION OF MICRO-GRID:

This section illustrates an adaptive protection system that can potentially solve problems identified in the previous section by anticipating an impact of micro-sources (DERs) and micro-grid configuration on the relay performance and accordingly change the relay settings to ensure that the whole micro-grid is protected at all times. Adaptive protection is as "an online activity that modifies the preferred protective response to a change in system conditions or requirements promptly through externally generated signals or control action" [8]. Technical requirements and suggestions for the practical implementation of an adaptive micro-grid protection system are as following:

- Use of numerical directional OC relays because fuses or electro-mechanical and standard solid-state relays are (especially for selectivity holding) inapplicable - they do not provide the flexibility for changing the settings of tripping characteristics and they have no current direction sensitivity feature.
- Numerical directional OC relays must dispose of the possibility of using different tripping characteristics (several settings groups) that can be parameterized locally or remotely automatically or manually.

A. System Description and Methodology

The proposed algorithm is tested on the 5 bus system, and case studies considering DG connected in bus 4 location of the grid structure are evaluated for section-4 fault location [9].
The 5 bus radial distribution test system without DG is shown in Fig1. The source voltage is 46.7V. The relevant data for the test system are presented in Table 1.

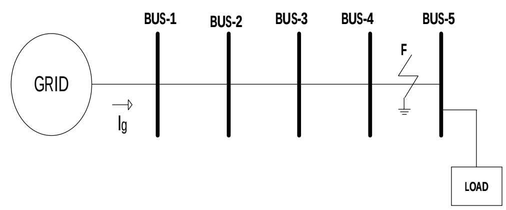


Fig 1: 5-Bus radial distribution system without DG

TABLE I
Distribution line data

Bus	R (ohms)	XL (ohms)	Load (W)
1-2	1.5	9.42	-
2-3	1.5	9.42	-
3-4	1.5	9.42	-
4-5	1.5	9.42	100

The 5 bus radial distribution test system with DG is shown in Fig2. The source voltage is 46.7V. The relevant data for the test system are presented in Table 1.

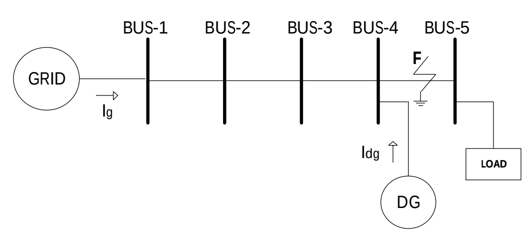


Fig 2: 5-Bus radial distribution system with DG

It should be noted that the DG unit is connected at 4 Bus. The generator type of DG plant is considered a synchronous machine. The capacity of the DG is 25W. The modified test system is subjected to the bi-directional power flow; directional over-current protection is used against the fault current that could circulate in both directions through the system. When the DG plant is connected to the grid, there are multiple local generating sources [10]. Hence, the nature of the distribution system changes with DG plants. Consequently, directional overcurrent relays (DOCRs) along the line are required in the system, and they should be placed along the line that links the grid with the DG.

The tripping of relays is provided using a time delay where the relay located at the furthest point from the source is tripped in the shortest time. The consecutive relays to the direction of the source are then tripped with greater time delays regarding the general selectivity concept. The characteristic curves for the relay operations are defined as follows:

$$Standard\ inverse\ (SI),$$

$$t = TMS * \frac{0.14}{[(\frac{I_f}{I_s})^{0.02} - 1]} \qquad (1)$$

$$Very\ inverse\ (VI),$$

$$t = TMS * \frac{13.5}{\left[\left(\frac{I_f}{I_s}\right) - 1\right]} \qquad (2)$$

$$Extreme\ inverse\ (EI),$$

$$t = TMS * \frac{80}{[(\frac{I_f}{I_s})^2 - 1]} \qquad (3)$$

$$Long\ time\ inverse,$$

$$t = TMS * \frac{120}{\left[\left(\frac{I_f}{I_s}\right) - 1\right]} \qquad (4)$$

Where Time Multiplier Setting (TMS) is the relevant set point for relay coordination, t is the operating time of relay, I_s is the pickup current of the relay, and I_f is the fault current. It should be noted that the pickup currents are normally set above the maximum load current.

Our studies have shown that only a few iterations were required for the solution of distribution networks using this power flow solution technique. For the weakly meshed transmission networks, the number of iterations was higher, due to the additional nonlinearities introduced by generator buses (PV nodes). The forward/backward sweep power flow technique was significantly more efficient than the Newton-Raphson power flow algorithm while converging to the same solution.

The solution method used for radial distribution networks is based on the direct application of the KVL and KCL. For our implementation, we developed a node and branch oriented approaches using an efficient numbering scheme to enhance the numerical performance of the solution method.

1) *Nodal current calculation*

A Nodal current calculation is defined as the required current by every single load installed in each node. For obtaining the current through the branches, a calculation can be performed with (5), where j is the node numeration and k is the iteration.

$$I_j^{(k)} = \frac{P_{Lj} + jQ_{Lj}}{V_j^{(k-1)}} \qquad (5)$$

2) *Backward sweep*

With the nodal current injection, it is possible to know the current flowing for each branch of the distribution network by applying (6). (6) Refers to the current flowing in a branch connected from node m to several downstream nodes n that could have loads. This process is made from the final nodes back to the feeder. In these equations, Imn is the current flowing from node m to node n. It is the current injected to the load at node n.

$$I_{mn}^{(k)} = I_n^{(k)} + \sum of\ all\ currents\ of\ branch\ emanted\ from\ bus \qquad (6)$$

3) *Forward sweep*

With the forward step, it is possible to update the voltages in each node of the system. This equation allows identifying the voltage profile while the branch currents are updated in the above step as the voltage drop depends on the branch impedance and the current flowing on the branch. Node voltages are updated by using the general (7). This process starts from the first node toward the final nodes.

$$V_n^{(k)} = V_m^{(k)} - Zmn * I_{mn}^{(k)} \qquad (7)$$

The algorithm to ensure the adaptive relay settings in the 5-Bus system with DG is depicted in Fig 2. The algorithm is explained step-by-step as follows [11]:

Step 1 The inputs required by the algorithm are introduced.

Step 2 The measurement of the currents of the grid and DG plant is realized. These measurements are then used for the calculations performed in Step3 for the grid and DG plant.

Step 3 This step consists of two separate parts. In the first part, the general calculations related to the DG are performed. These calculations start with the determination of buses Voltage where DG is connected. Then, the observation of the active or passive state of the DG plant is identified by observing if the mentioned DG injects current to the system or not. If yes, the DG is considered to be active in the relevant time period; else, the contrary holds. Lastly, calculations of impedances between the active DG plant and each bus in the system are performed. For the main grid calculations, the impedances between each bus of the system are calculated.

Step 4 The calculations of total possible short circuit currents in both directions in each line are performed in this step.

Step 5 The analysis of the fact of whether or not the main grid is available is realized in this step. If the main grid is available, then the adaptive relay settings are realized for grid-connected mode. If not, the mentioned calculations are provided for islanded mode operation.

Step6 This step also consists of two steps depending on the operating status of the system that is identified in Step5. If the system is in grid-connected mode, firstly, the standard TMS value is assigned for the relay that is connected to the most remote location for the point of the common coupling of the DG. Then, the selectivity-based calculations of the relay are performed using Equation (1). For the nodal points, the tripping times of the relay on the lines connected to the node are compared, and the greatest tripping time among them is selected. A similar calculation is realized for the islanded mode, but this time from the relay that is connected at the closest location concerning the point of common coupling of the DG to the relay that is connected to the most remote location.

Step 7 In this step, the TMS values are dynamically updated for the current time period, and then, the algorithm continues for the next time period.

III. RESULTS

This section shows two scenarios about a micro-grid configuration and the status of DG. Firstly, micro-grid without DG in the grid connected mode. Secondly, micro-grid with DG (synchronous machines) in the grid connected.

A. Micro-Grid Without DG

A distribution network is used in the simulation studies are presented here. It consists of four sections of distribution line, five buses, and one load. The nominal power frequency is 50Hz. The currents in the system are measured using instantaneous current measurements. The steady-state value of current and voltage are 0.78A and 37V at grid side. The system is simulated for different fault conditions using the MATLAB / Simulink software.

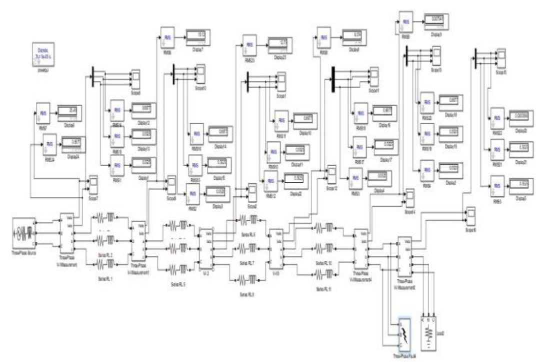


Fig 3: Distributed network simulated diagram without DG

a) Line-Ground fault at section four

A single line-to-ground fault on a distribution line occurs when one conductor drops to the ground or comes in contact with the neutral conductor. When the single line to ground fault occurs in the line. The voltage value is decreased and the current value is increased i.e., 0.6A to 1.12A. The time period of the fault is 1sec to 1.5sec after that the line is steady-state condition.

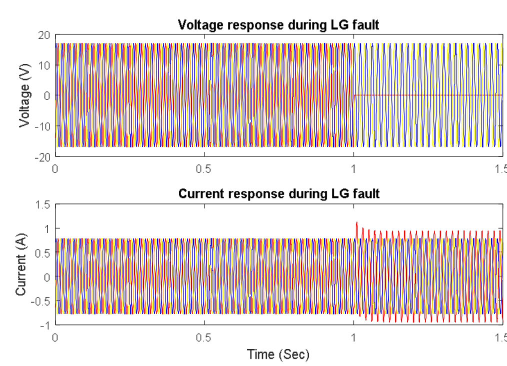


Fig 4: Voltage and Current waveform during Line-Ground Fault.

b) Line-Line-Ground fault at section four

A Double line to ground fault is one where short-circuiting occurs between two phases along with the earth at the same time. When the line-line-ground fault occurs in the distribution line section four. The voltage value is decreased and the current value is increased i.e., 0.7A to 1.21A. The time period of the fault is 1sec to 1.5sec after that the line is steady-state condition.

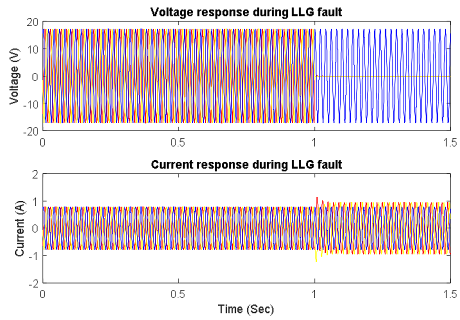


Fig 5: Voltage and Current waveform during Line-Line-Ground Fault.

c) Line-Line-Line fault at section four

An LLL fault or symmetrical fault occurs when two conductors are short-circuited. When the LLL fault occurs in the line. The voltage value is decreased and the current value is increased i.e., 0.6A to 1.23A. The time period of the fault is 1sec to 1.5sec after that the line is steady-state condition.

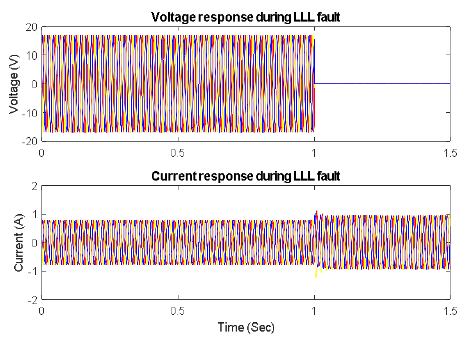


Fig 6: Voltage and Current waveform during Line-Line-Line Fault.

d) Line-Line-Line-Ground fault at section four

A triple line-to-ground fault occurs when three conductors fall on the ground or come in contact with the neutral conductor. When the LLLG occurs in the distribution line section four. The voltage value is slightly decreased to the normal value and the current value is increased i.e., 0.6A to 1.26A. The time period of the fault is 1sec to 1.5sec after that the line is steady-state condition.

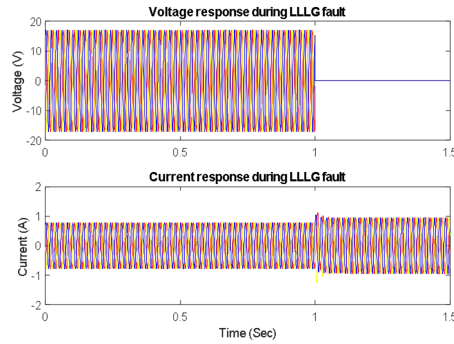
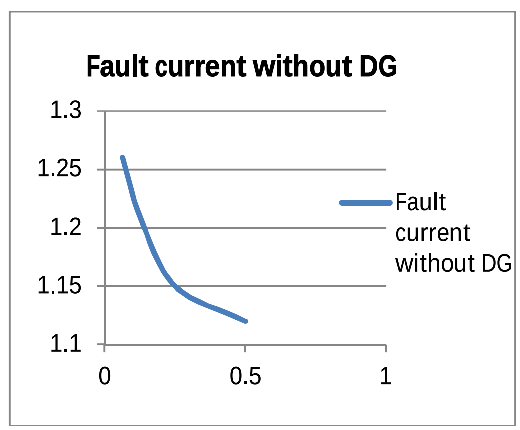


Fig 7: Voltage and Current waveform Line-Line-Line-Ground Fault.

TABLE II
Without DG fault current

With out DG	Fault current at each phase	LG	LLG	LLL	LLL G
	Ia	1.12	1.21	1.23	1.26
	Ib	0.78	1.22	1.23	1.24
	Ic	0.78	0.78	1.22	1.24

INVERSE CHARACTERISTIC OF OVERCURRENT RELAY SETTINGS OF THE RELAY



B. Micro-Grid With DG

A distribution network is used in the simulation studies are presented here. It consists of four sections of the distribution line, five buses, and one load. The nominal power frequency is 50Hz. The DG unit is connected at 4 Bus. The generator type of DG plant is considered a synchronous machine. The capacity of the DG is 25W. The currents in the system are measured using instantaneous current measurements. The steady-state values of current, voltage, and power as shown in table 3. The system is simulated for different fault conditions using the MATLAB / Simulink software.

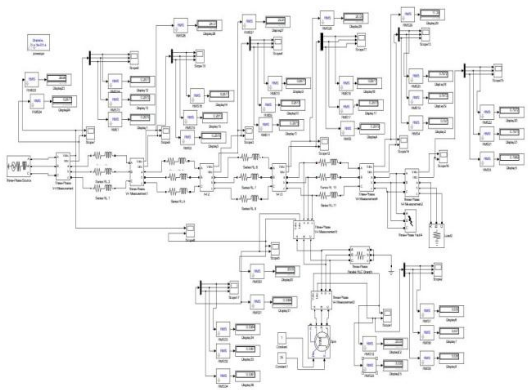


Fig 8: Distributed network simulated diagram with DG

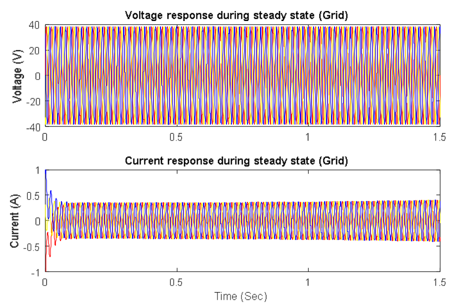


Fig 9: Voltage and Current waveform without fault at Grid

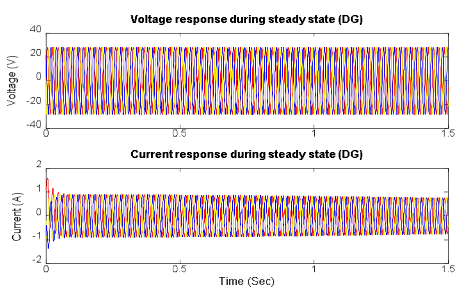


Fig 10: Voltage and Current waveform without fault at DG

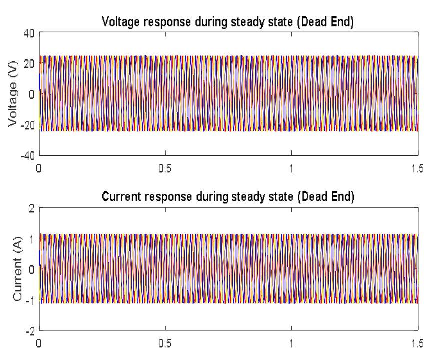


Fig 11: Voltage and Current waveform without fault at Section-4

TABLE III
Steady State Values of the system

Steady State Value		**Grid value**	**DG value**	**Section-4**
	Current (A)	0.39	0.74	1.13
	Voltage (V)	38.1	28.35	28.2

a) Line-Ground fault at section four

A single line-to-ground fault on a distribution line occurs when one conductor drops to the ground or comes in contact with the neutral conductor. When the single line to ground fault occurs in the section-4. The grid current is 0.41A because it has high resistance and the DG current is 2.58A. it has low resistance to the fault location. The total fault current at section-4 is 2.92A. The time period of the fault is 1sec to 1.5sec after that the line is steady-state condition.

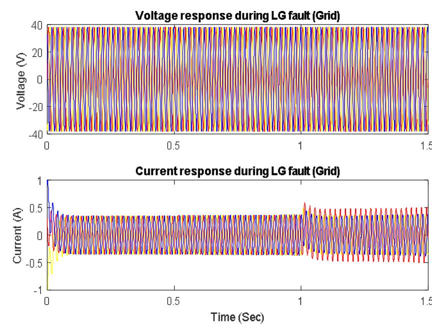


Fig 12: Voltage and Current waveform during L-G fault at Grid

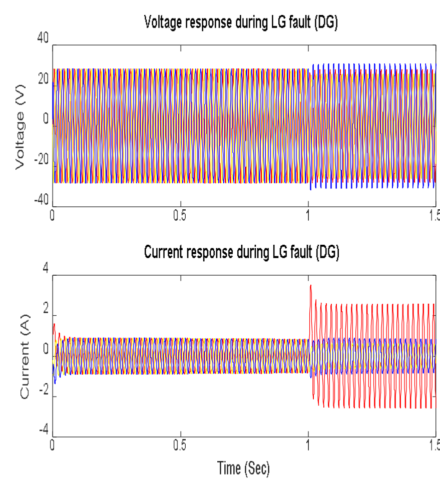


Fig 13: Voltage and Current waveform during L-G fault at DG

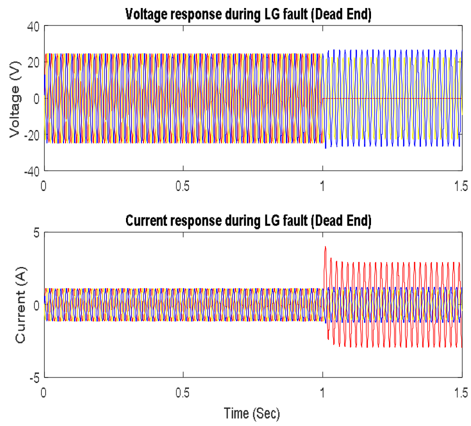


Fig 14: Voltage and Current waveform during L-G fault at Section-4.

b) Line-Line-Ground fault at section four

A Double line to ground fault is one where short-circuiting occurs between two phases along with the earth at the same time. When the line-line-ground fault occurs in the distribution line section four. The grid current is 0.42A because it has high resistance and the DG current is 2.60A. It has low resistance to the fault location. The total fault current at section-4 is 2.99A. The time period of the fault is 1sec to 1.5sec after that the line is steady-state condition.

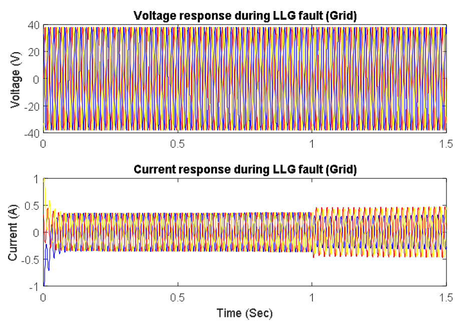


Fig 15: Voltage and Current waveform during L-L-G fault at Grid

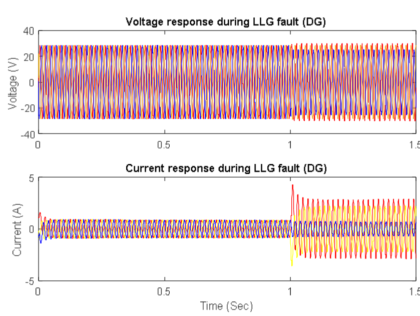


Fig 16: Voltage and Current waveform during L-L-G fault at DG

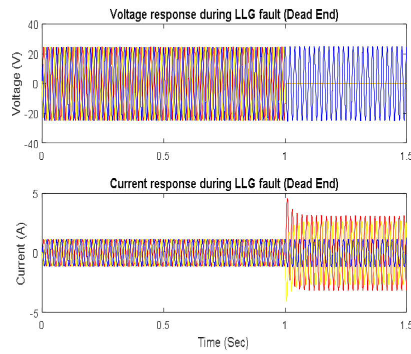


Fig 17: Voltage and Current waveform during L-L-G fault at Section-4.

c) Line-Line-Line fault at section four

An LLL fault or symmetrical fault occurs when two conductors are short-circuited. When the LLL fault occurs in the line. The grid current is 0.43A because it has high resistance and the DG current is 2.62A. It has low resistance to the fault location. The total fault current at section-4 is 3.05A. The time period of the fault is 1sec to 1.5sec after that the line is steady-state condition.

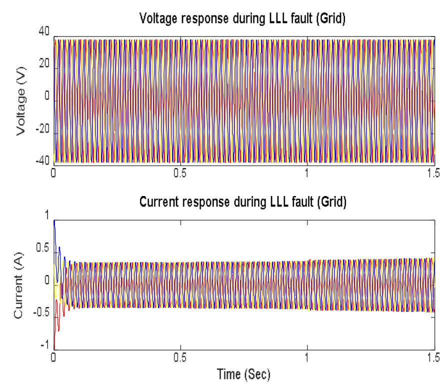


Fig 18: Voltage and Current waveform during L-L-L fault at Grid

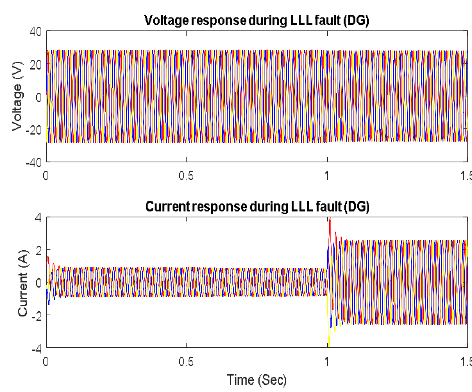


Fig 19: Voltage and Current waveform during L-L-L fault at DG

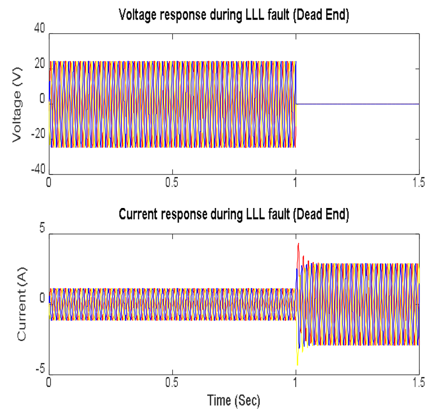


Fig 20: Voltage and Current waveform during L-L-L fault at Section-4.

d) Line-Line-Line-Ground fault at section four

A triple line-to-ground fault occurs when three conductors fall on the ground or come in contact with the neutral conductor. When the LLLG occurs in the distribution line section four. The grid current is 0.41A because it has high resistance and the DG current is 2.68A. It has low resistance to the fault location. The total fault current at section-4 is 3.08A. The time period of the fault is 1sec to 1.5sec after that the line is steady-state condition.

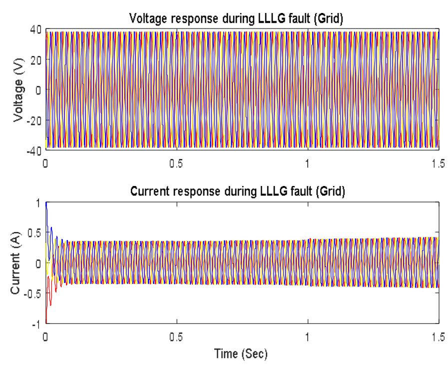


Fig 21: Voltage and Current waveform during L-L-L-G fault at Grid

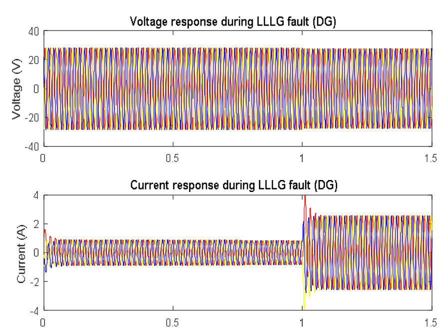


Fig 22: Voltage and Current waveform during L-L-L-G fault at DG

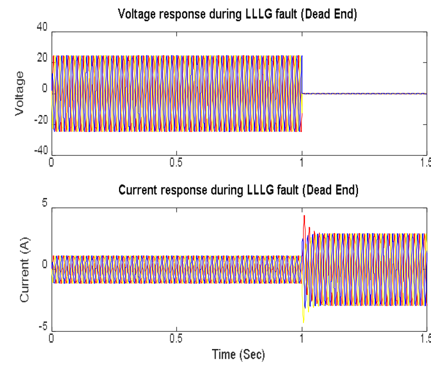
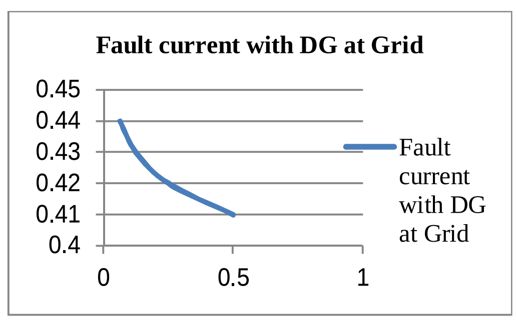


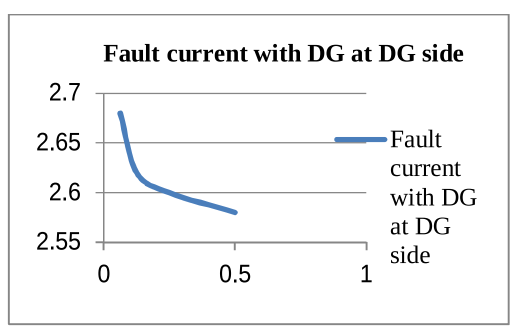
Fig 23: Voltage and Current waveform during L-L-L-G fault at Section-4.

TABLE IV
With DG fault currents

	Fault current at each phase	LG	LLG	LLL	LLLG
Grid Currents	Ia	0.41	0.42	0.43	0.44
	Ib	0.39	0.42	0.43	0.44
	Ic	0.39	0.39	0.43	0.44
DG Currents	Ia	2.58	2.60	2.62	2.68
	Ib	0.74	2.60	2.62	2.68
	Ic	0.74	0.74	2.62	2.68
Section -4	Ia	2.92	2.98	3.05	3.08
	Ib	1.13	2.99	3.05	3.08
	Ic	1.13	1.13	3.05	3.8

INVERSE CHARACTERISTIC OF OVERCURRENT RELAY SETTINGS OF THE RELAY (With DG)





C. Hardware Implementation in P441 Numerical relay

The distribution line model in the power system lab of the EEE department in VRSEC can simulate a 100 km length Distribution line. The transmission line is modeled as pi – network with four sections, each section represents a 25km transmission line or 25% length of the total length of the line. The parameters of each section i.e. for 25km are modeled as R=1.5 ohms, L=30 mH, C=1μF. P1, N1 is the sending end terminals of the distribution line, and P8, N2 is the receiving end terminals of the distribution line.

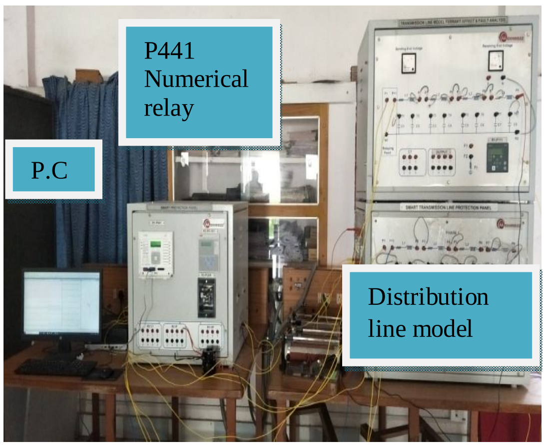


Fig 24: Practical Implementation in P441 Numerical Relay.

The Distribution line model is fed by a source of 50V AC and Single Line to Ground fault is created in the distribution line model, measurements are made using a metering facility in the P441 relay. The P441 relay is connected to a PC with Micom Agile software via USB cable and communication is established. Different type of faults is created in the distribution line and the response of the relay is observed in the LED display of the relay. The voltage and current values as seen by the relay metering displayed.

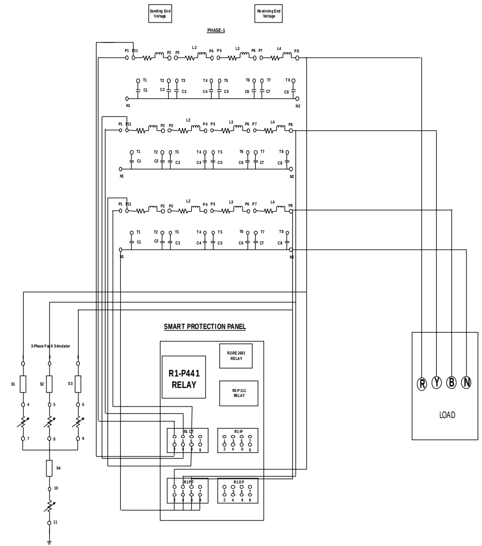


Fig 25: Connection diagram

a) Line-Ground fault at section four

For a Line to Ground Fault (L-G), any one of M.C.B's S_r, S_y, and S_b(only anyone based on fault condition simulation), here S_r switch is on. Along with ground M.C.B S_g is turned on for SLG fault study. The current value is increased to 0.61A to 1.21A. The voltage and current waveform during the L-G fault are shown below.

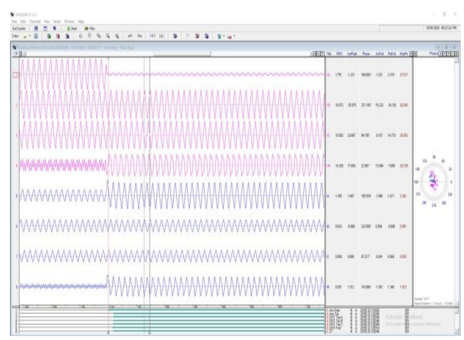


Fig 26: Voltage and Current waveforms during L-G fault.

b) Line-Line-Ground fault at section four

For a Double Line to Ground Fault (L-L-G) any two of M.C.B's S_r, S_y, and S_b(only any two based on fault condition simulation), here S_r and S_y switch is on. Along with ground M.C.B S_g is turned on for L-L-G fault study. The current value is increased to 0.59A to 1.23A. The voltage and current waveform during L-L-G fault are shown below.

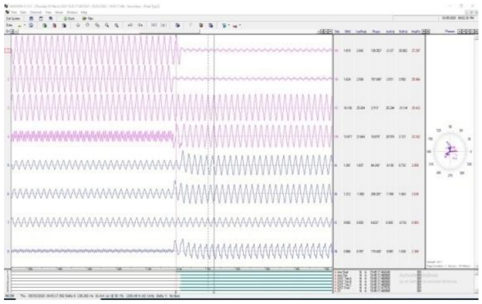


Fig 27: Voltage and Current waveforms during L-L-G fault

c) Line-Line-Line fault at section four

For Line to Line to Line Fault (LLL) all three M.C.B's S_r, S_y, and S_b are turned on for LLL fault study. The current value is increased to 0.61A to 1.25A. The voltage and current waveform during L-L-G fault are shown below.

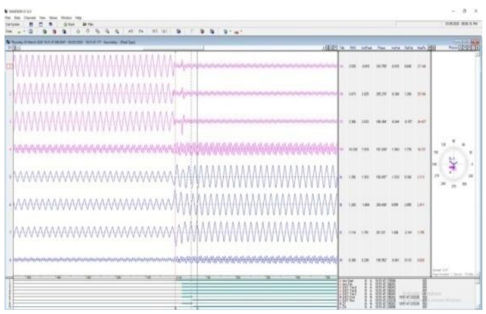


Fig 28: Voltage and Current waveforms during L-L-L fault

d) Line-Line-Line-Ground fault at section four

For a Line to Line to Line to Ground Fault (L-L-L-G) all three M.C.B's S_r, S_y, and S_b along with ground M.C.B S_g is turned on for L-L-L-G fault study. The current value is increased to 0.61A to 1.30A. The voltage and current waveform during L-L-L-G fault are shown below.

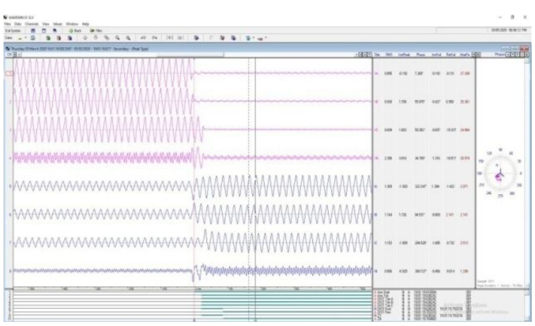


Fig 29: Voltage and Current waveforms during L-L-L-G fault

TABLE V
Hardware values without DG fault currents

With out DG (Hard ware Values)	Fault current at each phase	LG	LLG	LLL	LLL G
	Ia	1.21	1.23	1.25	1.30
	Ib	0.61	1.21	1.20	1.16
	Ic	0.59	0.59	1.11	1.15

V. CONCLUSIONS

The different types of fault that are focused on this paper in power systems. The radial network was modified and analyzed for different situations that are with DG and without DG. The penetration of DG some issues were extracted. The penetration of DG into a distribution system causes an increase in the fault current of the network at any fault location. The penetration of a DG in the system causes to loss of its radial power flow characteristics. As the distance between the DG and the fault location increases the value of the fault current decreases.

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