The Influence of Inverter-Based DGs and Their Controllers on Distribution Network Protection

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Abstract—The ever growing penetration of distributed generation (DG) in a distribution network has a profound impact on the network protection and stability. Traditional protection schemes and algorithms need to be extensively investigated as more and more DGs get introduced into the network. The current version of IEEE Std 1547 does not present a comprehensive solution for fault current detection in the presence of various kinds of DGs. Power electronic inverter-based DGs are of special concern in distribution network protection as they are often incapable of providing sufficient fault current and their controllers play a principal role in the DG behavior. In this paper, the effects of voltage and current controllers for inverter-based DGs on industrial and commercial power systems protection schemes are investigated. It is shown that the inverter control mode has a direct impact on its fault current levels and duration. A simplified distribution network model with inverter-based DG operating under voltage and current control modes was tested to verify the effects of these controllers. This paper also proposes an adaptive relaying algorithm to detect the faults in the presence of inverter-based DGs with various types of controllers.

Index Terms— Adaptive relaying, current controllers, fault characteristics, distributed generation, voltage source inverters, voltage controllers**.**

I. INTRODUCTION

Distributed generation (DG) including renewable like solar/photovoltaic and wind power are being increasingly installed by several industries to meet their environmental footprint and sustainability goals. Many DGs make use power electronic inverters for energy conversion to match the grid voltage and frequency [1]. However, such DGs are known to have a great impact on the stability and protection of distribution network [2]. The inverter-based DGs can affect network protection when an electrical fault occurs on account of fault current detection issues [3]-[7]. This is because they do not produce high levels of fault current when a short-circuit occurs. Besides, small rated DGs also have inadequate inertia to continuously feed the fault current unlike the traditional large rotating machine generators [8].

The study of fault current characteristics of the inverter-based DGs requires a comprehensive re-evaluation of various protection design aspects.

A Voltage Source Inverter (VSI) typically has a dc-link capacitor that is sized to decouple the prime-mover dynamics from those of network. Accordingly, the effect of prime-mover itself on fault current can be neglected, and only the dynamics of inverter with its associated controller(s) are considered [9]. Moreover, the inverter-based DGs have their own internal protection to insure safety of semiconductor devices against large over currents flowing through them [10]. Usually, this current is in the range of 2-3 times the rated load current [11], [12]. The effect of such an internal protection needs to be considered in the overall network protection scheme since the inverter internal protection cannot detect fault currents with levels lower than its settings.

There are principally two types of control schemes that generally govern inverter-based DGs, *viz.*, voltage control and current control [9]. This paper conducts a detailed investigation of network protection schemes for a typical industrial and commercial power distribution system, shown in Fig.1, containing inverter-based DGs with both control types. In addition, it also includes a comprehensive analysis of the fault current contributions of various DGs, as well as the impact of changes in inverter control between current control mode and voltage control mode on the associated feeder protection.

The effect of inverter-based DG controller on protection was earlier studied in [13]-[17]. The authors in [13]-[15] proposed adding fault current limiters in series with feeders containing DGs in order to limit the current contribution fed from them. Adaptive relaying algorithms were proposed in [16], [17] to solve the detection problems of the inverter-based DGs. In [18], the authors studied the effect on fuse saving schemes, whereas in [3] the authors introduced a flywheel energy storage system in parallel with the DG. While these schemes showed promising results, they are expensive solutions requiring extra equipment to be installed in the network. Furthermore, all the above mentioned publications [13]-[18] did not investigate the effects on protection scheme caused by different types of controllers employed in inverter based DGs. On the other hand, in the few papers that considered the effect of inverter controllers (viz., [19], [20]), the authors provided solutions that are limited in scope of

In this paper, a comprehensive analysis was conducted to investigate the differences between voltage and current control modes for inverter-based DGs' fault characteristics and a novel protection scheme for the distribution network was proposed. In particular, an adaptive relaying algorithm has been designed to protect the distribution network shown in Fig. 1 from fault contributions of inverter based DGs that can change their operational mode from current control to voltage control or vice versa.

II. CURRENT AND VOLTAGE CONTROLLED INVERTER BASED DGS

Many commercial DGs utilize a three-phase VSI based on pulse-width modulation (PWM) as the utility/load interface. The controls of these inverter based DGs enable them to meet the wide-ranging demands of their integration with the existing

distribution network. The advances made in the control of applications like uninterruptible power supplies (UPS) and ac motor drives gave impetus to the design of controllers for inverter based DGs. For all practical purposes,
there are chiefly two types of control schemes for regulation of the inverter output [19] – a voltage controller that will enable it to produce a three phase ac voltage, and a current controller that will force the current supplied to follow a reference signal that is locked in phase with the grid voltage by means of phase-locked loop (PLL).

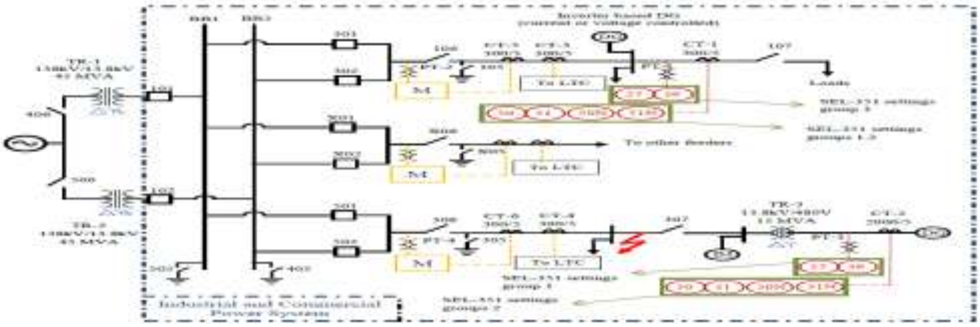


Fig. 1: One-line diagram of a typical industrial and commercial power system distribution network with inverter based DG installations application.

Current controllers for VSIs have become attractive in various power electronic applications including UPS, active power filters, ac motor drives, high power factor ac/dc converters and grid-connected inverters [21]. The current controller type and structure can be precisely tailored for each application as it plays a significant role in the performance of the converter as well as the power quality of its output. Many types of current controllers were suggested in the literature for various applications [21], [22]. However, current controlled DGs suffer from the major disadvantage of inability to independently maintain their terminal voltage to the distribution network levels. They rely on the utility grid or other voltage controlled DGs for maintenance of voltage, and in the absence of such a voltage support the current controlled
DG terminal becomes vulnerable to under voltage faults. On the other hand, voltage controllers have also been applied for VSIs in applications such as parallel connected standalone inverters [23] and plug-and-play operation of micro grids [24]. Inverter-based DGs under voltage control mode have become indispensable as they help in regulating the voltage of micro grid especially during the islanded conditions. Inverter based DGs operating in voltage control mode are unable to precisely regulate their output current, and these are therefore highly susceptible to overcurrent faults upon a short circuit.
Fig. 2 illustrates the conditional analogy of an inverter based DG to a current source or voltage source that is dependent upon the employed control scheme - whether it is operated in the current control mode or voltage control mode. The generic block diagrams of both current controlled and voltage controlled inverters in DG applications are illustrated in Fig. 3(a) and Fig. 3(b), respectively. These controllers are generally implemented in a digital signal processor (DSP). It is to be noted that the purpose of the protection analysis carried out in this paper is to highlight the key problems caused by a broad range of commercially available DGs used in industrial power systems. Therefore, Fig. 2 and Fig. 3 contain only representative block diagrams even though numerous variations are known to exist in the exact methods of controller implementation (as noted in the literature [21]-[24]).

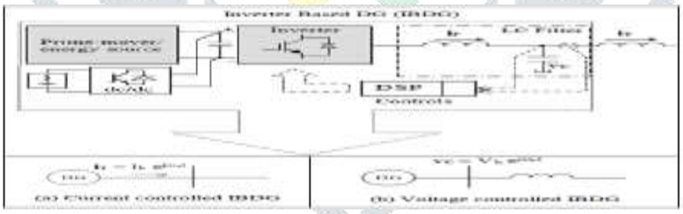
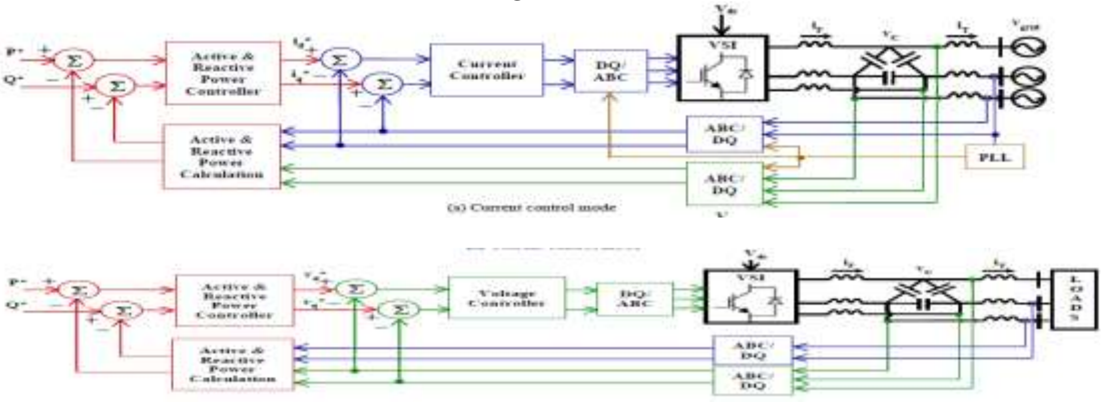


Fig. 2: Conditional analogy of an *Inverter Based DG* (IBDG), based on the employed control scheme, to (a) current source or (b) voltage source



(b) Voltage control mode

Fig. 3: Generic block diagrams illustrating the operation of inverter based DGs during (a) current control and (b) voltage control modes

Multifunction inverters are also commercially available from various manufacturers like SatCon, SMA, Xantrex etc. They are generally installed in industrial sites where uninterrupted operation is desired in both grid-connected and standalone (islanded) conditions. Such inverter based DGs are frequently used with renewable sources like solar/photovoltaic (PV) and wind power together with energy storage. For instance, SatCon Technology Corporation manufactures inverter products from low kW through MW ratings with functionalities that include standalone and grid-connected modes, synchronization, power factor correction and utility outage ride-through. The operation of these inverters is known to transition between the current control mode and voltage control mode based on system requirements and the state of interconnection [25], [26]. The protection schemes at industrial sites employing such DGs need special attention and a detailed investigation is carried out in the following section.

III. INVESTIGATION OF CURRENT CONTROLLED AND VOLTAGE CONTROLLED DGS ON DISTRIBUTION NETWORK PROTECTION

In order to examine the effects of current and voltage controlled inverter-based DGs on a distribution network, they have been modeled in MATLAB®/Simulink® together with the Thevenin's equivalent for the rest of system in Fig. 1. Subsequently, a fault was created across the nearby load and contribution of the inverter based DG to fault current was evaluated. The operation parameters for inverter based DG were as follows: 3-phase, 50-kW, 60-Hz, 480-Vac (line-line), IGBT based VSI - PWM inverter operating at 3.6 kHz switching frequency with a 750-V dc bus.

The voltage controlled inverter based DG was investigated at first under a three-phase short-circuit condition with a fault impedance of 3 Ω. Such a high impedance fault was chosen in order to avoid triggering the inverter's internal protection that is typically designed to limit the inverter current to 2-3 times of full load current [11], [12]. Fig. 4 shows the inverter output voltage and current waveforms during the fault occurrence. It was observed, as expected, that the output current of the DG increases instantaneously when the fault occurs. The voltage controller regulates the terminal voltage within the acceptable range during the fault event. It is to be noted that if a fault occurs with a lower fault impedance, the internal protection of the inverter will reduce the output current to the internal protection limit after a few cycles. In this paper, the internal protection of the inverter has been set to 2 times the rated current.

Then again, in the case of inverter based DG being current controlled, the inverter response was examined under a short-circuit fault with an impedance of 1 mΩ. Fig. 5 illustrates the inverter output voltage and current waveforms during this fault. In contrast to the voltage controlled DG, the current controlled DG had a regulated output current that was not affected by the fault. However, as expected its output voltage dropped to 105 V (line-line).

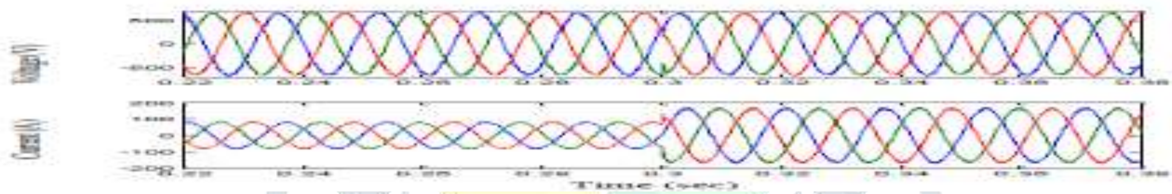


Fig.4: DG under voltage control mode: output voltage (top) and output current (bottom) for a short-circuit fault at t = 0.3 sec

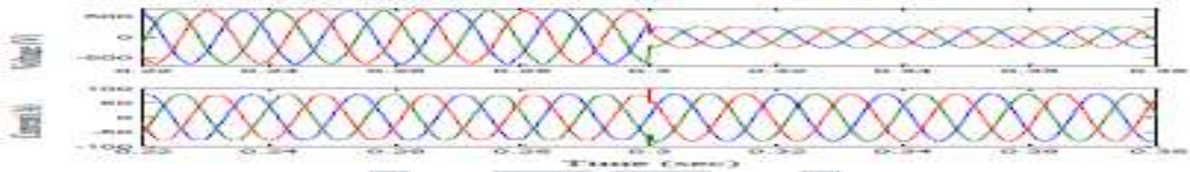


Fig.5: DG under current control mode: output voltage (top) and output current (bottom) for a short-circuit fault at t = 0.3 sec

In order to carefully analyze the differences in fault characteristics between the voltage and current controlled inverter-based DGs, many fault scenarios with different impedances, fault locations, and fault types were investigated. In all the tested scenarios, the voltage controlled inverter-based DG's voltage waveforms were almost unaffected although currents increased to different levels based on fault location and impedance. On the contrary, in the case of a current controlled DG the current almost remained constant while the voltage varied according to the fault type, location, and impedance. Fig. 6 illustrates selected results of the inverter output voltage and current waveforms for different fault locations. The faults were chosen to occur at 5 and 10 miles respectively from the inverter terminal (with the line impedance given as 1.35 Ω/mile).

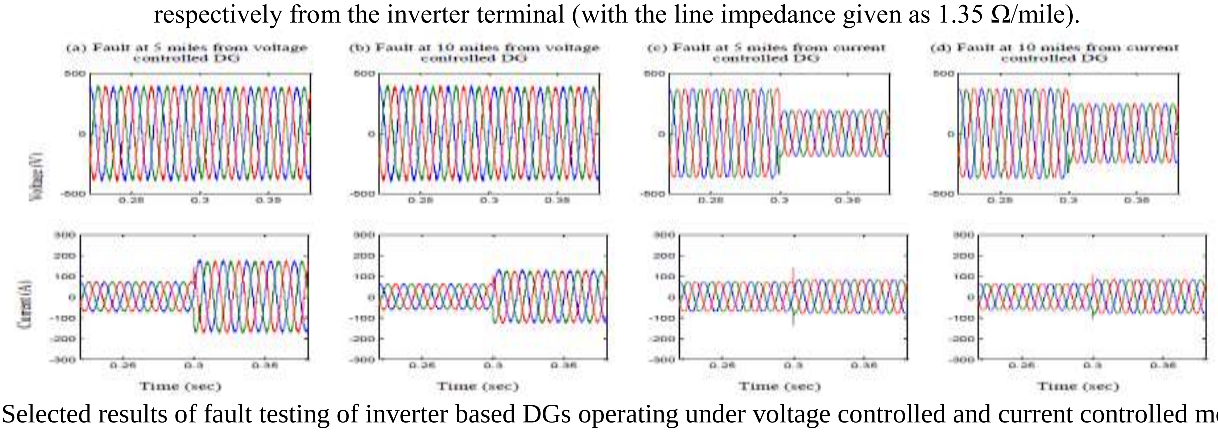


Fig.6: Selected results of fault testing of inverter based DGs operating under voltage controlled and current controlled modes for different fault locations

In all the above tests, the load connected near inverter based DG was purely resistive. Under this condition, as seen in Fig.5 for the current controlled mode, the transient overshoot in the inverter output current waveform had vanished almost instantaneously that it could be ignored. Interestingly however, the same transient overshoot had skyrocketed and could not be neglected when the fault was tested with the presence of an inductance in parallel with the 50-kW resistive load, as shown in Fig. 7 for three different values of power factor. Such transient overshoots are not unusual and in fact have been observed in the output of current controlled photovoltaic (PV) inverters during tests on commercial units, as reported in [8], [27]. Special care needs to be taken under such circumstances because the current overshoot can more likely trigger the inverter internal protection and/or the instantaneous overcurrent settings of the feeder protective relays if any. From Fig. 7, it can be seen that the transient overshoots may reach very high values compared to the rated current, and their duration may extend up to a few milliseconds depending on the power factor.

Another significant case that resulted in an overvoltage condition upon a fault was when a DG operating in current control mode supplied load through an ungrounded Y-□ transformer. Such adverse circumstances are commonly encountered in the event of generation from renewables exceeding the local load demand and the grid connection was lost. It is presumed that the inverter-based DG, after disconnection from the utility grid, malfunctioned and continued to operate in the current control mode; *i.e.* it failed to change its operation mode to the voltage control mode. Then an overvoltage condition can occur immediately following a single line to ground fault, particularly if the

transformer has Y-side ungrounded. Fig. 8 shows the voltage waveforms of three cases where a single line to ground fault occurred in phase A. It has been observed that the amount of overvoltage increased as the generation to load ratio increased. Three cases are presented in Fig. 8 for load demands of 50 kW, 30 kW, and 20 kW when the generation was equal to 50 kW.

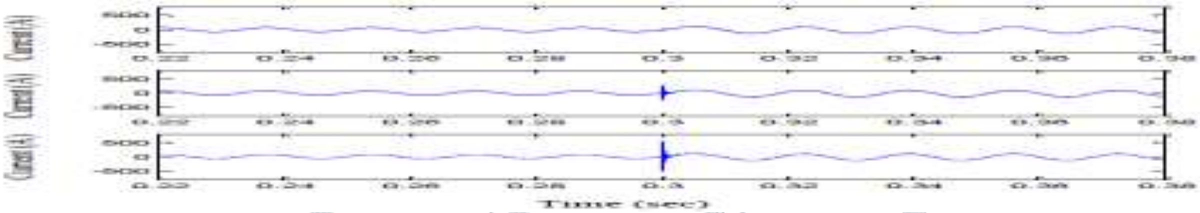


Fig. 7: Output current waveforms of DG under current control mode with different load reactive power for a fault at t = 0.3 sec. Top (0 kVAR), middle (3 kVAR), bottom (10 kVAR).

In order to effectively address the wide ranging protection issues explained above, and which are commonly encountered at any industrial distribution network, a novel adaptive relaying algorithm for the inverter-based DGs has been proposed in the next section.

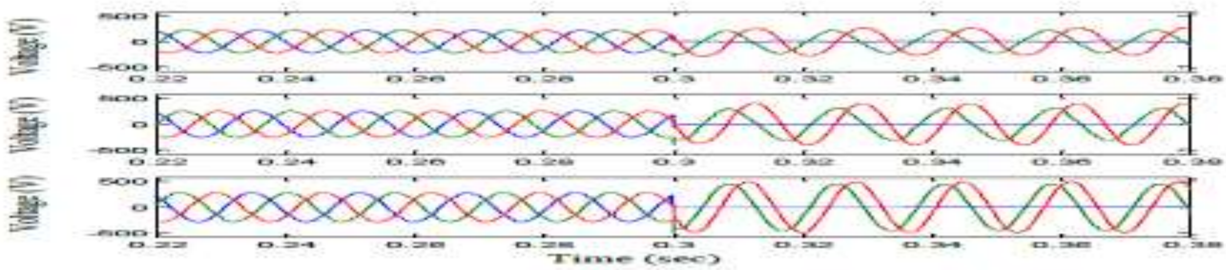


Fig. 8: Output voltage waveforms of DG operating under current control mode in an islanded condition. A single line to ground fault occurred at time t = 0.3 sec. For a 50-kW generation, the loads considered were 50 kW (top), 30 kW (middle), and 20 kW (bottom)

IV. PROPOSED ADAPTIVE RELAYING ALGORITHM

In the recent past, many fault detection algorithms and techniques were presented in the literature for inverter based DGs [5], [11], [13]-[17], [28]. However, they did not address adequately the new-found problems of greater significance of inverter control methods on the fault current contributions. It was clearly identified in the previous section that the operation and control mode of inverter based DG has a major influence on the distribution network protection. Most of published research in this area postulated that the fault characteristics for the current control mode are exactly the same as those for the voltage control mode. This paper has identified the key problems encountered at industrial sites due to the ever increasing penetration of DGs in their distribution network. Proceeding on that ground, a novel protection algorithm that considers the impact of inverter-based DG controllers is proposed in this section. The proposed algorithm is also adaptive to any changes in microgrid mode of operation as well as to the transition of inverter based DG operation between current control and voltage control modes. Fig. 9 presents a flow diagram of a generalized adaptive relaying algorithm. It is applicable for fault current detection in industrial microgrids during both grid-connected and islanded conditions.

During the grid-connected mode of operation, assuming that the stiffness of the grid tie-line is high, there are generally no fault detection problems. This is because the utility grid can provide sufficient amount of fault current. Hence, overcurrent relays (50, 51) are able to provide suitable functionality at the time of a fault. Fig. 10 displays the current waveforms detected by the overcurrent relays when the microgrid was operating in the grid-connected mode. As seen in this figure, the DG output current in the fault condition can be 5-7 times the rated current, and the relay settings have been made between the rated full load and the minimum fault currents.

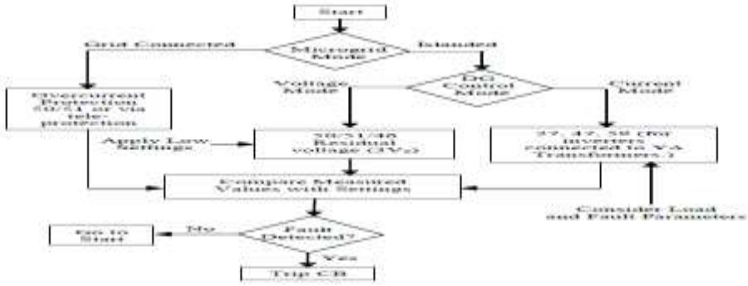


Fig. 9: Flow diagram of the proposed adaptive relaying algorithm

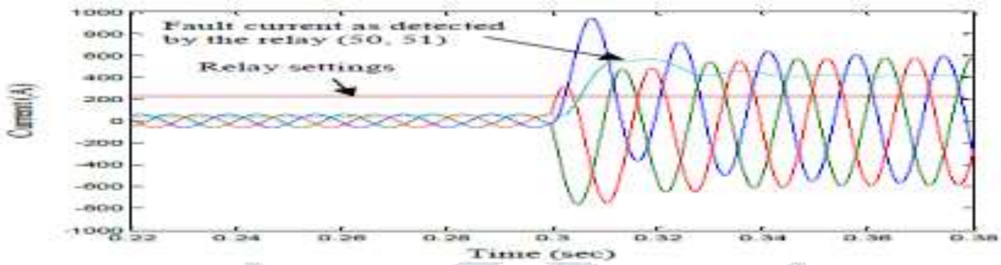


Fig. 10: Fault current detected by an overcurrent (50, 51) relay for a three phase fault during grid connected mode

But for the islanded mode of operation of the microgrid there is still further analysis required to be conducted, and appropriate protections must be determined from the fault characteristics for every operation mode. The negative and zero sequence components of voltage were studied during different kinds of faults. Fig. 11 and Fig. 12 illustrate the negative and zero sequence components of voltage for a single line to ground fault and double phase fault, respectively. From Fig. 11, it can be observed that the DG produced less negative sequence content when operating under voltage control mode. On the contrary, as seen in Fig. 12, the DG operating under current control mode produced lesser zero sequence content for the same fault conditions. The same observations were also verified for various other fault scenarios, and Table 1 summarizes the results for different fault types, locations, and impedances. As seen in this table, for all kinds of fault scenarios, the negative sequence contents in voltage were less in the voltage control mode of operation, and the zero sequence contents were less in the case of current control mode of operation. It is to be noted that in the case of current waveforms quite the opposite was observed - when similar investigation was conducted on the negative sequence and zero sequence components of DG currents. The results for current waveforms have been excluded for brevity.

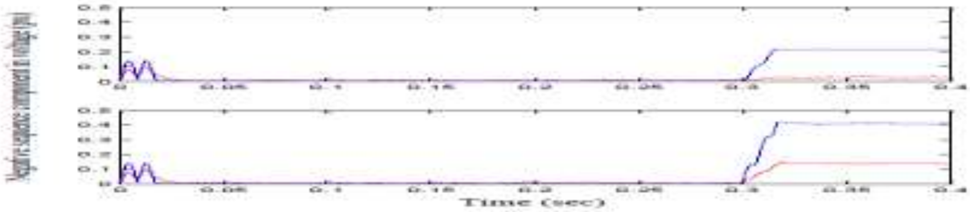


Fig. 11: Negative sequence component of voltage waveform during single line to ground fault (top) and double phase fault (bottom). DG operates in voltage control mode (red) and current control mode (blue).

Fig. 12: Zero sequence component of voltage waveform during single line to ground fault (top) and double phase fault (bottom). DG operates in voltage control mode (red) and current control mode (blue).

Table 1: Negative and zero sequence contents of DG voltage when operating under voltage and current control modes

S. No.	Fault location (km)	Fault impedance (Ω)	Fault type	Voltage control mode		Current control mode	
				Voltage negative sequence	Voltage zero sequence	Voltage negative sequence	Voltage zero sequence
1	1	1	A-G	0.03	0.40	0.22	0.23
2	1	0.01	A-B	0.41	0	0.46	0
3	1	0.01	A-B-C	0	0	0	0
4	1	3	A-G	0.1	0.19	0.13	0.14
5	1	3	A-B-G	0.04	0.12	0.24	0.11
6	1	0.01	A-B-C	0	0	0	0
7	5	1	A-G	0.02	0.32	0.18	0.22
8	5	0.01	B-C	0.14	0	0.41	0
9	5	0.01	A-B-C	0	0	0	0
10	5	3	B-G	0.01	0.1	0.07	0.1
11	5	3	A-C-G	0.02	0.1	0.21	0.1
12	5	0.01	A-B-C	0	0	0	0
13	10	3	C-G	0.01	0.09	0.05	0.08
14	10	3	B-C-G	0.02	0.09	16	0.09
15	10	0.01	A-B-C	0	0	0	0
16	10	3	A-G	0	0.13	0.08	0.12
17	10	0.01	A-B	0.06	0	0.30	0
18	10	0.01	A-B-C	0	0	0	0

From the above discussion, it can be deduced that the protection philosophies, which are based on negative sequence voltage (47), are sufficient to protect the utility feeders with DGs operating in current control mode from unsymmetrical faults. Whereas protection mechanisms based on negative sequence current (46) and residual voltage will be sufficient to protect feeders with

DGs operating in voltage control mode from the unsymmetrical faults. For symmetrical faults, which have no negative or zero sequence contents, the above strategies do not work. However, it can be concluded from Fig. 5 that the DGs operating in current control mode suffer from undervoltage when subjected to three phase faults, and therefore an undervoltage protection (27) will be sufficient to detect these faults. On the other hand, DGs operating under voltage control mode can produce higher fault currents (within the limits imposed by their power semiconductor devices), so overcurrent settings (50, 51) with low settings and definite time delay should solve the fault detection problems. Of particular importance is the coordination between the distribution feeder protection and the inverter internal protection of the DG. For example, the overcurrent settings of the DGs in voltage control mode must be lower than their inverter internal protection, but with high (around 150 ms) definite tripping time. In addition, the fault time, which includes the fault detection and fault isolation processing, should be within the low voltage ride-through specifications. In USA and CANADA, the fault clearance time to avoid unintentional disconnection of DGs from the utility grid is 0.625 sec [29].

As stated earlier, for islanded microgrids that are dominated by inverter-based DGs operating under voltage control mode, the overcurrent relays (50, 51) with low settings are required to detect symmetrical faults. Fig. 13 illustrates a general procedure to lower the overcurrent relay settings. The process of making changes to the settings has become simple and easy to implement in the commercial relays sold nowadays. For instance, the setting modification procedure, shown in Fig. 13, in using Schweitzer Engineering Laboratories overcurrent relay (SEL-351) requires adjusting (minimizing) the definite time overcurrent element: 50P1P or 50P6P, and adjusting the time overcurrent element: 51P1T or 51P2T that also include the pick-up settings: 51P1P/51P2P, the curve type settings: 51P1C/51P2C, and the time dial settings: 51P1TD/51P2TD. The current negative sequence element 50Q1P and the residual voltage element 59N1P can be utilized to detect the unsymmetrical faults. On the other hand, when the inverter-based DGs operate in the islanded condition of microgrid under current control mode, symmetrical faults will cause a drop in voltage that can be detected by undervoltage relays (27) and the unsymmetrical faults can be detected by voltage negative sequence element 59Q1P. It is to be noted that the overvoltage element (59) must be used if the inverter is connected to the grid through a YΔ transformer. On the same lines, the settings for commercial relay products from other equipment manufacturers can be also easily formulated.group 2, and in this case the overcurrent and earth fault settings are more sensitive. While changing the controller of the DG from voltage control mode to the current control mode, it is necessary to make the relay switch from setting group 2 to setting group 3, in which case the undervoltage settings have two steps and each one has its own tripping time.

Table 2: Recommended settings of SEL-351 for the industrial and commercial power system in Fig. 1

Setting group number			1	2	3
Grid mode of operation			Connected	Islanded	Islanded
Controller type			N/A	Voltage	Current
Relay inputs			Grid CB position	DG controller & CB position	DG controller & CB position
Over-current settings	Definite	50P1P	5	1.9	N/A
	Time settings	51PP	1	N/A	N/A
		51PC	U2	N/A	N/A
		51PTD	3	N/A	N/A
Earth fault settings	Definite	50N1P	0.5	0.3	0.3
	Time Settings	50NP	0.1	0.1	0.1
		51NC	U3	U3	U3
		51NTD	3	1	1
Current negative sequence		50Q1P	0.15	0.15	N/A
Under voltage settings		27P1P	0.88	N/A	0.88
		27P2P	0.5	N/A	0.5
Over voltage settings		59P1P	1.2	1.2	1.2
Voltage zero sequence		59N1P	0.15	0.1	N/A
Voltage negative sequence		59Q1P	0.15	N/A	0.15

The proposed adaptive relaying algorithm that considers the effects of changing the inverter controller type was tested by applying the settings of Table 2 for multiple fault scenarios. Its effectiveness has been proven for clearing all types of faults as against other algorithms found in literature. For example: Fig. 14 gives a comparison of its performance against the conventional techniques using methods presented in [11]. As seen in this figure, the conventional settings failed to detect several types of faults - as their protection philosophy does not consider the effects of inverter controller. On the other hand, the proposed algorithm helped in detecting all of them. The three phase faults were detected by undervoltage relays when the DG is operated under current control mode and by overcurrent when the DG is under voltage mode. The double phase fault (applied on the DG that is operated in voltage control mode) was detected by current negative sequence protection and the single line to ground fault (applied on the DG that is operated in current control mode) was detected by voltage negative sequence protection. It is to be noted that the settings of the relays were chosen to be within IEEE 1547 specifications [30].

The settings of proposed adaptive scheme for SEL relay require specific input configuration, where two opto-isolated inputs (IN101 and IN102) will be necessary. The first input represents the main grid breaker or static switch status (*i.e.* OPEN or CLOSE) and the second input represents the operation mode for inverter controller (*i.e.* voltage control mode or current control mode). The reception of these inputs will switch the relay from one group to another one as shown in Fig. 15. A general connection diagram of the relay inputs wiring is illustrated in Fig. 16.

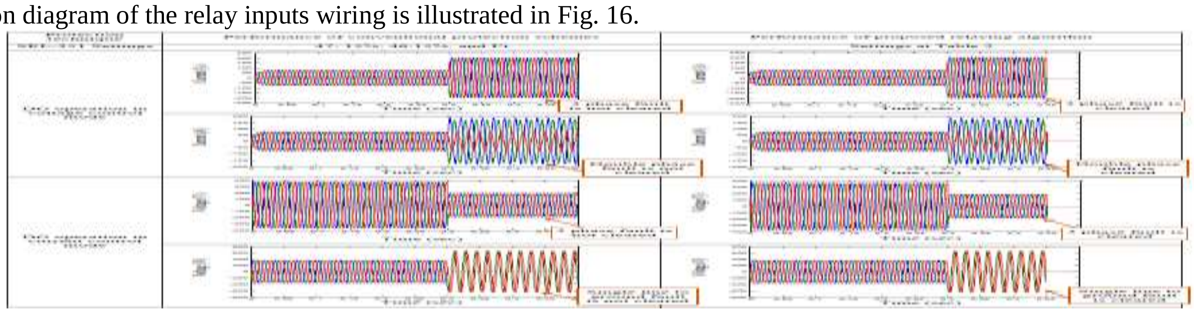


Fig. 14: Comparison between conventional protection techniques (as presented in [11]) and the proposed adaptive relaying algorithm

Fig. 15: Screenshot of AcSELerator (SEL relay interface software) shows how to program the settings groups with the relays inputs.

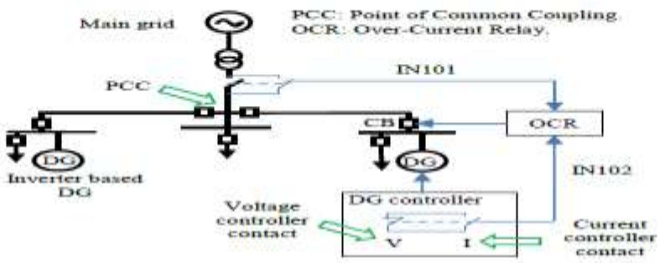


Fig. 16: Illustration of SEL-351 inputs to achieve the proposed scheme

V. CONCLUSIONS

In this paper, the fault current contributions from inverter-based DGs in a distribution network of an industrial and commercial power system were examined in greater detail. In particular, the impact of inverter-based DGs and their controllers on distribution network protection was thoroughly investigated. Previous published works on protection schemes for inverter based DGs have provided only particular solutions and not a comprehensive solution that adequately addresses both current controlled and voltage controlled inverter-based DGs. They ignored the discrepancies in fault characteristics of the voltage controlled and current controlled inverter-based DGs. This is especially a serious concern with the high penetration of DGs and rapid deployment of commercially available multifunction inverters that are commonly installed in industrial sites where uninterrupted operation is desired in both grid-connected and standalone (islanded) conditions. Such inverter based DGs are frequently used with renewable sources like solar/photovoltaic (PV) and wind power together with energy storage. The operation of these inverters is known to transition between the current control mode and voltage control mode based on system requirements and the state of interconnection. The protection schemes at industrial sites employing such DGs need special attention and a detailed investigation has been carried out in this paper. Based on the new-found conditions for protection of the distribution network, a novel relaying algorithm that considers the impact of inverter-based DG controllers has been proposed. This algorithm is even adaptive to any changes in the microgrid mode of operation as well as to the transition of inverter based DG between current control and voltage control modes of operation.

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