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Line Protection in Inverter Supplied Networks

Manjula Dewadasa, Arindam Ghosh and Gerard Ledwich

Abstract-New protection methods are required to protect a distribution system when supplied by current limited converters. In this paper, a method of converter control is proposed to limit the current by reducing the voltage in the faulted phase or phases while keeping the voltage of the healthy phases unaltered. Unsymmetrical fault analysis is performed to calculate the sequence currents and voltages at the relay location, when system is supplied by a converter. Based on that converter control, distance relay performances have been evaluated in both grid-connected and islanded mode operations. Distance relay, combined with MHO and negative sequence impedance directional characteristics, is proposed as a protection scheme for the distribution system for different types of faults under the current limited environment. The results are validated through PSCAD/EMTDC simulation and MATLAB calculations.

Index Terms: Apparent impedance, Distance protection, Sequence components, Unsymmetrical faults.

I. Introduction

With the environmental policies encouraging reducing green house gas emissions, distributed generation using renewable energy sources is gaining importance. Previously it was expected that 20% of power generation will be DGs by the year 2020 [1]. However with most countries ratifying the Kyoto Protocol to avoid climate change, the penetration level of DGs is expected to be higher by that time. Some of the currently available renewable energy based distributed generators (DGs) are wind turbines, mini-hydro, photovoltaic arrays, biomass, etc The cost of transmission and distribution is rising with the increase in load demand [2]. However the cost of DG technologies is expected to reduce with mass production and governmental subsidies. Thus from costing point of view, it will become attractive to increase the generation at the distribution level. In addition, there are several benefits that are available for both utilities and consumers from utilizing DG sources. They can reduce power loss, improve voltage profile, enhance reliability and diversification of energy sources, and contribute to reduce green house gas emissions as well as transmission and distribution costs [2, 3].

Most of the existing distribution networks are radial due to its simplicity and low cost of overcurrent protection [1, 4]. Moreover protective device coordination based on the current is relatively easy in these radial networks. But fault current and direction may change in the presence of DGs in the system. Its impact depends on the size, type, number of the DGs, and location of the DG [5, 6]. In addition, most of the DGs are connected to the distribution network through the power electronic inverters. Commonly these inverter interfaced generators have been designed to limit the output current to a value twice the rated current in the event of a fault. As a result, overcurrent devices may not respond or may take long time to respond [7-9]. A possible approach that facilitates to use the existing overcurrent protection is up-rating of the converters, such that required fault current can be supplied. This however will be expensive. Once such method is reported in [9], which uses flywheel energy storage during fault system to supply the necessary fault current in the event of a fault.

This paper discusses a method to analysis the fault behaviour of a current limited converter in a distribution network. Each phase of the converter is controlled independently. In the event of a fault, output current of the converter is limited by reducing the voltage of the faulted phase or phases while keeping the voltage of unfaulted phase or phases unaltered. Converter structure and control mechanism are presented. Converter is considered as an unsymmetrical source in the event of a fault. Thus a method is proposed to calculate the faulted voltages and currents at the relay location using the symmetrical components. Moreover response of distance relays has been analysed under the current limited converter environment in both grid-connected and islanded modes of operation. Further negative sequence impedance analysis has been carried out to propose an efficient protection scheme. The results are verified through MATLAB calculations and PSCAD simulations.

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II. Converter Structure

The proposed converter structure is shown in Fig. 1. The DG is assumed to be an ideal dc voltage source supplying V_{dc} to the voltage source converter (VSC). The converter contains three H-bridges. The outputs of the H-bridges are connected to three single-phase transformers that are connected in wye for required isolation and voltage boosting [10]. The resistance R_f represents the switching and transformer losses, while the inductance L_f represents the leakage reactance of the transformers. A filter capacitor, C_f, is connected to the output of the transformers to bypass switching harmonics. The advantage of the converter structure shown in Fig. 1 is that it is capable of generating unbalanced voltages in the three phases independently. To protect the inverter in case of a fault, the currents in all the three phases are restricted. One way of accomplishing this is by injecting a balanced current that can be about twice the rated current. This will however cause the voltages in the unfaulted phases to rise in case of unbalanced faults [11]. This obviously is not desirable as the single-phase loads in the healthy phases will be stressed by the higher current through them. Since the converter of Fig. 1 can supply unbalanced voltages, we propose to reduce the voltage in the faulted phases, while keeping the voltage of the healthy phases unaltered in the event of a fault.

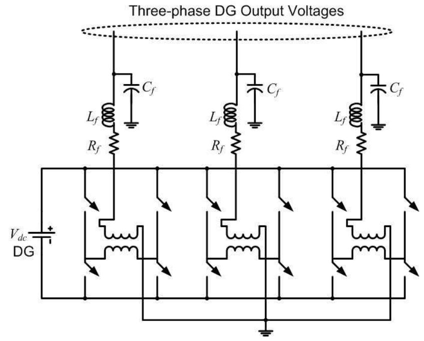

Fig. 1. Converter structure

A. Converter Control

The equivalent circuit of one phase of the converter is shown in Fig. 2. In this, $u \cdot V_{dc}$ represents the converter output voltage, where $u = \pm 1$. The main aim of the converter control is to generate u. From the circuit of Fig. 2, the state space description of the system can be given as,

$$\dot{x} = Ax + Bu_c \tag{1}$$

where u_c is the continuous time control input, based on which the switching function u is determined. The discrete-time equivalent of (1) is

$$x(k+1) = Fx(k) + Gu_c(k) \tag{2}$$

Let the output of the system given in (2) be v_{cf}. The reference for this voltage is given by the instantaneous peak and phase angle of each phase. Let this be denoted by v^*. The input-output relationship of the system in (2) can be written as,

$$\frac{v_{cf}(z)}{u_c(z)} = \frac{M(z^{-1})}{N(z^{-1})} \tag{3}$$

The control is computed from

$$u_c(z) = \frac{S(z^{-1})}{R(z^{-1})}\left\{v^*(z) - v_{cf}(z)\right\} \tag{4}$$

The closed-loop transfer function of the system is then

$$\frac{v_{cf}(z)}{v^*(z)} = \frac{M(z^{-1})S(z^{-1})}{N(z^{-1})R(z^{-1}) + M(z^{-1})S(z^{-1})} \tag{5}$$

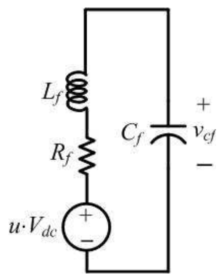

Fig. 2. Equivalent circuit of one phase of the converter.

The coefficients of the polynomials S and R can be chosen based on a pole placement strategy [12]. Once u_c is computed from (5), the switching function u can be generated as

$$\begin{aligned} &\text{If } u_c > h \text{ then } u = +1 \\ &\text{elseif } u_c < -h \text{ then } u = -1 \end{aligned} \tag{6}$$

where h is a small number.

B. Reference Voltage Generation

The control in (4) is computed based on the reference voltage v^* and the feedback of the capacitor voltage v_{cf}. The reference voltages are given by

$$\begin{aligned} v_a^* &= V_n \sin(\omega t) \\ v_b^* &= V_n \sin(\omega t - 120°) \\ v_c^* &= V_n \sin(\omega t + 120°) \end{aligned} \tag{7}$$

where V_n is the instantaneous peak voltage magnitude. Under nominal condition, $V_n = V_{n0}$. The rms values of the VSC output currents of all the three phases are monitored continuously. Once a fault occurs, the output currents shoot up. When the rms values of a particular phase crosses a threshold, the reference voltage of that phase is quenched by choosing $V_n = V_{nf}$, where $V_{nf} << V_{n0}$. The value of V_{nf} is chosen based on the worst case current (i.e., a fault near VSC terminals) that the converter can inject. Note that for an internal fault, the VSC is switched off to protect its switches and hence the network protection issue does not arise.

III. Unsymmetrical Fault Calculation

For the calculation of fault currents, we shall make the assumption that the system is balanced before the fault occurs. Thus, before the fault, the VSC supplies a set of balanced voltages (i.e., with the same peak and phase displacement of 120°). Once a fault is detected in one of the phases, the voltage of the particular phase is reduced, while it phase angle is retained such that the VSC output voltages are still phase displaced by 120°. The faulted network will be as shown in Fig. 3, where the relay location will be at node R and fault is at node K. Impedance between relay and fault point is denoted by Z_{RK} and voltages at the relay location are denoted by V_{Ra}, V_{Rb}, V_{Rc}. Currents in the three faulted phases are I_{fa}, I_{fb} and I_{fc}.

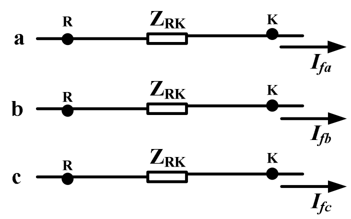

Fig. 3. Representation of faulted network

Let us take zero, positive and negative Thevenin sequence impedances at the relay point as Z_{RR0}, Z_{RR1} and Z_{RR2} respectively. Also Thevenin voltages at relay point are denoted by V_{tha}, V_{thb}, and V_{thc}.We shall now find expressions of sequence fault currents and sequence voltages for a single line to ground (SLG) fault. The Thevenin equivalent of the sequence network is shown in Fig. 4 where it is assumed that phase-a has been grounded through an impedance Z_f. Assuming that the system is unloaded before the occurrence of the fault, it is well-known that the sequence components of the fault current will be given by [13, 14],

$$I_{fa0} = I_{fa1} = I_{fa2} = \frac{I_{fa}}{3} \tag{8}$$

For a SLG fault in phase-a, the VSC output voltage in phase-a will be reduced, while the output voltages of phase-b and phase-c will remain unaltered. The Thevenin voltages at the relay point can be expressed as,

$$V_{tha} = V_f \angle 0°, V_{thb} = V_m \angle -120°, V_{thc} = V_m \angle 120° \tag{9}$$

In (9), V_m is the magnitude of unfaulted rms voltage and V_f is the magnitude of reduced rms voltage in the faulted phase. Then the sequence components of the voltages are,

$$V_{tha012} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_f \angle 0° \\ V_m \angle -120° \\ V_m \angle 120° \end{bmatrix} \tag{10}$$

Also note since the source voltages are unbalanced, the negative and zero sequence Thevenin voltages will not be zero. From (10), we get

$$V_{tha012} = \frac{1}{3}\begin{bmatrix} V_f + a^2 V_m + a V_m \\ V_f + a^3 V_m + a^3 V_m \\ V_f + a V_m + a^2 V_m \end{bmatrix} = \frac{1}{3}\begin{bmatrix} V_f - V_m \\ V_f + 2V_m \\ V_f - V_m \end{bmatrix} \tag{11}$$

We can then write,

$$\begin{aligned} V_{Ra0} &= V_{tha0} - Z_{RR0} I_{fa0} \\ V_{Ra1} &= V_{tha1} - Z_{RR1} I_{fa1} \\ V_{Ra2} &= V_{tha2} - Z_{RR2} I_{fa2} \end{aligned} \tag{12}$$

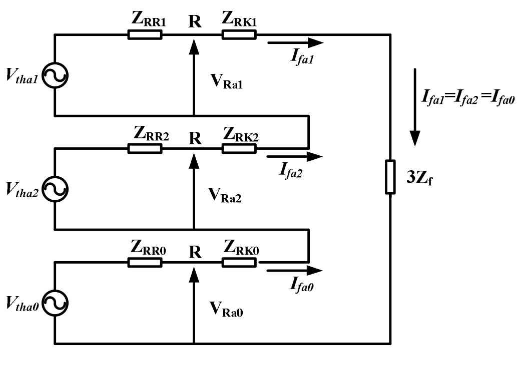

Fig. 4. Thevenin equivalent of a SLG fault

By adding we get the voltage at relay point as,

$$\begin{aligned} V_{Ra} &= V_{Ra0} + V_{Ra1} + V_{Ra2} \\ &= V_{tha0} + V_{tha1} + V_{tha2} - (Z_{RR0} + Z_{RR1} + Z_{RR2}) I_{fa0} \end{aligned} \tag{13}$$

Combining (11) and (13),

$$V_{Ra} = V_f - (Z_{RR0} + Z_{RR1} + Z_{RR2}) I_{fa0} \tag{14}$$

Again we can write

$$V_{Ra} = 3Z_f I_{fa0} \tag{15}$$

Using (14) and (15) we can express the zero sequence current at relay location as,

$$I_{fa0} = \frac{V_f}{(Z_{RR0} + Z_{RR1} + Z_{RR2}) + (Z_{RK0} + Z_{RK1} + Z_{RK2}) + 3Z_f} \tag{16}$$

Sequence voltages and currents can be calculated by using the equations (12) and (16) at the relay point. The equations derived for the SLG fault calculation is similar to the standard equations used for fault calculation assuming positive sequence source voltage only [13, 14]. However the major difference is that the fault currents are dependent on the reduced voltage magnitude V_f of the faulted phase and not on the nominal voltage magnitude V_m. This is a major finding that will help us to analyse voltage limited (or even current limited) faulted networks.

IV. Evaluation of Distance Relay Protection Scheme

A study has been conducted to find out the suitability of application of distance relays for protection of distribution network under the converter reduced voltage environment during the faults. Distance relays having MHO characteristic with two zones of protection are used to protect the system in grid connected and islanded modes. The conventional method of calculating the apparent impedance seen by a distance relay is given by (17)-(19).

$$Z_{LG} = \frac{V_{phase}}{I_{phase} + KI_0} \tag{17}$$

$$K = \frac{Z_0 - Z_1}{Z_1} \tag{18}$$

$$Z_{LL} = \frac{V_{phase1} - V_{phase2}}{I_{phase1} - I_{phase2}} \tag{19}$$

Equation (17) is used for earth fault and it includes the residual compensation factor K and zero sequence current I_0. For inter-phase faults, (19) is used based on the voltage and current differences between the phases. We shall now present some of the results. A four bus bar radial system is considered for the simulation in PSCAD. The schematic diagram of one phase of the system is shown in Fig. 5.

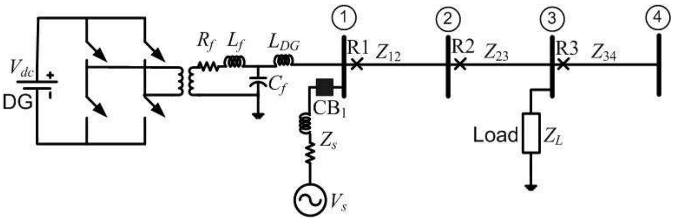

Fig. 5. The schematic diagram of the study system.

In Fig. 5, the DG is represented by the dc voltage source V_{dc}. The utility supply is denoted by V_s, while the source feeder impedance is denoted by Z_s. The distribution feeder impedances are denoted by Z_{12}, Z_{23} and Z_{34}. A load with impedance of Z_L has been assumed to be connected at Bus-3. The system parameters are given in Table I. Zone settings are chosen such that Zone-1 covers 80 per cent of the protected line, while Zone-2 covers the entire protected line, plus 50 per cent of the adjacent line. For example, relay R_2 protects 80% of Line 2-3 in Zone-1 and 100% of Line 2-3 and 50% of Line 3-4 in Zone-2.

Different types of faults are generated at different locations with changes in fault resistance and load conditions. But results have shown only for the SLG fault and we have assumed that the fault occurs at Bus-2. In this case equations (12)-(18) can be used to calculate the apparent impedance seen by R1 neglecting the load. However, same procedure can be extended to calculate the apparent impedance seen by each relay in the system with a load. Figs. 6 and 7 give the apparent impedance plot of R1 and R2 with the variation of fault resistance in the grid connected and islanded mode operation respectively. It can be seen that operation of R1 is the same for the both modes, while R2 shows a slight difference for the islanded mode. The relay R2 sees this fault as reverse since it is located downstream from the fault. Therefore R2 operates in Zone-1 while R1 operates in Zone-2 for small fault resistance values. Thus R2 responds before the R1 and opens the circuit breaker at Bus-2. From the point of relay discrimination, this can be identified as an unacceptable operation.

The PSCAD simulation results for the islanded case are shown in Fig. 8 in which the fault occurs at 0.1 s. It can be seen in Fig. 8(a), as soon as the fault is detected, the VSC voltage of phase-a reduces. Even though the current in the other two phases are unaltered till R2 trips, phase-a supplies a relatively large fault current as shown in Fig 8(b). The relay R2 operates at 0.133 s as indicated in Fig. 8(d) thereby disconnecting of the

TABLE I: SYSTEM DATA

System data	Values
System frequency	50 Hz
Source voltage (V_s)	11 kV rms (L-L)
Source impedance	$Z_s = 0.078 + j\,0.785\ \Omega$
Feeder impedance	$Z_{12} = Z_{23} = Z_{34} = 0.195 + j\,1.4451\ \Omega$
Load Impedance	$Z_L = 40.33 + j\,0\ \Omega$
Converter data	
DC voltage (V_{dc})	3.5 kV
Transformer rating	3.5 kV/11 kV, 1 MVA, 0.1 pu reactance
VSC losses (R_f)	3.0 Ω
Filter capacitance (C_f)	100 µF
Input inductance	L_{DG} =10 mH

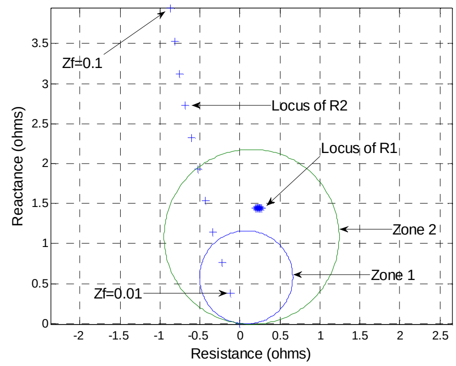

Fig. 6. Impedance plot of R1 & R2 for SLG with fault resistance variation (0.01 Ω -0.1Ω) in grid connected mode with a load of 3 MW.

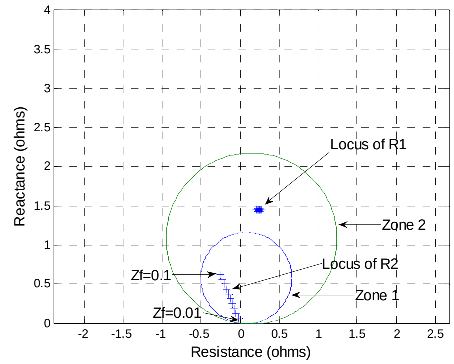

Fig. 7. Impedance plot of R1 & R2 for SLG with fault resistance variation (0.01-0.1Ω) in islanded mode with a load of 3 MW.

load from the supply. However the phase-a current still continues to flow since the fault location is upstream from R2. The fault is isolated at 0.426 s as in Fig. 8(c), when the relay R1 operates. The inverter voltages attain their nominal values thereafter. The relay R3 does not operate as shown in Fig. 8(e).

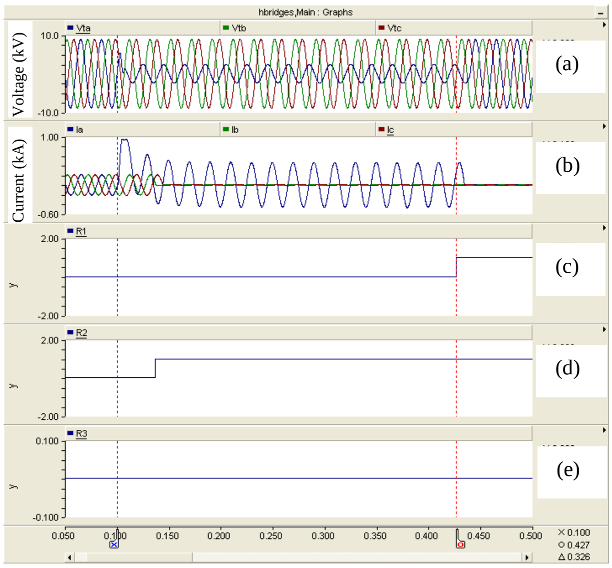

Fig. 8. System response to a SLG fault.

V. NEGATIVE SEQUENCE IMPEDANCE ANALYSIS

As highlighted from above observations, there is a need to add another feature to the relay downstream to achieve an efficient solution for the SLG faults. Therefore a negative sequence impedance analysis is carried out to find out whether it is possible to identify if the fault is either in forward or reverse direction in the presence of converter phase voltage reduction. The negative sequences are only present under system unbalances such as unbalanced faults, unbalanced loads and unsymmetrical sources. Negative impedance measurement at each relay location has been conducted in both grid connected and islanded mode operation. In this case, same system configuration is used (i.e. fault is at Bus-2 and load is at Bus-3) as shown in Fig. 5. The ratio between negative sequence voltage and current is used to calculate the negative sequence impedance seen by R1 and R2. Figs. 9 and 10 give the negative sequence impedance plot of R1 and R2 with the variation of fault resistance in the grid connected and islanded mode operation respectively.

According to the obtained results, it can be seen that there is a slight difference in the negative sequence impedance plot of R1 in grid connected and islanded modes. The fault resistance does not affect the negative sequence impedance seen by R1 in grid connected mode. However the fault resistance affects the R1 in islanding operation as can be seen in Fig. 10. In the case of R2, the locus is identical irrespective of fault resistance in both operations. Moreover R2 measures the negative sequence impedance towards the loads correctly and the measured value is always positive. However, we can see that the reactive part of the negative sequence impedance measured by R1 is always negative and that is for R2 is always positive. Therefore the reactive part of the negative sequence impedance can be used to identify if the fault is forward or reverse direction from a particular relay location. Thus we can conclude that to obtain an efficient protection solution for a radial network with loads operated under current limited converter, MHO relays with negative sequence measurement should be used in tripping decision. The decision making process is shown in Fig. 11.

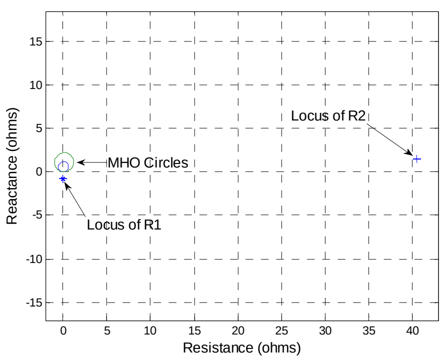

Fig. 9. Negative sequence impedance plot of R1 and R2 with fault resistance variation (0.01Ω -2Ω) in grid connected mode with a load of 3MW

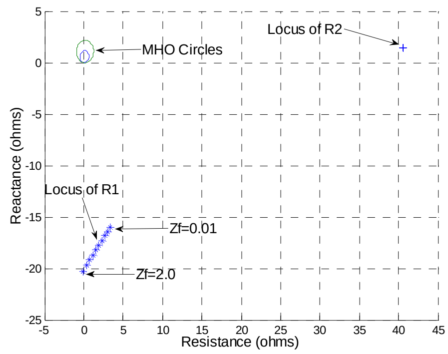

Fig. 10. Negative sequence impedance plot of R1 and R2 with fault resistance variation (0.01Ω -2Ω) in islanded mode with a load of 3MW

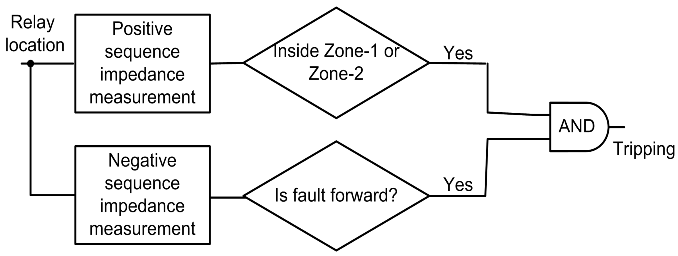

Fig. 11. Process of distance relay tripping decision making

VI. CONCLUSIONS

Converter structure and control mechanisms are presented to connect a distributed generator to a distribution network. In this converter, the output current is limited by reducing the output voltage of the faulted phase(s) in the event of a fault. Then a method for analysing fault characteristics in such a converter controlled distributed system is discussed in this paper. Based on this method, sequence currents and voltages at the relay locations have been calculated. Moreover, the distance relay performances are evaluated considering the effects of fault resistance and load conditions. It has been shown that the relay downstream to the fault operates unnecessarily for ground faults when a star connected load is connected downstream from the fault and the low fault resistance appears at the fault point. Therefore, the impedance relays with MHO characteristics may lead to an unnecessary operation by violating the coordination rules.

To alleviate this problem, negative sequence impedance analysis is carried out at each relay location. It has been shown that the reactive part of the negative sequence impedance can be used to discriminate forward and reverse faults effectively. Therefore, MHO relay with negative sequence impedance measurement can be used to protect a radial network operated by current limited converter connected DG in grid connected and islanded modes of operation.

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