

Protection Philosophy for Distribution Grids with High Penetration of Distributed Generation

S. P. S. Matos, M. C. Vargas, L. G. V. Fracalossi, L. F. Encarnação, and O. E. Batista

***Abstract* – Distributed Generation (DG) can cause several problems in electrical systems that are not prepared to deal with these new sources: situations such as bidirectional power flow and large variations in short-circuit current values. This article presents changes in the actual distribution systems protection philosophy that intend to make the protection system always work properly and reliably eliminate any short-circuit. Furthermore, it shows that the actual philosophy is inefficient in systems with high DG penetration level and, through modifications in the actual philosophy, using available functions in the protection devices, it is possible to increase the reliability and assertiveness of the protection system for any fault.**

***Keywords*: distributed generation, photovoltaic, power system protection, inverter-based generators, recloser protection.**

I. Introduction

POWER distribution networks are changing from passive to active networks due to the integration of distributed generation (DG). Most of these generators are installed near or by the consumer units, and therefore, are dispersed in the distribution network. Furthermore, the dispatch of energy from these sources is not controlled, as well as the control of active and reactive power. Accordingly, their generation is uncertain, since the most common renewable sources used, such as solar photovoltaic (PV) and wind, are intermittent or dependent on the rainfall regime [1], [2].

There is also the complexity of predicting and estimating the behavior and impacts of the power-electronics based generators during fault events. These equipment have a low or zero mechanical inertia, depending on the technology used, and lack of inductive characteristics, not developing fault currents based on electromagnetic and rotating characteristics. In addition to having a very fast envelope decay for fault currents, their behavior in these events depends mainly on the internal manufacturer control strategy than on their physical parameters and the type and location of the fault [3], [4]. Moreover, the output current is limited due to the low thermal limit of the semiconductors used in its construction in order to avoid overheating and compromising its operation. Recent studies [3], [5], [6] show that the fault current of these generators can vary from 1.06 pu up to 7.0 pu, depending on the power, type and technology embedded. As a well-accepted general rule, it is common to use values in the range of 1.06 pu to 2.0 pu [3], [4].

This paper proposes an improvement in the protection philosophy of a distribution feeder dominated by PV distributed generators (PVDG) using three-phase short-circuit and applying existing phase protection functions in reclosers to improve the protection assertiveness, avoiding adaptive protection due to the changes on the grid, the exchange of equipment or acquisition and installation of external devices.

II. Protection of Networks with DG

Regardless of the type of generation source or the technology embedded in the generators (classical rotating machines or power-electronics based), these can cause problems in the protection of the distribution system such as serious miscoordination, damage to equipment, saturation of the current transformers and failure in detect islanding or unintended islanding decreasing the protection system reliability [7]–[11].

The potential problems associated with the integration of DG into network protection can be the prohibition of automatic reclosing, desynchronized reclosing, recloser-recloser, recloser-fuse and fuse-fuse miscoordination, unintentional islanding, blind protection, and false or sympathetic tripping [1], [7], [12], [13].

Several studies have been carried out trying to solve these problems, however a standard solution or methodology has not yet been addressed and the levels of DG penetration continue to increase each year. In order to try to improve the performance of the protection system, two strategies can be highlighted: the disconnection of the DG during faults or the modification of the design of the protection system.

The first strategy allows the short-circuit level during the fault to be minimally changed, maintaining the precision and assertiveness level of the conventional protection scheme. However, depending on the DG penetration level, this disconnection can cause instability in the system's power balance and increase synchronization problems during and reconnection of the generators, reducing the reliability of protection [14]. Additionally, this practice goes against the trend of recent regulations [15] who started to suggest that the DG should remain connected to the network during voltage and/or frequency variation events to provide support through the injection or consumption of reactive and/or active power.

The second strategy relies on a wide range of tools and techniques that can be used, from limiting the fault current of the generators, optimum location of the protection devices or generators, modification of the protection parameters or

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implementation of new functions or communication links on equipments. Limiting the fault current of the generators can be done through internal generator control, limiting the current of all connected sources [16], [17] or through the use of fault current limiting devices [18], [19]. However, the use of these alternatives results in a high cost, low reliability and an accurate sizing of the external device. The authors in [20] proposed an adaptive protection coordination algorithm tested on the IEEE 4-Node test system with 3 DG units and uses communication to verify if they are connected or not to the grid. The authors in [21] presented the principle of partitioning the microgrid into smaller grids to propose a regional protection scheme adopting negative-sequence directional protection. However, the DGs parameters were adjusted according to the simulations requirement, so no unusual generation/load combination was simulated.

The use of adaptive protection has been widely studied [22], [23], mainly in microgrids. It is possible to highlight the changing of the adjustments in real-time based on the level of short-circuit and connection status of the DG. The use of new programmable relays, directional overcurrent relays, with positive-sequence function, distance relays, pilot relay has also been proposed in [24]–[28] to solve the problem of lack of coordination and selectivity.

The adaptive protection requires some tools to address the need to change protection settings due to increase or decrease of the number of DG connected to the grid. Optimization algorithms such as Linear and Nonlinear Programming, Particle Swarm Optimization, Evolutionary and Genetic Algorithms are being widespread studied to define protection settings [18], [29], [30]. However, due to the high complexity of the algorithms, they fall into a high initial cost if the current protection device of the system does not have the functions embedded and not ready to be activated. Also, it is difficult to use those tools for dynamic problems, such as constant modification of the numbers of DGs connected to the grid. The implementation of a communication network is also a high-cost problem.

Simulation softwares are also used to analyze the electrical and protection systems. It is possible to define load flow, short-circuits and transients given an initial condition. Thenceforth, all the protection settings are defined based on the result of the simulation. If the initial condition changes, such as the number of DGs or the amount of power injected to the grid, it is necessary to run another simulation to define the new short-circuit values, and the new protection settings [31].

III. Methodology

For the development of the proposed approach, it is necessary to obtain the three-phase short-circuit currents at the installation points of the reclosers, considering the PVDG. The simulation scenarios were performed considering all combinations of the connection and disconnection situation of the generators in the network. When a generator is connected, its power will vary following a typical curve of hourly power variation according to the solar incidence during the day. Additionally, regardless of whether the generators are connected or not, the connected loads vary their power consumption following a typical hourly demand curve. Thus, the simulations will be performed at each hour of the day, assigning the powers of the DGs and the loads according to Fig. 1. No unusual generation/load combination was simulated.

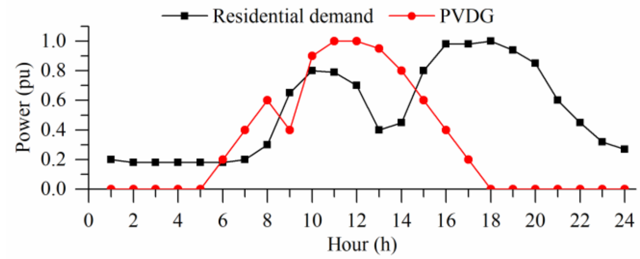

Fig. 1. Hourly curve of demand for a residential load from 0 to 100 kW, in pu, and the photovoltaic generator (PVDG) in pu.

Short-circuit currents are obtained by applying faults located at the most distant point of the substation for each protection region defined by each recloser. Additionally, it was defined that the fault points are applied at the network nodes, with no fault point at the connection extensions. For each location and type of fault, at each hour interval on the typical hourly curve of generation and load, the values of the short-circuit currents passed by the reclosers are obtained.

Thus, for the analyzed network, considering all the possible combination of the nine DGs connected to the grid, generation and load curves with 24-hour thresholds and symmetrical faults, 26,624 simulations were performed that served as a basis to analyze the behavior of the short-circuit.

IV. Case Study

A. IEEE 13-Node Radial Distribution Test Feeder

In this paper, the IEEE 13-Node Distribution Test Feeder, shown in Fig. 2, was used to study the proposed protection philosophy.

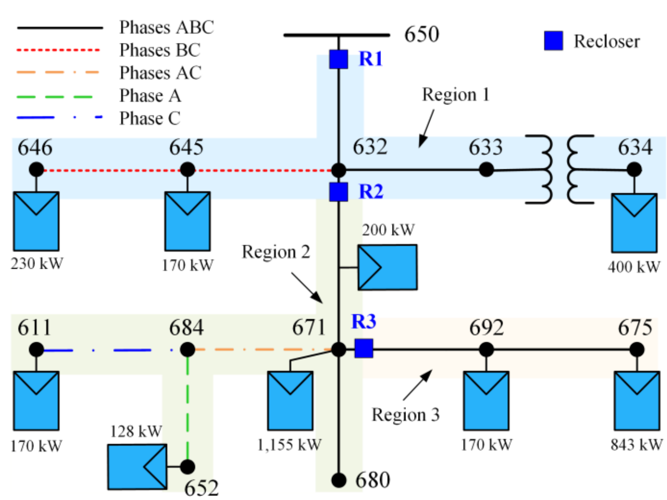

Fig. 2. Single-line diagram of IEEE 13-Node Test Feeder with the location of reclosers, and its protection regions, and distributed photovoltaic generators.

The positioning of the reclosers were defined according to [32]. The feeder is relatively loaded, since the since the loading order is approximately 75% of the substation transformer. The DG penetration level in this case is 100% indicating a high penetration, as stated by the authors in [33], [34] that define DG penetration as the percentage of the maximum DG generation of the feeder divided by the maximum loading of the distribution feeder.

The modelling of the feeder, as well as the loads and PVDGs, were based on the work of [35]. The PVDGs have been installed only where loads are connected. As the analyzed system in question has a small size, a typical load curve for residential consumers from 0 to 100 kW and the solar irradiation and power variation of the PVDGs was considered, as already presented in Fig. 1.

A. Photovoltaic Generator Model

The model of the generator chosen for the study was the PV solar. Its model was implemented in MATLAB/Simulink, according to [36], with adaptations to short-circuit conditions, as [37].

The model consists of a voltage-dependent current source at the point of common coupling (PCC) with the grid, the active power generated and the power factor configured for generator operation [36]. For normal voltage conditions, within the range of 0.8 pu and 1.0 pu of the nominal voltage in the PCC, the PVDG has a unit power factor. For voltages in the PCC outside this range, PVDG has the ability to withstand under and over voltages with injection or reactive power consumption, meeting the new network codes.

For voltages from 1.0 pu to 1.1 pu in the PCC, PVDG consumes reactive energy following the curve presented in [37] up to the limit of 0.9 inductive and is disconnected from the grid for voltages above 1.1 pu. For voltages between 0.1 pu and 0.8 pu in the PCC, the PVDG injects reactive energy into the network, according to the curve presented again in [37], up to the limit of 0.9 capacitive, being disconnected for voltages below 0.1 pu. The current of the PVDG is limited to 2.0 pu to protect its internal components, as discussed earlier. In this work, the maximum connection times between the generator and the grid for the voltage ranges presented were not considered. Thus, it is considered that the PVDGs remain connected during the evaluation interval of the variation of the level of the short-circuit of the network.

These modes of operation of the PVDG show the complexity of estimating the short-circuit current injected by generators based on power electronics, differently from classic rotating machines. Additionally, the support functions for under and over voltages with injection capacity or reactive energy consumption add a new variable to the problem.

B. Overcurrent Protection

Utilities usually adjust only the time phase overcurrent protections (function 51 ANSI) and set time (function 50 ANSI), in addition to the time delay neutral overcurrent protections (function 51N ANSI) and time set (function 50N ANSI). In this way, the reclosers have been adjusted to meet the following requirements:

- Phase current (phase pickup):

$$f_G . I_L < I_{ph}^{pu} < \frac{I_{\phi\phi-\min}^{SC}}{f_S} \quad (1)$$

in which f_G is the load growth factor, I_L is the maximum load current, I_{ph}^{pu} is the pickup current of the phase element, $I_{\varphi\varphi-min}^{SC}$ is the short-circuit current between phases, and f_S is the safety factor that normally has a value between 1.5 and 2.

- Neutral current (neutral pickup):

$$f_N < I_g^{pu} < I_{\phi g-\min}^{SC} \quad (2)$$

in which f_N is the current to earth under normal operating conditions (neutral current), I_g^{pu} is the pickup current of the neutral element, and $I_{\varphi g-min}^{SC}$ is the minimum phase-to-ground short-circuit current.

C. Directional and Undervoltage Protection

The use of the directional function in overcurrent protection aims to indicate in which position the fault is in relation to the protection device. Directional overcurrent is the calculation of the difference between the current and voltage phase angles. For cases where the voltage and current vectors indicate the same direction, the defect is probably in the direct direction. If the vectors indicate opposite directions, the defect will be in an opposite, or reverse, direction to that expected.

A transmission or distribution system undervoltage condition may occur due to the lack of reactive power to maintain the voltage profile. This can lead to a voltage collapse if no action is taken to return the system to a new breakeven point. However, it should be addressed by deployment of some system protection scheme, and the generation must not be tripped. This protection has an undervoltage element and an associated time delay. Settings must be chosen to avoid maloperation during inevitable voltage sags during system fault clearance but it has to protect the system of operating in a low or critical voltage profile.

The settings of the reclosers R1, R2 and R3, located according to Fig. 2, are those shown in the Table I, disregarding the integration of DG in the system.

TABLE I
PROTECTION SETTINGS FOR RECLOSERS WITHOUT DG INTEGRATION

	I_L	$I_{\varphi\varphi-min}^{SC}$	$I_{\varphi g-min}^{SC}$	I_{ph}^{pu}	I_g^{pu}
R1	327.42 A	2,736.92 A	1,776.30 A	700 A	700 A
R2	291.43 A	2,731.63 A	1,770.84 A	600 A	600 A
R3	140.86 A	2,730.32 A	1,769.27 A	500 A	500 A

From the short-circuit results obtained, the current philosophy of protection of radial systems is analyzed and changes are proposed: functions 50/51 phase and neutral for the direct direction, 50/51 for negative-sequence, and directional overcurrent (function 67 ANSI) for the reverse direction with undervoltage release (function 27 ANSI); chronometric coordination between reclosers in both directions.

The proposed philosophy will consist of the 50/51 phase and neutral protection function without directionality, with the adjustments defined in the Table I; and protection function 50/51 of negative-sequence enabled by function 67 for the reverse direction, with an adjustment of 10 A to accommodate possible situations of natural unbalance of currents in a radial distribution system. Additionally, it will only act in the reverse direction (direction from the current to the source). This protection will not be adjusted in R1 and will be adjusted in R2 and R3. The settings of the 50/51 negative-sequence protection function must be greater than the negative-sequence current measured by the device under normal conditions, and less than the smallest negative-sequence current of the faulty system. Function 27 will be set to 90% as it is the precarious voltage limit for systems between 1 kV and 230 kV, according to the Brazilian standard [38].

Chronological coordination for forward and reverse direction should allow coordination with fuses and disconnectors that may exist in the electrical system and should coordinate between reclosers, respecting the minimum coordination time interval (CTI) of 200 ms to accommodate protection processing delays and delays in the opening of reclosers. In this way, for protections in the direct direction, the CTI for recloser R3 will be 400 ms, for recloser R2 it will be 600 ms and for recloser R1 it will be 800 ms. For reverse protections, the CTI for recloser R3 will be 600 ms, for recloser R2 it will be 400 ms. Recloser R1 will not have protection set to the reverse direction.

V. Results

The reclosers tripped correctly for 100% of the short-circuit cases according to the actual protection philosophy of radial systems, disregarding the influence of any DG, confirming that the overcurrent settings defined above are correct. However, when the DGs begins to be inserted in the system, it is necessary to observe the region where the defect is, shown in Fig. 2 and the direction of the currents in each recloser to determine whether the protection should or should not act.

Therefore, for faults in Region 1, reclosers R1 and R2 must trip simultaneously to eliminate the defect. For faults in Region 2, the reclosers R2 and R3 must trip simultaneously and, for faults in Region 3 only the recloser R3 must trip to eliminate the fault. This is due to the fact that a reverse power flow appears, and consequently the DGs short-circuit contributions can occur in a reverse way in the system in question. For this reason, it is necessary to isolate the faulty region by tripping all reclosers that are at its limits. In this case, we are considering overcurrent protection without directionality. The results show that R1 protection trips correctly for 100% of cases, R2 for 76%, and R3 for 25%.

It is observed that the insertion of DG in the electrical system reduces the probability of correct tripping of the recloser protections, which can cause several disturbances to consumers connected to the network. For a fault in Region 1, it is necessary that R1 and R2 recloser protections act to isolate the fault. In this case, the results are that R1 protection trips correctly for 100% of cases, R2 protection trips correctly for 4.02% of cases and R3 does not have any protection tripping, which is correct for 100% of the cases. However, R3 will not be a backup of R2 in reverse direction. These results are represented in Fig. 3 (a), (b), and (c).

For a fault in Region 2, it is necessary that R2 and R3 recloser protections trip to isolate the fault. In this case, the results are that R1 protection trips correctly for 100% of cases (acting as a backup protection for R2 recloser), R2 for 100% of cases and R3 does not have any protection tripping, which is correct for 0% of the cases. These results are represented in Fig. 3 (d), (e), and (f).

For a fault in Region 3, it is necessary that R3 recloser protection trips to isolate the fault. In this case, the results are that R1 and R2 protections trips correctly for 100% of cases (acting as a backup protection for R3 recloser) and R3 trips correctly for 100% of cases. These results are represented in Fig. 3 (g), (h), and (i).

The reverse load current for recloser R2 is 186.56 A and for recloser R3 is 35.99 A. The minimum reverse three-phase short-circuit current seen by recloser R2 is 4.3 A and the current minimum three-phase short-circuit in the reverse direction seen by recloser R3 is 3.5 A. Adding to the current protection philosophy the protection function 50/51 of negative-sequence enabled by function 67 for the reverse direction, the results are: for a fault in Region 1, R1 protection trips correctly for 100% of cases, R2 for 78.37% of cases, and R3 for 43.03% of cases (acting as a backup protection for R2 recloser); for a fault in Region 2, R1 protection trips correctly for 100% of cases (acting as a backup of R2 recloser), R2 for 100% of cases, and R3 for 21.15% of cases; for a fault in Region 3, R1 protection trips correctly for 100% of cases (acting as a backup of R2 recloser), R2 for 100% of cases (acting as a backup of R3 recloser), and R3 for 100% of cases.

The negative-sequence function with parameterized directionality still has some weaknesses: failure to act on balanced three-phase defects for protection in the reverse direction; incorrect operation due to an increase in the natural imbalance of the radial distribution system due to the network expansions; no action due to the need for high pickup adjustment to accommodate the system's natural imbalance; and dependence on chronological coordination.

In order to eliminate the weaknesses found, in addition to directionality, it is necessary to use the function 27 to further improve the protection's assertiveness. The results of the simulations indicate that the highest voltage value found among all simulations was 71% of the nominal voltage. Therefore, the pickup value of the function 27 can be adjusted conservatively to 90%, which will cover all simulated fault cases. Since the system will be under fault when the voltage on a bus drops below 90% of the nominal voltage, it is possible to reduce the pickup value of the 10 A negative-sequence overcurrent protection function to the lowest possible value parameterized in the recloser protection, covering all simulated cases, and reaching 100% assertiveness in the protection performance with this philosophy, according to the simulated scenarios. However, the proposed philosophy is still dependent on chronological coordination, which implies the need to change the time settings of all reclosers if the electrical system is expanded and new reclosers are

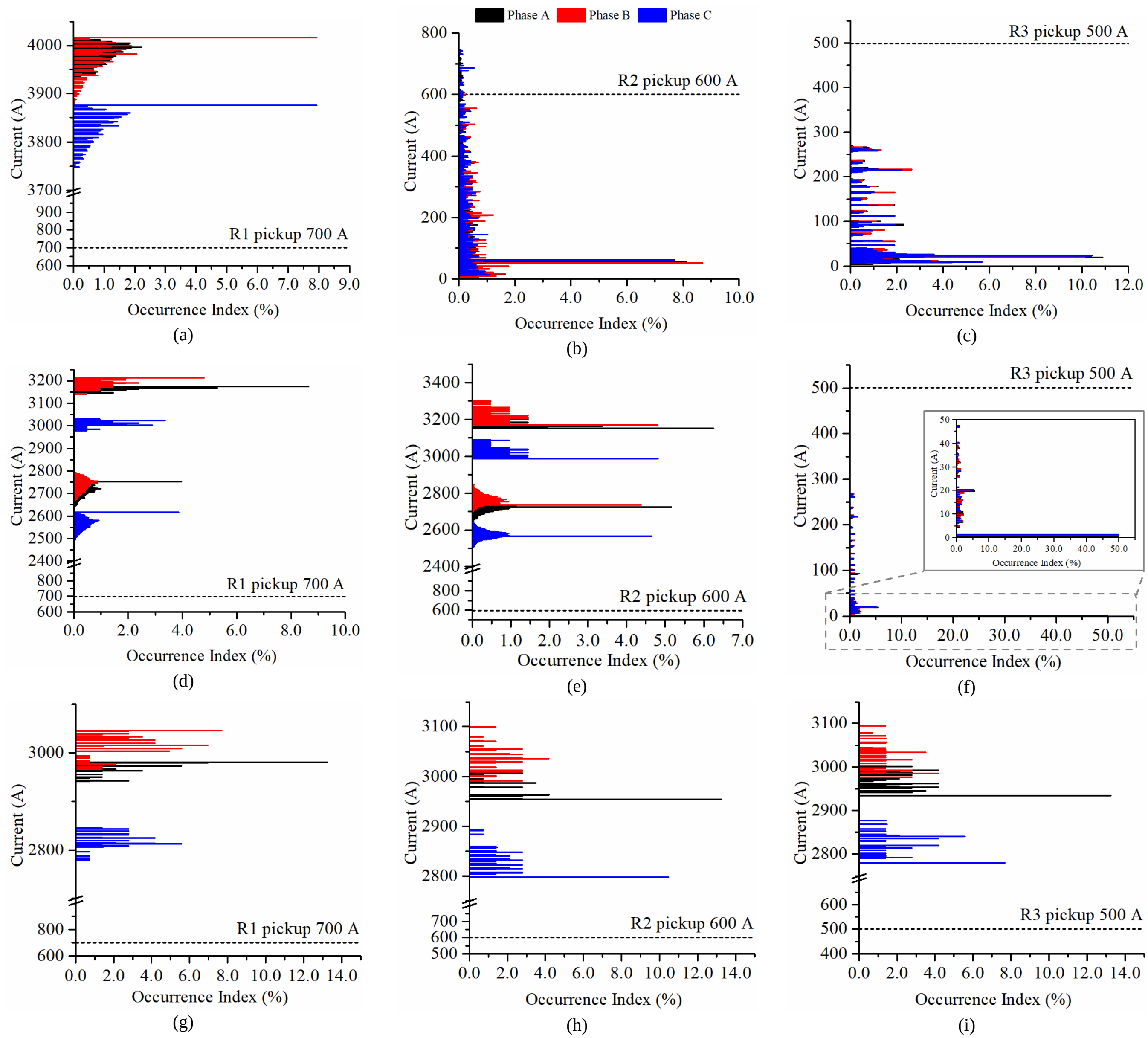

Fig. 3. Fault occurrence indices in the reclosers and pickup current for a fault in the (a), (b), (c) Region 1; (d), (e), (f) Region 2; and (g), (h), (i) Region 3.

installed. The proposed philosophy logic is shown in Fig. 4.

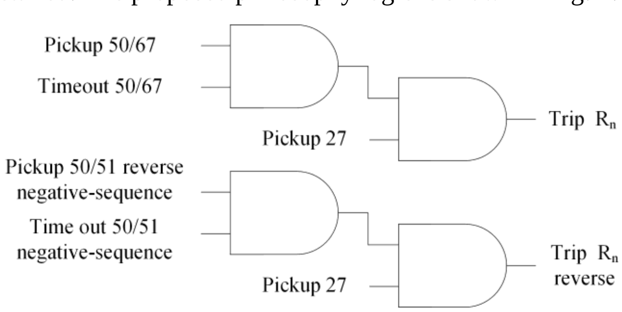

Fig. 4. Logic of proposed protection philosophy.

This work did not focus on simulating unusual conditions of generation and load. A possible unusual condition would be to have all generators at maximum generation and no load connected. However, this proposed philosophy may be able to trip correctly in this condition because the forward pickup functions should still be lower than the short-circuit value read by the recloser, and the reverse functions will trip correctly because the recloser will read a higher short-circuit current from the DG.

VI. Conclusion

This paper presented a new protection philosophy in order to be more assertive and reliable. The advantages of this proposed philosophy are that uses functions and logic already available at the existing reclosers, it does not need to be modified in network expansions and can be widely used in any distribution system. If the network is highly unbalanced, it may be difficult to adjust the negative-sequence pickup, due to high values of negative-sequence current at normal conditions. To mitigate this possible problem, the undervoltage function releases the protection trip after the positive-sequence of negative-sequence overcurrent protection pickup. On the other hand, for the installation of each new recloser, it will be necessary to review all the time settings of all the other reclosers in the network and, if it becomes bigger, the time settings may be so high that it may become impractical. A possible solution for this problem is to use communication links between the reclosers.

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