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Research paper

Investigating the Impact of Distributed Generation (DG) in Radial Distribution Networks and Optimizing Protective Devices Using the PSO Optimization Algorithm

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Abstract

Integrating distributed energy resources into existing power networks can lead to significant challenges. These challenges often arise from the coordination of protective devices within the network. In this paper, we investigate the impact of connecting Distributed Generation (DG) to radial distribution networks and propose a novel approach for optimizing protective device settings to enhance their coordination. By analyzing different relay settings in the DigSilent software under various fault conditions, we determine the optimal configurations for the system in the presence of DG. The Particle Swarm Optimization (PSO) algorithm is employed using MATLAB. The proposed approach is applied to a radial distribution network, and the results are evaluated under different fault scenarios. In each scenario, a short circuit happens and relays operate in order; the operation intervals for relays are 0.02s, approximately.

1. Introduction

The demand for electrical energy is increasing day by day. To meet this demand, new technologies called Distributed Generators (DGs) are being introduced into the system. These include renewable energy sources such as photovoltaic (PV), wind, fuel cells, biomass, etc. Integrating DGs into existing networks enhances network robustness, reduces losses, and operational costs at peak times, while improving voltage profiles and load factors [1]. In this situation, the reliability of electricity supply to consumers is enhanced.

However, placing new energy sources close to consumers introduces various operational challenges in the system. Implementing Distributed Generation (DG) in the system can create significant issues in distribution networks because existing distribution systems are designed for radial flow. The presence of DG may impact or violate existing planning and operational procedures [2]. Integrating distributed generation and other storage devices into radial networks alters the traditional unidirectional power flow, significantly affecting the coordination of protective devices used in the system.

By adding DG to existing feeders, nominal current or fault current is redistributed through the feeder. This can significantly impact load current and fault current seen by protective devices. In such scenarios, variations in fault current levels occur. Increased short-circuit capacity and changes in fault current direction in the distribution network affect the coordination of protective relays installed in the distribution system, thereby compromising the performance, selection, and reliability of protection schemes [3].

M. H. Bresten and et al, investigate the aspects of grid-connected converters and their inherent influence on the power grid [4] and in 2023, laboratory tests of distribution feeder protection response was done with inverter-based resources [5].

Optimal settings for protective coordination devices in DG-connected systems are essential (Abbay, 2007). To achieve this, relay operation times have been optimized using various optimization methods. Common trial-and-error approaches are also used to determine parameter settings for different operational conditions. Artificial intelligence methods have proven highly effective for optimizing coordination parameters in DG-connected networks [7].

In this article, the main objective is to utilize an artificial intelligence-based algorithm for optimizing the coordination parameters of protection systems in distribution networks connected to DG. Protection plays a crucial role in these networks and is essential in the power industry.

Genetic algorithms and Particle Swarm Optimization (PSO) are computational intelligence techniques proposed for solving optimization problems. The genetic algorithm mimics evolutionary biology to find approximate optimal solutions [8]. While it can quickly find good solutions, it has drawbacks, including convergence toward local optima instead of global solutions and difficulties in execution due to dynamic data sets.

In specific optimization problems with computational time constraints, simpler optimization methods may yield better results than this algorithm. As reported in studies by Hasan et al, (2005) [9] and Arya et al, (2010) [10], the PSO algorithm consistently achieves superior results compared to other optimization methods, especially genetic algorithms.

The advantages of the PSO method over other approaches, particularly genetic algorithms, are as follows:

Executing PSO with fewer parameters for tuning is easier.

1. Executing PSO with fewer parameters for tuning is easier.
2. The memory capability of PSO is more effective than the genetic algorithm because each particle is able to memorize its previous best position and local location in the best possible way.
3. PSO is more efficient for maintaining diversity within a population. This is because PSO utilizes the most successful information to move toward better solutions, similar to the social behavior of a community. In contrast, genetics disregards inferior solutions and only retains good ones.

This article focuses on the impact of DG on the coordination of protection systems in radial distribution networks. An optimal protection scheme has been developed to determine the best settings for protective devices. A 4-bus system is studied, simulated using DigSilent software, and optimized using the PSO algorithm in Matlab. The structure of the article is as follows: In the second section, various protection issues in radial distribution networks with distributed generation (DG) are discussed. The third section introduces the PSO optimization algorithm and explains how it relates to the two software programs. The fourth section describes a 4-bus system case study and presents the simulation results. Finally, the article concludes with suggestions for future research in this field.

2. Protective Issues in the Presence of DG

For reliable operation of DG connected to the system, proper coordination with the network is essential. DG is connected to the network through the Point of Common Coupling (PCC). This PCC must be adequately protected to prevent damage to DG equipment and auxiliary tools. Therefore, appropriate coordination of protective devices is necessary. Coordination of protective equipment in simple radial networks is straightforward because the network has a single source [2], resulting in unidirectional fault current flow. The entry of DG into the distribution network results in bidirectional current flow and complexity in network topology. Protective device settings and features must be adjusted according to the new topology.

DG can be utilized at different locations in the distribution network:

1) End of the line with fault creation in the direction of the main source and distributed generation.

2) Between the end of the line and the main network.

3) At the end of the line and the occurrence of an error in a branch other than the main source and DG.

Therefore, to analyze the effects of DG, a three-bus general network is examined under three different scenarios.

2.1 First System Configuration

The first state of the 3-bus test system is shown in Figure (1). In this system, an error has occurred at bus 2.

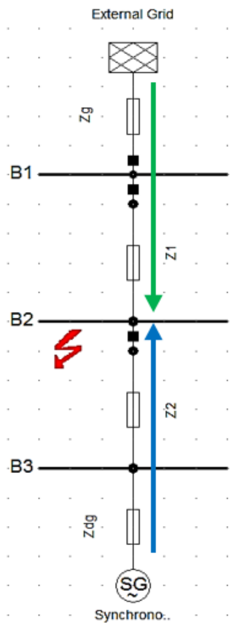

Figure 1: First case study of a 3-bus system.

Considering the circuit in Figure 1, the three-phase short-circuit current is the sum of the short-circuit currents from the network and the DG at the fault point. These are represented by the green and blue directional lines, respectively. The short-circuit currents from the network (I_g) and DG (I_{dg}) can be expressed as follows:

$$I_g = \frac{U_g}{Z_g + Z_1} \tag{1}$$

$$I_{dg} = \frac{U_{dg}}{Z_{dg} + Z_2} \tag{2}$$

In the formulas (1) and (2), U_g and U_{dg} , respectively represent the external network voltage and the DG-generated voltage. Z_g, Z_{dg} , Z_1 and Z_2 , respectively denote the internal impedance of the network, the internal impedance of DG, and the impedances of the first and second lines.
The value of the internal impedance of distributed generation can be calculated as follows:

$$Z_{dg} = X''_{dg} \frac{S_{sys}}{S_{dg}} \tag{3}$$

X''_{dg}, Underpass reactance of DG. S_{sys} denotes the system base power in MVA. S_{dg} is DG capacity (MVA).

Here, the fault current exists in both directions relative to the fault point. Therefore, bidirectional relays are necessary to detect reverse current.

2.2 second System Configuration:

The second case study involves a three-bus experimental system, as shown in Figure 2. In this scenario, a fault is created at bus 3.

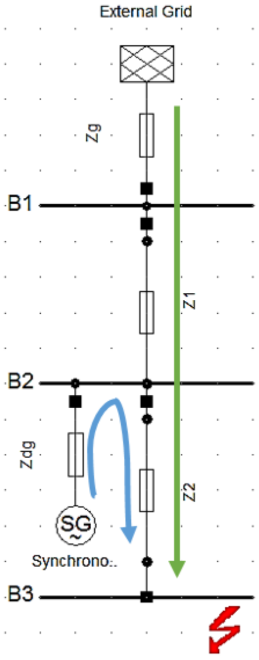

Figure 2: Second case study of a 3-bus system.

In the circuit shown in Figure 2, the three-phase short-circuit current at bus 3 is equal to the sum of the short-circuit currents from the network and DG. The short-circuit currents from the network (I_g) and DG (I_{dg}) can be expressed as follows:

$$I_g = \frac{Z_{dg}}{Z_{dg}(Z_g + Z_1 + Z_2) + Z_2(Z_g + Z_1)} U_g \tag{4}$$

$$I_{dg} = \frac{1}{Z_{dg} + Z_2}\left[U_{dg} - \frac{Z_2 Z_{dg}}{Z_{dg}(Z_g + Z_1 + Z_2) + Z_2(Z_g + Z_1)} U_g\right] \tag{5}$$

As observed, the main network current at the fault point depends on the presence of DG and its location. This may impact the sensitivity and selection of the relay connected to the system. The lower value of the main network current at the fault location affects the performance of the feeder end relay. The relevant relay does not turn off when it sees the fault or is disconnected after a long delay.

2.3 Third System Configuration

Figure 3 illustrates the third case study of a three-bus experimental system. In this scenario, a fault occurs at bus 3 in a branch separate from the network path to DG.

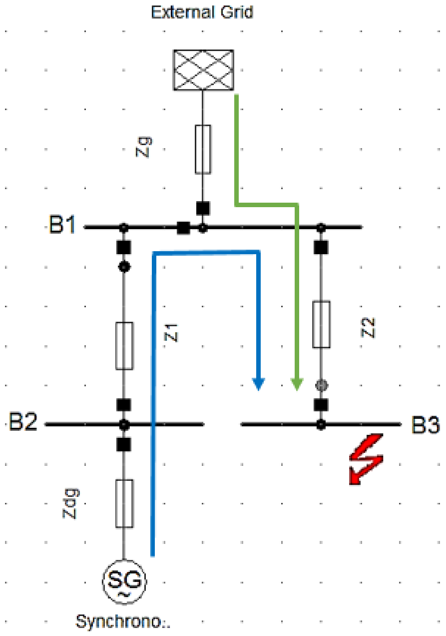

Figure 3: Third case study of a 3-bus system.

As observed in the circuit shown in Figure 3, the three-phase short-circuit current at bus 3 is equal to the sum of the short-circuit currents from the network (green) and DG (blue). The short-circuit currents from the network (I_g) and DG (I_{dg}) can be expressed as follows:

$$I_g = \frac{(Z_g + Z_1 + Z_2)U_g - Z_2 U_{dg}}{(Z_1 + Z_{dg})(Z_2 + Z_g) + Z_g} \tag{6}$$

$$I_{dg} = [\frac{\left(Z_g - Z_2(Z_g + Z_2)\right) U_g + Z_2(Z_g + Z_2)U_{dg}}{(Z_1 + Z_{dg})(Z_g + Z_2) + Z_g}] \tag{7}$$

The impact of this system can be considered as an example of false tripping. For a significant share of DG current at the fault point, Feeder 2 trips instead of Feeder 3, which is unacceptable.

2.4 DG Impact on Distribution Networks

Considering the three systems examined in the previous subsections, the effects of Distributed Generation (DG) in the distribution network can be summarized as follows. Considering the presence of Distributed Generation (DG) in the network, the fault current direction changes, and this topology causes bidirectional fault current to vary. The fault current level increases or decreases, which leads to a loss of sensitivity and selectivity in the protective device. With an increase in the nominal current, the protective device issues incorrect trip commands. Conversely, when the network current decreases, blind spots are created in protection. The fault current level that is less than the instantaneous pickup value affects the trip time. These issues [9] directly or indirectly related to each other. Changes in the short-circuit current level are the main cause of protection coordination mismatch.

3. Study Methodology

In this section, the PSO method in Matlab software and the connection between Matlab and DigSilent are presented.

3.1 PSO Optimization Method

Mathematically, the search process can be expressed using simple equations involving position vector $X_i = [x_{i1}. x_{i2}. \dots . x_{id}]$ and velocity vector $V_i = [v_{i1}. v_{i2}. \dots . v_{id}]$ in a d-dimensional search space. The optimality of the solution in the PSO algorithm depends on the update of particle positions and velocities, which are calculated using equations (8) and (9) (Del Valle et al., 2008).

$$V_i^{k+1} = wV_i^k + c_1 r_1 [X_{pbest}^k - X_i^k] + c_2 r_2 [X_{gbest}^k - X_i^k] \tag{8}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{9}$$

In the above equations, i represents the particle index. V_i^k and X_i^k are, respectively, the velocity and position of the i-th particle in the k-th iteration. w is the inertia constant, typically within the range [0, 1]. c_1 and c_2 are convergence coefficients within the interval [0, 2]. r_1 and r_2 are random values generated for updating the velocity. X_{gbest} and X_{pbest} represents the global best position across all iterations, and represents the local best position in the current iteration.

3.2 The connection between Matlab and DigSilent software:

In this article, an algorithm for optimizing the existing relay settings in medium-voltage networks has been developed using the PSO method within the Matlab software. The calculations related to short-circuit analysis, fault current magnitude, and total relay operating time are performed using the DigSilent software. Figure 4 illustrates the input and output connections between the DigSilent and Matlab software platforms.

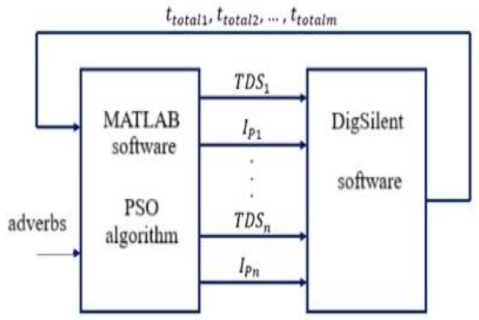

Figure 4: Illustration of the communication between DigSilent and Matlab software platforms.

In Figure 4, m, n and t_{total}, represent the number of buses (or the number of short-circuit calculations created in each bus), the number of relays, and the total relay operating time, respectively. These values are calculated using Equation (10).

$$t_{totalh} = t_{1h} + t_{2h} + \cdots + t_{nh} \quad . \quad 1 < h < m \qquad (10)$$

In the given equation, t_1 to t_n, represent the operating time of the first to the n-th relay present in the network. In the designed PSO algorithm, there exists a constraint and an objective. The defined constraint pertains to the first relays that must operate after a fault occurs. The objective is to minimize the total relay operating times for fault occurrences in each bus.

4. Simulation Conducted

This section comprises two subsections, which include the studied system and simulation results.

4.1 Studied System

The studied system is depicted in Figure 5.

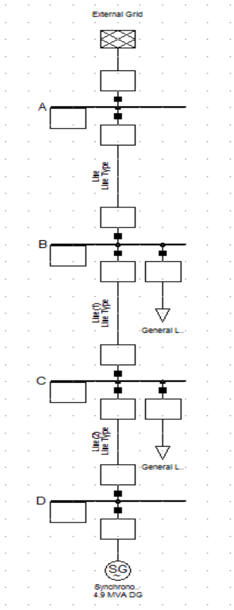

Figure 5: The studied system.

This distribution system consists of 4 buses, a main network, two loads, and one DG unit. Additionally, there is a relay at the beginning and end of each line. The relays present in the system are depicted in Figure 6.

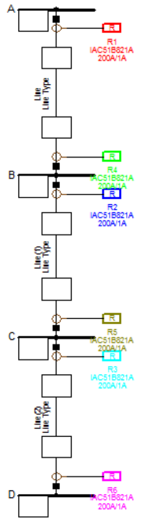

Figure 6: Relays present in the studied system.

4.2 Simulation Results

The applied constraint in the PSO algorithm is listed in Table 1.

By running 1178 iterations in the PSO algorithm, the results obtained for the optimal values of TDS and I_p for each relay are presented in Table (2).

In figures (7) to (10), the results obtained in the Digsilent software are visible.

Table (1): Constraints Applied in the PSO Algorithm

The sequence of operation of the bus low-side relay.	The sequence of operation of the bus high-side relay	The bus where the error occurred
1-4-2-5-3-6	-	A
2-5-3-6	4-1	B
3-6	5-2-4-1	C
-	6-3-5-2-4-1	D

Table (2): Results obtained from the designed PSO algorithm

I_p	TDS	Relay
0.39	0.051	R_1
0.5	0.05	R_2
0.55	0.051	R_3
1.2	0.05	R_4
0.9	0.05	R_5
0.7	0.052	R_6

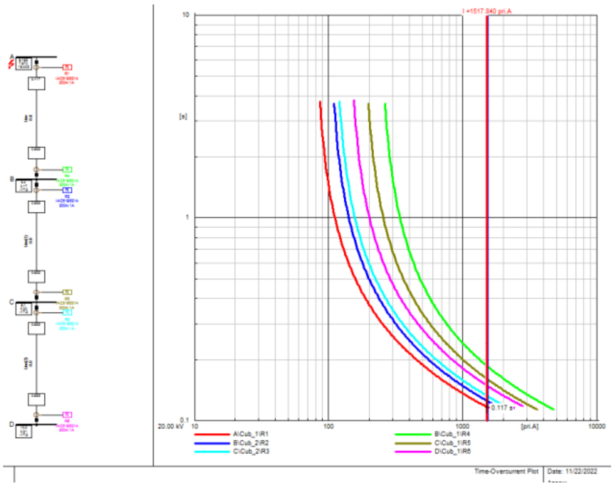

Figure (7): The results of relay performance with an error in the first bus.

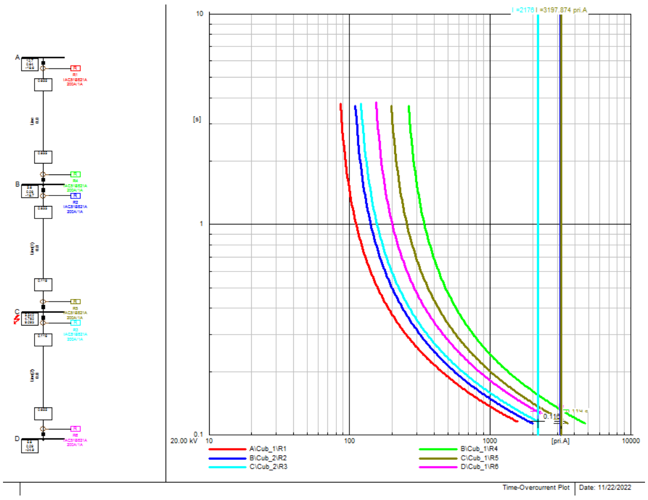

Figure (9): The results of relay performance with an error in the third bus

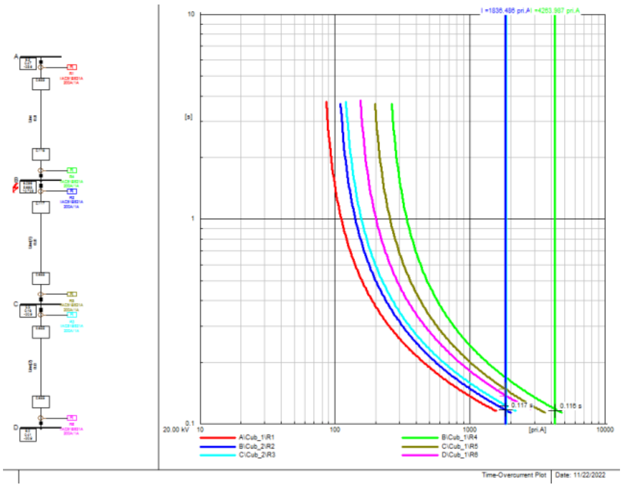

Figure (8): The results of relay performance with an error in the second bus

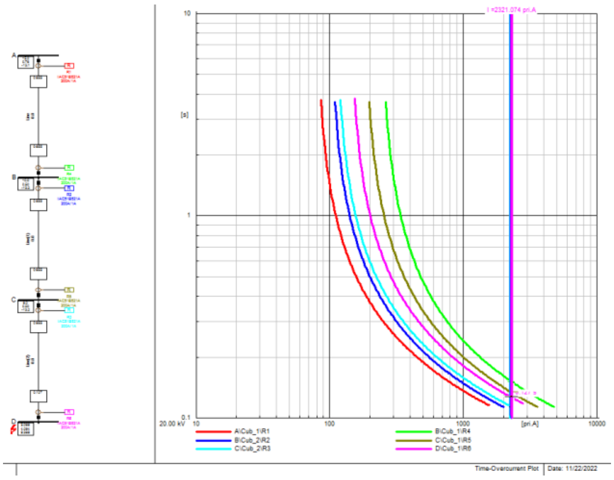

Figure (10): The results of relay performance with an error in the fourth bus

As observed in figures (7) to (10), the relay performance sequence has been correctly adhered to for each fault.

5. Conclusion and Recommendations:

The objective of this article is to determine the optimal settings for relays in the network when DG is introduced. As seen in section 4, with the integration of DG into the network, the entire relay settings require review. The PSO algorithm was employed to identify the best settings. By introducing faults in each bus, the affected bus is isolated by the existing relays, while the rest of the network remains energized by the main network and DG.

In future work, additional constraints, such as relay operation time intervals, could be incorporated into the PSO algorithm, or an alternative generalized optimization method could replace the algorithm used in this study.

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