IMPROVEMENT OF POWER SYSTEM DISTRIBUTION PROTECTION SCHEME WITH INCORPORATION OF DISTRIBUTED GENERATION

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ABSTRACT: Distributed Generation (DG) has been mostly employed in power system due to progression in exploiting renewable energy resources, necessity for enhanced power quality and reliability of power system. However, installing DG in an electric power system changes its protection coordination, thereby increasing the fault level of the power system. This research paper therefore, improves the power system protection scheme on distribution system based on integration of DG. Load flow at contingence on 33-bus Ilorin industrial distribution feeder with incorporation of DG was performed using Bus Injection to Branch Current (BIBC) and Branch Current to Bus Voltage (BCBV) iterative technique. The coordination problem of the protection scheme in-feed from the DG was improved using Salp Swarm Algorithm (SSA) and simulation was carried out in MATLAB R2021a. The results obtained demonstrated the effectiveness of the SSA in providing optimal solution for industrial distribution feeder system protection with DG incorporated. Thus, this study can be used in electrical power system protection and monitoring.
Keywords: Power System, Distributed Generation, Renewable Energy Resources, BIBC-BCBV, Salp Swarm Algorithm, Distribution Feeder, Protection Scheme.
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I. Introduction

Electrical protection system is the art or science of continuously monitoring the power system, detecting the presence of a fault and initiating the correct tripping of the circuit breaker. Its objectives are to limit the extent and duration of service interruption whenever equipment failure, human error, or adverse natural events occur on any portion of the power system; and to minimize damage to the power system components involved in the failure and prevention of human injury [1, 2]. This protection system is designed to detect abnormal system condition and take pre-planned, corrective action to provide acceptable system performance. Such action includes changes in demand (load shedding), changes in generation or system configuration to maintain system stability or integrity and specific actions to maintain or restore acceptable voltage levels [2, 3]

Thus, for a good protection system reliability and efficiency during faults, each electrical component in the power system must be protected These protection scenarios leads to the formulation of the protective relay coordination, which consists of selection of a suitable setting of each relay such that their fundamental protective functions (sensitivity, selectivity, reliability and speed) are met under the desirable qualities of protective relaying [4, 5]

However, integrating Distributed Generation (DG) into distribution system territories as back-up power sources increases the complexity in the system operation and change the existing protection scheme. These protection issues are considered a major concern as it directly relates to safety and reliability of the power system [1, 3, 5]. In addition, due to the DG impact on system protection, especially the disturbance caused to the existing relay coordination, the setting of all protection relays need to be checked as to mitigate relay mis-coordination in the power system [6, 7].

Thus, in order to improve the efficiency of power system with DG interconnection, rapid detection of abnormal situation in the power system and preventing the propagation of the fault in the power system, an optimal protection schemes that explicitly consider DG design regarding the number, size location and technology of the DG connected must be taken into account [3, 5, 7, 8]. Thus, there is the need to improve the coordination of the protection system scheme optimally when additional power source is provided to the distribution system via DG as to decrease the fault current and overvoltage that occur in power system.

II. Problem Formulation for the Protection Scheme

The fast growing of energy demands, reliability challenges, emission concerns and electricity loss due to long transmission lines highlight the role of the DG in power system. However, the increase of penetration of DG in electrical distribution system provides an additional fault current which affects the performance of the existing system protection scheme. Thus, the main objective function of this paper is to improve the coordination of the distribution protection system scheme when additional power source is provided to the power system via DG. This is formulated as a multi-objective optimization problem so as to determine the optimal solution to the protective scheme coordination.

This can be mathematically formulated as in equation s (1) to (5) [2, 7, 9, 10]

$$\min . f(X) = \sum_{i=1}^{N} \left(\sum \left[f_1(x), f_2(x), f_3(x) \right] \right) \tag{1}$$

where;

$$f_1(x) = \sum_{i=2}^{N} \sum_{k=1}^{N-1} \left(\frac{P_i^2 + Q_i^2}{V_i^2} \right) * R_i \qquad i = N_{k+1}, \ldots,, N \tag{2}$$

$$f_2(x) = \sum_{Qi=1}^{N} V_{VCi} * V_{VPi} \tag{3}$$

$$f_3(x) = T = K_1 \frac{TDS}{M^{K_2} + K_3} \tag{4}$$

$$M = \frac{I}{I_P} \tag{5}$$

where; f_1 is the total active power loss of the system, f_2 is the voltage profile of the systems, f_3 is the relay operating time setting, x is the variable constasnt, V_i is the voltage at bus i,. P_j and Q_j are the total effective active and reactive power loads, respectively, $N-1$ is the total number of system branches, R_i is the constant resistance of the system, V_{VCi} is the voltage violation constraint, V_{VPi} is the voltage penalty factor for bus i, N is the number of buses, I is the relay current, I_P is the relay's picp-up current, K_1, K_2 and K_3 are constant depending on the type of the relay simulated. TDS is the time dial setting of the relay, M is the plug multiplier setting

The multi-objective function needs to satisfy all the operational constraints (equality and inequality constraints).

The equality constraints consist of load flow constraints as in Equations (6) and (7):

$$P_i + P_{DGi} - P_{Di} + P_{Loss} = 0 \tag{6}$$

$$Q_i + Q_{DGi} - Q_{Di} + Q_{Loss} = 0 \tag{7}$$

Inequality Constraints: The constraints comprising of generator voltages, real power outputs and reactive power outputs are restricted by their lower and upper limits as equations (8) to (12)

$$V_{Gi}^{Min} \le V_{Gi} \le V_{Gi}^{Max} \tag{8}$$

$$P_{Gi}^{Min} \le P_{Gi} \le P_{Gi}^{Max} \tag{9}$$

$$Q_{Gi}^{Min} \leq Q_{Gi} \leq Q_{Gi}^{Max} \quad (10)$$

$$P_{DGi}^{Min} \leq P_{DGi} \leq P_{DGi}^{Max} \quad (11)$$

$$Q_{DGi}^{Min} \leq Q_{DGi} \leq Q_{DGi}^{Max} \quad (12)$$

For $i = 1, \ldots, NG$

The relay operating time with DG must be greater than the primary relay operating time as in Equation (3.13):

$$t_{op,j} \geq t_{op,i} + \Delta t \quad (13)$$

where: P_i is real power flow at bus i in kW, Q_i is reactive power flow at bus i in kVAR, P_{DGi} is real power generation from DG placed at bus i in kW, Q_{DGi} is reactive power generation from DG placed at bus i in kVAR, P_{Di} is real power demand at bus i in kW, Q_{Di} is reactive power demand at bus i in kVAR

A. BIBC-BCBV Load Flow for Contingency with DG

The Bus Injection to Branch Current (BIBC) and Branch Current to Bus Voltage (BCBV) load flow on 33-bus Ilorin industrial distribution feeder shown in Figure 1 at contingency was performed by increasing the load bus of the distribution feeder to 70 % loading [11-15] to check the stability of the system during failure of the components and to verify the DG effect on system protection coordination. The protection coordination and sequence of relay operation for faults in different buses were checked. The critical buses were identified and ranked based on network power loss. The simulation for BIBC and BCBV load flow with DG for contingency was carried out in MATLAB R2021a

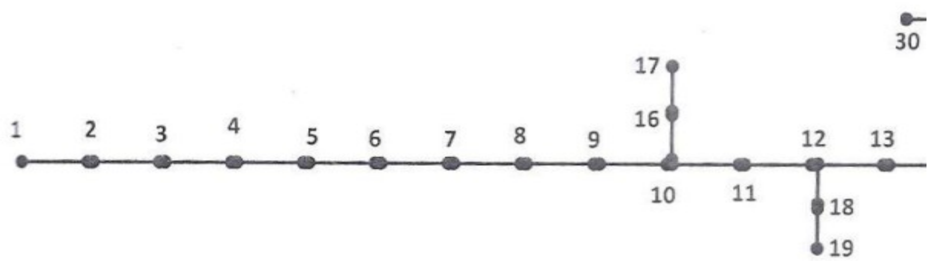

Figure 1: 33kV 33-Bus Ilorin Industrial Distribution Feeder

In order to meet the relay coordination requirements, the following parameters were required for fault calculation:

i. Pre-fault and Post-fault current (with DG) were calculated
ii. Tentative locations for relays, sectionalizing devices, switch gears and reclosers were established.
iii. The protective relays for the fault current and fault impedance were set between (0.3 – 0.5 seconds) for the tripping, isolation of the faulty line and for regular operational planning [16 -18]:
iv. An appropriate relay coordination scheme was put in place.
v. The short circuit current was reduced by increasing the impedance on the line between the feeder and point of location of fault in order to avoid damage of equipment.

The symmetrical pre-fault current was calculated according to [19-22] as in equation (14):

$$I_a = I_{fMin} = \frac{E}{Z_k + Z_f} \quad (14)$$

With integration of DG into distribution network, the system fault current of DG downstream protection was calculated as in equation (15):

$$I_{DG} = \frac{KE_{\phi}}{Z_{s\min} + Z_d} \quad (15)$$

For protective relay settings calculation, the measuring impedance and protective relay for tripping were calculated using equations (16) and (17):

$$Z_m = \frac{V_m}{I_m} \quad (16)$$

$$Z_{set}^i = K_{rel}^i \left(Z_{line} + K_b\right) \quad (17)$$

The co-ordination of the relay time settings with incorporation of DG was calculated using Equations (18) to (19).

$$t_{op} = TD\left[\frac{A}{M^p - 1} + B\right] + IT \quad (18)$$

$$M = \frac{I_{in}}{I_{pickup}} \quad (19)$$

where; I_{fMin} is minimum fault current before integration of DG, Z_k is the total positive sequence bus impendence, Z_f is the fault impendence, E is the induced e.m.f under load condition, V_m is the relay measuring voltage, I_m is the current at the relay point, K_b is the branch coefficient that offsets the infeed fault current, K_{rel} is the reliability coefficient at i^{th} terms, Z_{line} is the line impedance of the feeder

From the above fault calculation, the results of relay settings were recorded.

B. Implementation of SSA for Optimal Relay Coordination

The Salp Swarm Algorithm (SSA) technique was used as optimization technique to solve coordination problem of the relays with DG and to provide optimal solutions for DG placement with system protection. The capacity of DG was determined according to the working range of distribution system. The BIBC and BCBV load flow of DG with adaptive distance relay were performed and the stability of the system was determined. The SSA were implemented and each solution in the optimization process was updated. The positions of slaps were updated using equations (20) to (22) [10, 15, 21]:

$$x_n^1 = \begin{cases} F_n + c_1\left(\left(u_n - l_n\right)\cdot c_2 + l_n\right) & c_3 \geq 0 \\ F_n - c_1\left(\left(u_n - l_n\right)\cdot c_2 + l_n\right) & c_3 < 0 \end{cases} \quad (20)$$

$$c_1 = 2e^{-\left(\frac{4a}{A}\right)^2} \quad (21)$$

$$x_n^i = \frac{1}{2}\left(x_n^i + x_n^{i-1}\right) \quad (22)$$

The fitness function of each Salp was evaluated using equation (23).

$$Optimize\, f(X) = \sum_{i=1}^{N}\left(\sum\left[f_1(x), f_2(x), f_3(x)\right]\right) \quad (23)$$

where; x_n^1 is the position of the leader, F_n is the best solution, u_n and l_n are the upper and lower bounds respectively, c_1, c_2 and c_3 are variables of random numbers. a and A are the current iteration and the maximum number of iterations respectively, $X = \left(x_{.1}, x_2, x_3 ......x_n\right)\cdot \varepsilon R^n$ and $x = \left(V_i, P_{GDI}, Q_{GDi}, n_{Bus}\right)$ are the vector variables.

The simulation of SSA was carried out in MATLAB R(2021) according to the flowchart shown in Figure 2

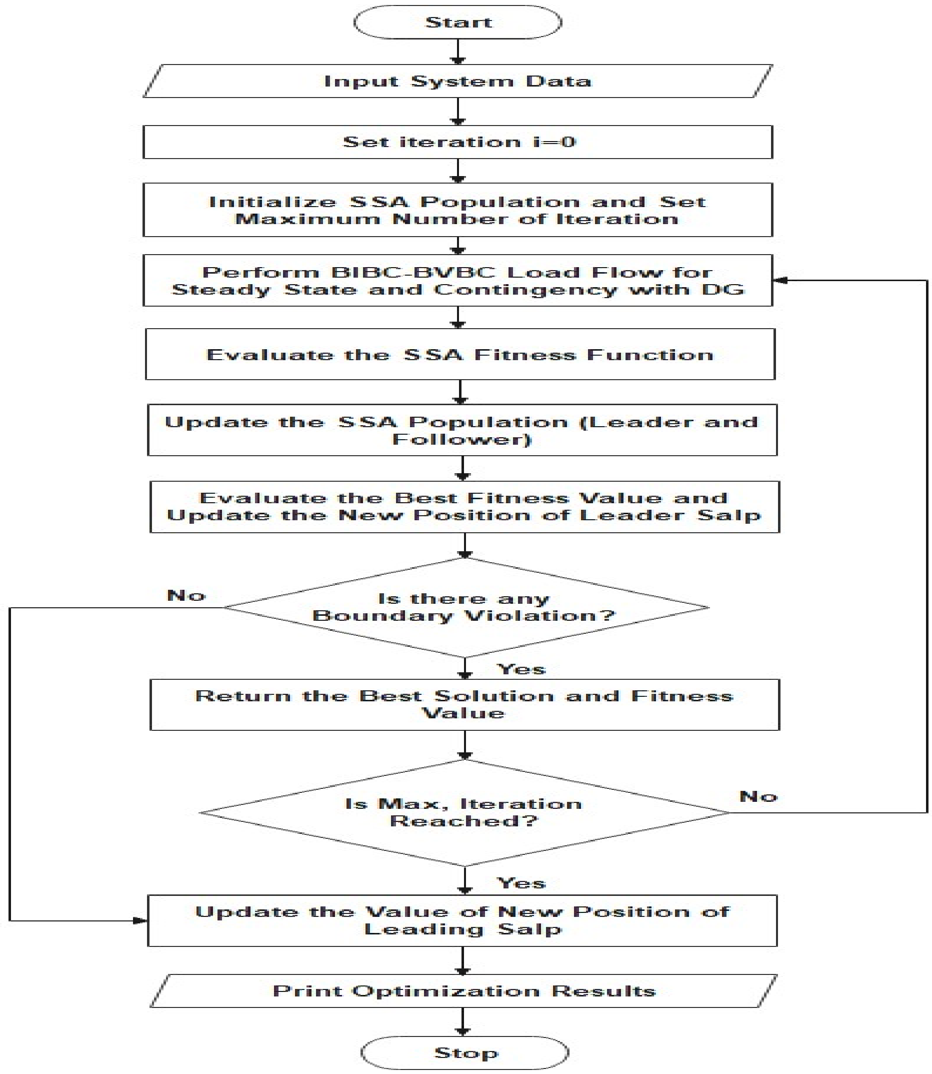

Figure 2: Flowchart of SSA for Optimal Solution of Protection System.

III. Results and Discussion

This research employed SSA for improvement of the protective relay coordination problem on 33-bus Ilorin industrial feeder with interconnection of DG. This was done to provide effective relay operating time setting after DG integration and to provide optimal solutions for DG placement in order to overcome variable infeed from the DG to the feeder during contingency.

With 70% increase in load bus of the 33-bus Ilorin industrial feeder, the stability of the feeder during failure of the components were achieved to verify the DG effect on system protection coordination. The DG size of 10, 12.5, 15 and 12.5 MW and primary relay power rating of 30, 45, 35 and 50 MVar were incorporated on selected buses 5, 14, 19 and 31 whose voltage magnitude fell short of the ±5 % tolerance margin of the voltage criterion as shown in Figure 3. The Figure showed the comparison of voltage magnitude with the bus number of the 33-bus Ilorin industrial feeder with inclusion of DG at contingency (post fault). It was observed that the voltage magnitude of the selected buses reduced tremendously to 0.9660, 0.9570, 0.9520 and 0.9500 p.u with corresponding voltage angles of 9.6320, -1.3770, -11.4740 and 2.4450 degree, respectively.

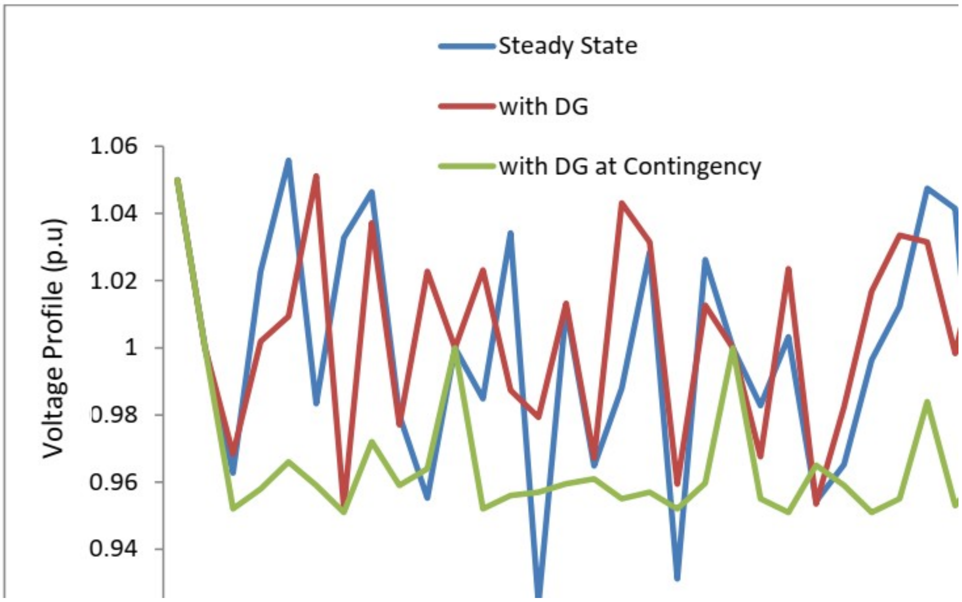

Figure 3: Voltage Magnitude of 33-Bus Ilorin Feeder with DG at contingency

In addition, the comparison of system current with the bus number of the 33-bus Ilorin industrial feeder with inclusion of DG at contingency (post) is presented in Figure 4. From the Figure, the system current in the selected buses 5, 14, 19 and 31 whose voltage magnitude fell short of the ±5 % tolerance margin of the voltage criterion at steady state were increased tremendously to 33.612, 19.815, 20.812 and 26.495 p.u compared with system current value of 17.967, 17.568, 10.228 and 16.458 p.u,, respectively with DG.

Figure 5 illustrated the comparison of relay operating time of the 33-bus Ilorin industrial feeder with inclusion of DG at contingency (post). The primary relay operating time of the selected buses 5, 14, 19 and 31 at steady state were increased to 0.13, 0.10, 0.11 and 0.12 seconds compare with relay operating time value of 0.1 and 0.2 seconds, respectively with DG only.

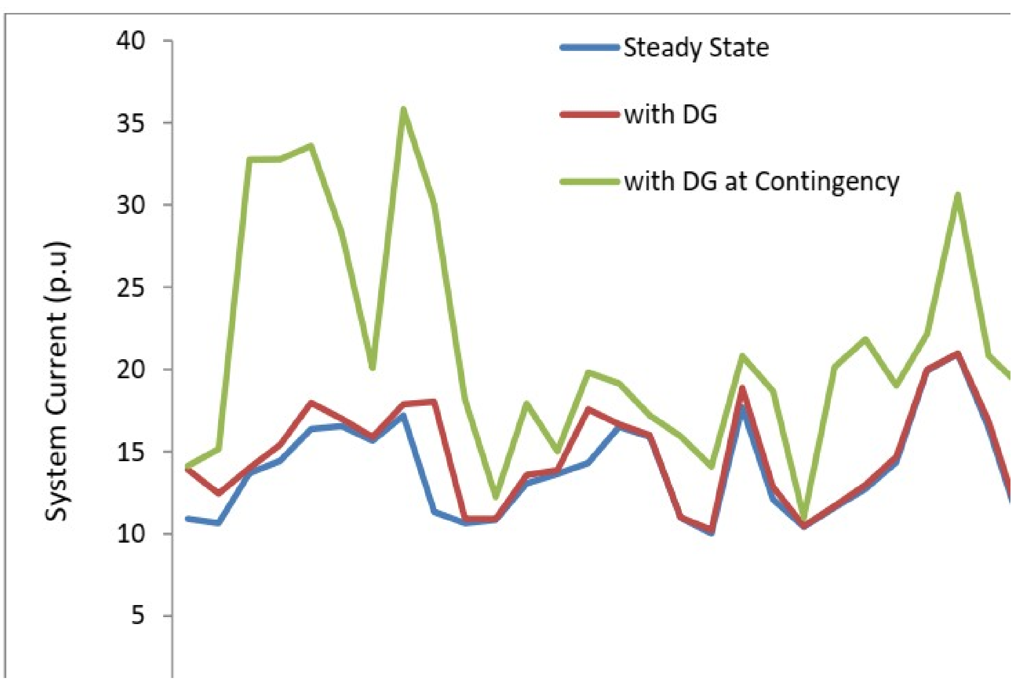

Figure 4: System Current of 33-Bus Ilorin Feeder with DG at contingency

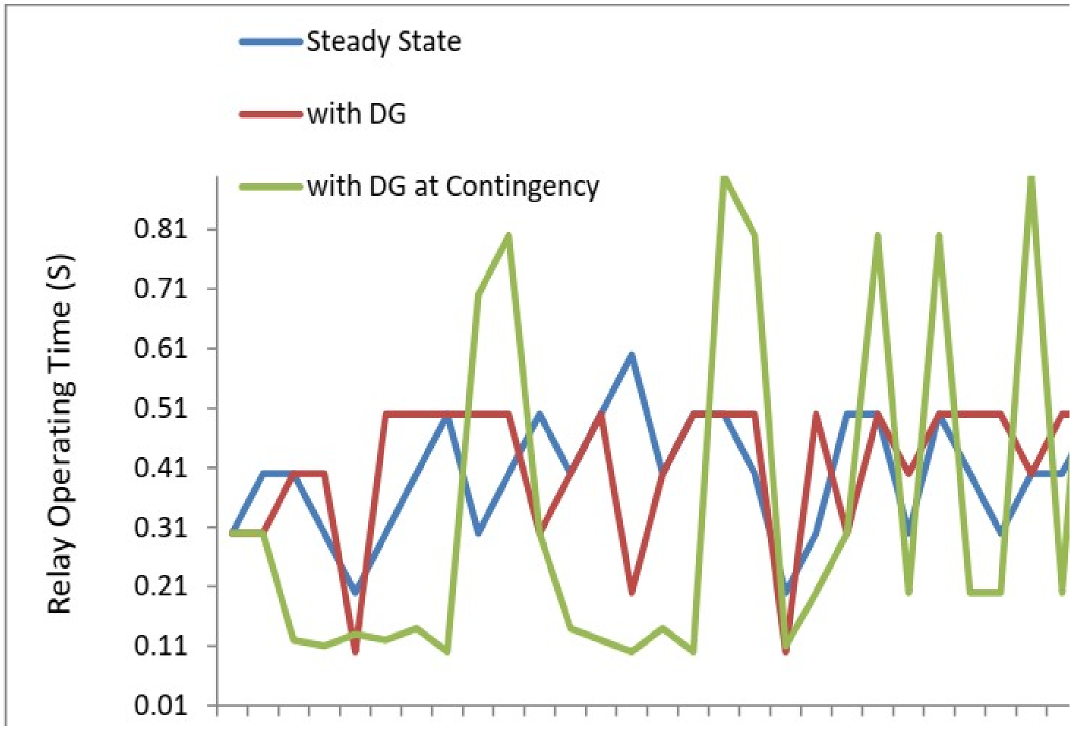

Figure 5: Relay Operating Time of 33-Bus Ilorin Feeder with DG at contingency

In order to solve the problem of protective relay false tripping settings and to provide optimal placement for DG unit with protective relay in 33-bus Ilorin industrial distribution feeder. SSA technique was employed as optimization technique with the application of SSA,

Figure 6 presented the optimization results of voltage magnitude with the bus number of the 33-bus Ilorin industrial feeder with adaptive distance relay and DG incorporated contingency (post fault) using Salp Swarm Algorithm (SSA). The voltage magnitudes of the selected buses 5, 14, 19 and 31 whose voltage magnitude fell short of the ±5 % tolerance margin at steady state were improved to 1.0000 p.u each compared with values of 0.9600, 0.9500, 0.9500 and 0.9500 p.u, respectively, obtained with protective relay and DG at contingency only. It was observed that the other buses voltages were upgraded to 1.0000 p.u

Figure 7 analyzed the optimization results of system current with the bus number of the 33-bus Ilorin industrial feeder with adaptive distance relay and DG incorporated at contingency using SSA. The system current in the selected buses 5, 14, 19 and 31 were redistributed to 16.163, 14.008, 16.972 and 13.891 p.u, compared with system current value of 20.612, 18.815, 19.812 and 16.495 p.u, respectively, with adaptive distance relay and DG at contingency. Figure 8 presented the optimization results of relay operating time of the feeder with adaptive distance relay and DG incorporated at contingency using SSA. The protective relay operating time of the selected buses 5, 14, 19 and 31 were improved to 0.5 seconds each. It was observed that the abnormal increment of system current in these buses was rectified. Similarly, false tripping issue of adaptive distance relay with DG was resolved with application of SSA. It was observed that the relay operating time in these buses were rectified

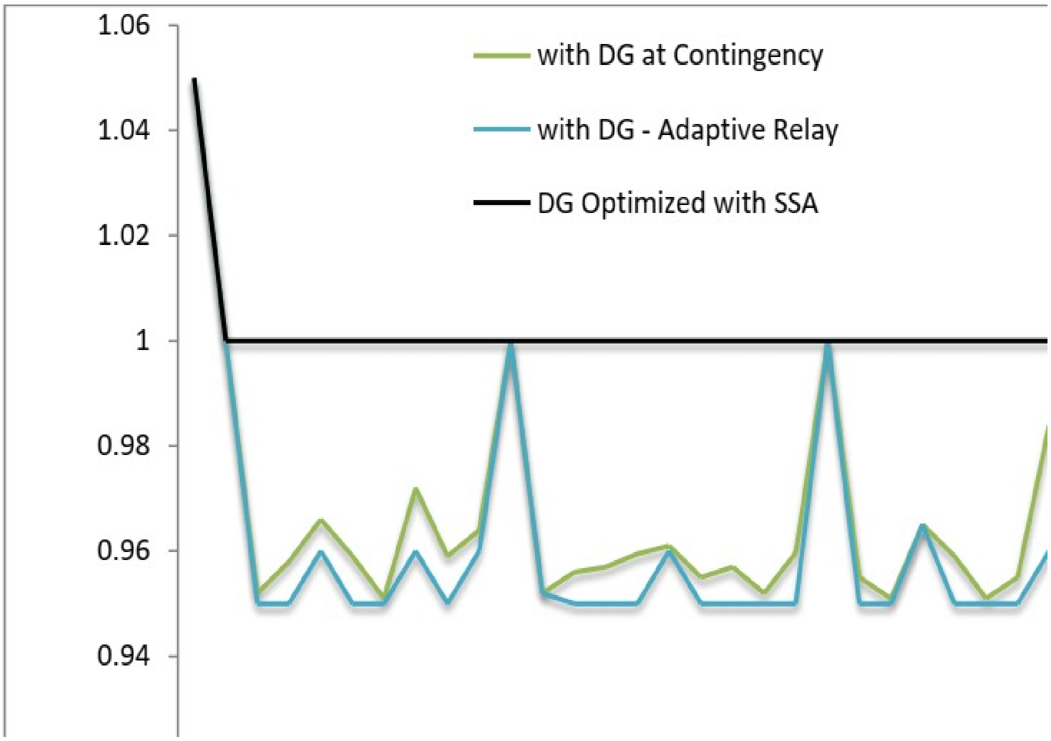

Figure 6: Voltage Magnitude of 33-Bus Ilorin Feeder Optimized with SSA

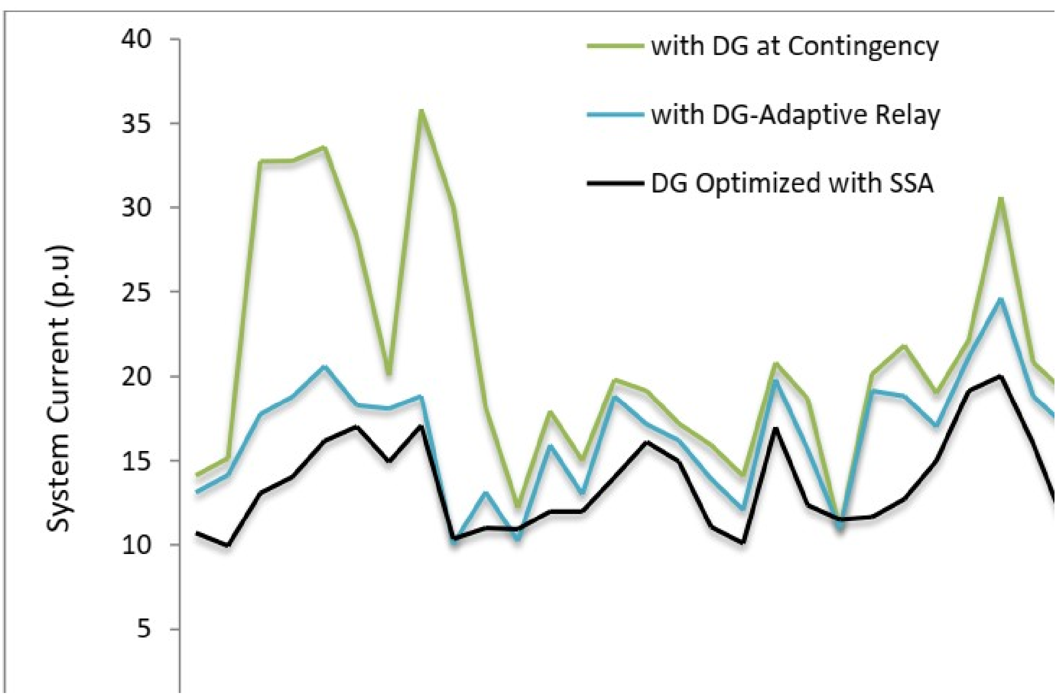

Figure 7: System Current of 33-Bus Ilorin Feeder Optimized with SSA

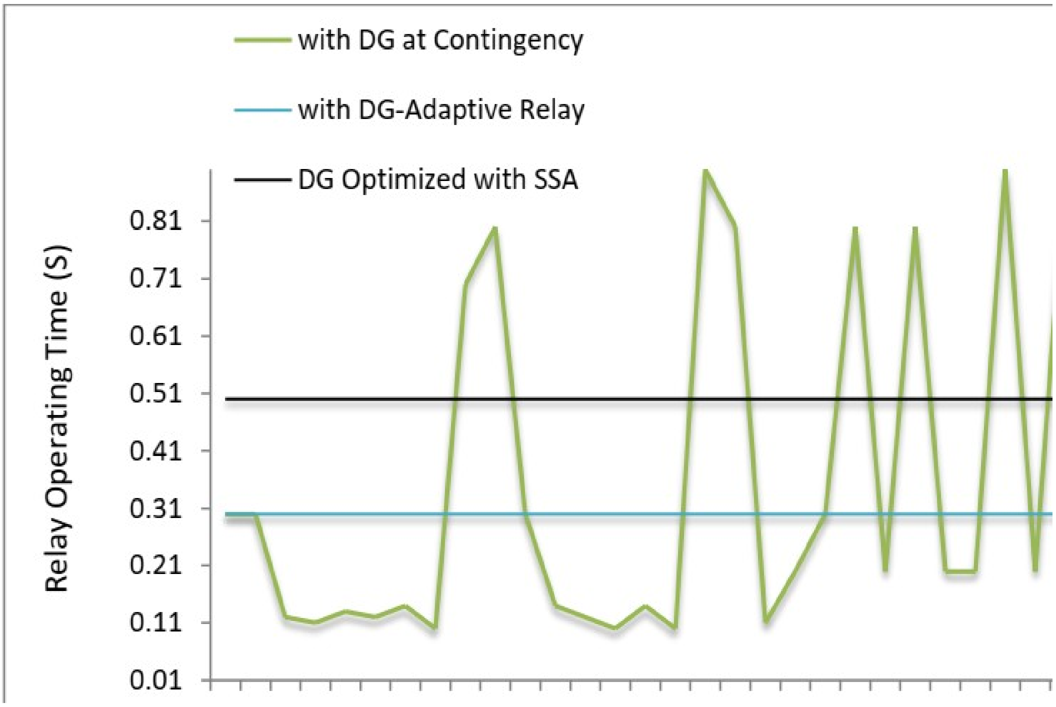

Figure 8: Relay Operating Time of 33-Bus Ilorin Feeder Optimized with SSA

Table 1 indicated the best location and size of DG unit with protective scheme in the feeder using SSA. The best location and size of the DG unit in the feeder were at buses 4, 8 and 17 with DG size of 12.5, 15.0 and 10.0 MW, respectively, and protective relay power rating of 35 MVar each.

Table 1: Optimal Placement and Sizing of DG in 33-Bus Ilorin Feeder with SSA

Case	DG Bus	Voltage Profile (p.u)	Current (p.u)	DG Size (MW)	Relay Operating Time (s)	Relay Power Rating (MVAR)
Steady State	5	1.0558	16.367	10	0.2	30
	14	0.9237	14.308	12.5	0.6	45
	19	0.9312	17.674	15	0.2	35
	31	1.0542	13.931	12.5	0.1	50
DG with SSA						
	4	1.0000	14.041	12.5	0.5	35
	8	1.0000	17.090	15	0.5	35
	17	1.0000	11.069	10	0.5	35

IV. Conclusion

This research paper has presented an improvement of power system protection scheme for distribution system with inclusion of DG. A BIBC and BCBV distribution load flow was performed prior to integration of DG and for contingency (70% loading) to determine the initial operating status of the power system and to identify DG effect on protection coordination. The load flow results of 33-bus of Ilorin industrial feeder at contingency with DG revealed that the power station was unstable as the system current increased abnormally and relay operating time setting was reduced due to changes in the relay sensing path. This verified the radial nature of the power system which made it to experience voltage instability. With the implementation of SSA for optimal placement of DG with protective relay in the feeder, the voltage magnitude in the feeder was controlled within their permissible voltage limit, the system current was reduced to acceptable limit and the relay false tripping settings and mis-coordination was rectified.

Therefore, it can be safely concluded that, the application of SSA for optimal placement of DG with adaptive distance relay provided the required technical support in controlling the effect of DG on system current and protection relay to the fault current.

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