Adaptive Protection Coordination with Setting Groups Allocation

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Received: 09.03.2019 Accepted:14.04.2019

Abstract- Distributed Generations (DGs) plug & play operation changes the fault current levels, which results in Directional Over-Current Relay (DOCR) miss-coordination and non-optimal tripping times. Adaptive protection is a great solution to tackle the adverse effects of DGs on distribution network. Some adaptive protection coordination for all DG connection statuses requires vast communication infrastructure and equipment upgrade where the non-adaptive coordination leads to high operating time of relays. In this paper, a new adaptive protection concept is introduced as a trade-off where the settings of some relay are adaptively changed based on its neighbourhood DGs connection. The number of Settings Groups (SGs) of each DOCR is found by calculating the proposed sensitivity matrix. The SGs are only added in relays experiencing the high changes in short circuit levels. The proposed method is simulated on IEEE-30 Bus and the results indicate the capability of the proposed method in efficient and optimum design of adaptive protection schemes with proper SGs allocation.

Keywords Protection coordination, adaptive protection, distribution network, distributed generation, setting groups.

1. Introduction

DGs penetration in distribution despite its advantages, adversely affects the protections system. DGs contribution changes the short circuit levels where the DOCRs settings should be modified to cope with new fault current patterns imposed by DGs. Moreover, plug & play operation of DGs produces different sets of fault currents where the protection settings should satisfy both sensitivity and selectivity for all modes of operation.

Protection blinding, nuisance tripping and loss of coordination due to DGs penetration in distribution network are investigated in [1]. DOCRs coordination for all modes of DGs connection status is used in [2-5]. Interval linear programming is used in [2] to define the worst coordination constraint that covers constraints related to all topologies. The optimization framework is used in [3] for optimal coordination in microgrids based on N-1 criterion. To enhance the optimization process due to high number of constraints belonging to different modes of operation, hybrid Genetic algorithm-linear programming is used for fast convergence [4]. In [5], the coordination of relays with time-current-voltage characteristics are is performed for different topologies. Due to voltage dependent feature of these relays, they are less vulnerable to misscoordination due to DGs penetration. Voltage dependent relays were used in [6] where the relays settings are adapted based on the measure voltage to tackle to DGs effect on load currents. A new coordination strategy according the relative location of DGs and the fault are studied in [7] trying to minimize the reliability indices.

The overcurrent relays coordination is performed for different operating condition of grid i.e. DGs plug & play and topology change. This approach leads to high operating time of relays which can bring damage to cables and transformers. Fault Current Limiters (FCLs) can be used to limit the DGs contribution and restore the protection coordination [8-12]. The unidirectional fault current limiter is installed at microgrid point of connection to prevent the microgrid contribution in upstream grid faults [8]. Fault current allocation with minmax regret criterion is introduced in [9] to deal with uncertainty in DGs connection status and minimize the cost of installation. In [11], fault current limiters are used to limit the grid-connected fault currents in microgrid and use single settings for both modes of operation. FCLs are usually installed at DG terminal to limit fault current being injected by DG which prevents the DGs contribution in reactive power support during faults.

Adaptive protection is a great solution to face with uncertainties in DGs connection where the DOCRs settings are updated based on the connection status of DGs. In [13], a simple adaptive protection is proposed where trip characteristic of relays are updated based on local information. Adaptive protection for microgrids is proposed in [14] where the directional interlock and circuit breakers with adaption in tripping curve are used. In [15], full communication network and Intelligent Electronic Devices (IEDs) are used for adaptive protection of distribution grid where the settings of relays are calculated for different loading condition of grid and DGs penetration. Online adaptive protection coordination is proposed in [16] where the thevenin equivalent impedance is estimated for short circuit calculation. The relays settings are adaptively changed in [17] based on DGs connection status and its control mode in a multi-agent approach. Branch contribution factor matrix is also suggested to eliminate DGs impact and restore validity of relay settings [18]. Online adaptive protection with fault current and relays settings calculation are studied in [19-20]. The fault currents and relay settings are calculated for new operation modes and after comparison, the new settings are sent to relays. A dynamic adaptive protection is presented in [21] where to restore the relays sensitivity, the minimum fault current and the load current of each mode are transmitted to the protective relays. Adaptive protection based on positive and negative sequence currents is also used in [22] for distribution grids with low fault currents. Cooperative multi agent scheme is proposed in [23] for adaptive protection of microgrid based on the probabilistic miss-coordination index.

SGs of DOCRs can be used as a solution for adaptive protection. Commercial relays are equipped with about 4-6 SGs that can cover the uncertainties in distribution grids. In [24] the adaptive protection based on SGs of DOCRs are proposed where the different operation modes of relays is mapped to available SGs by clustering analysis. Hardware in loop simulation of adaptive protection coordination using SGs are presented in [25]. Similar work is presented in [26] where SGs utilization is simulated in real simulators. A coordination index, optimized by GA is also proposed in [27] to cover different connection statuses of DGs under four SGs. After this, optimal protection coordination of each SGs for dedicated patterns of DGs connection is performed. Further work is done in [28] in which the hybrid GA-linear programming is used to classify different scenarios of grid to limited number of SGs. Moreover the SGs number of total operating times is also studied to find the optimum number of SGs.

In this paper, a new adaptive protection concept is introduced where only some of grid relays settings are updated in response to DGs plug and play operation. In the previous studies, the equal number of SGs is used for all relays. However, some relays due to high fault current variation need high number of SGs while some relays may not require additional GSs and fault current seen by them remains almost constant. Therefore the number of each relay SGs should be determined based on its operating time sensitivity to DGs connection status. A sensitivity matrix is proposed to assign the number of SGs dedicated to each relay. The SGs addition of DOCRs is performed based on the calculated sensitivity indices. Rather than same number of SGs for all relays, SGs are included with high variations of short circuit levels in different operating modes. The proposed method is simulated in IEEE 30 bus distribution grid where SGs are added based on the proposed approach. The results indicate that the approach efficiently reduces the operating time of relays while curbing the high number utilization of SGs.

The paper is organized as follows. The next section describes the conventional protection coordination. DGs impact on coordination constraints and sensitivity matrix are introduced in section 3. Section 4 represents the adaptive protection with the SGs allocation method. Simulation results for different scenarios are included in section 5.

2. DGs Impact and Proposed Sensitivity Matrix

DGs penetration in distribution networks changes the fault currents magnitude and adversely affects the protection coordination of relays. DGs impact on protection coordination depends on relative locations of DGs, fault and relays which is explained as follows. It is assumed that relays are fully coordinated previous to DGs penetration.

2.1. DGs Fault Current Passes Both Primary -Backup Relays

This case is illustrated regarding the simple system depicted in Fig. 1. As the DG contributes in fault current, the current seen by both primary and backup relays is increased and therefore the time difference between $\mathrm{R_p}$ and $\mathrm{R_b}$ reduces from CTI to CTI*. To restore the coordination, the sensitivity of backup relays should be reduced which results in delayed operation in No DG condition.

2.2. DGs Fault Current Only Passes through Primary Relay

In this case, the DG is located between primary and backup relay as shown in Fig. 2. The overall fault current is increased due to DG contribution. The fault current passing through back relay is decreased which is compensated with increase in fault current seen by primary relay. The DG presence forces the time gap to increase from CTI to CTI^* where no miss-coordination is experienced.

2.3. DGs Fault Current Only Passes through Primary Relay

A new index is proposed to find the most severe coordination constraints i.e. fault current variations. The proposed index is defined as (1). The proposed index is composed of two terms. The left term indicates the relative tripping time variation and miss-coordination of backup-primary relay pair. This term can be positive or negative, dependent on the relative location of DG and the relays. For example, if the DG is connected between two relays, the term becomes negative. The right term reflects miss-coordination due to increased short circuit level. The Index is calculated for each backup-main pair as n and each DGs connection status m, forming a sensitivity matrix of size (N_{pairs}, M) which is used to determine number of SGs for DOCRs. current seen by primary relay.

$$S_{mn} = \left(\frac{{I_f}_{Rb}^{new}}{{I_f}_{Rb}^{old}} - \frac{{I_f}_{Rp}^{new}}{{I_f}_{Rp}^{old}}\right) + \frac{1}{2}\left(\frac{{I_f}_{Rb}^{new}}{{I_f}_{Rb}^{old}} + \frac{{I_f}_{Rp}^{new}}{{I_f}_{Rp}^{old}}\right) \quad (1)$$

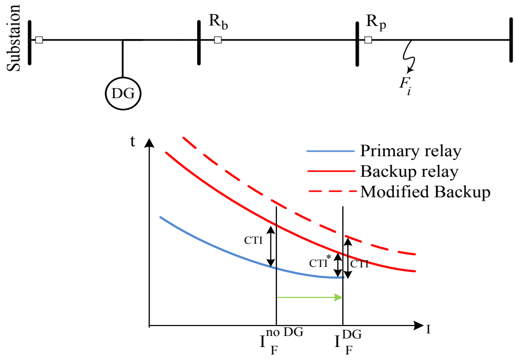

Fig. 1. Increased CTI due to DG's contribution seen by both relays

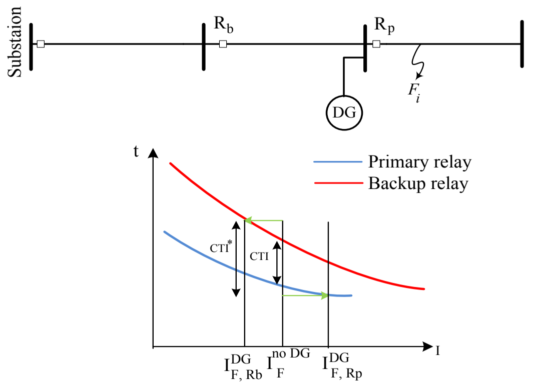

Fig. 2. Reduced CTI due to DG's contribution seen by primary relay

3. Adaptive Protection Coordination

As mentioned before, Adaptive protection can be used to tackle the different coordination constraints for different combination of DGs connection. The SGs in DOCRs enables to use different settings under plug & play operation of DGs.

3.1. Formulation of Adaptive Protection

The optimal adaptive protection coordination can be formulated as an optimization problem with an objective function stated in (2).

$$\min \sum_{m=1}^{M}\sum_{f=1}^{fn}\sum_{i=1}^{n} t_{i,f_i} \quad (2)$$

where f indicates the near-end and far-end faults, i represents primary relay indices and t_{i,f_i} is the operating time of primary relay i for a near end fault f_i . The indicator m represents the connection mode of DGs where for a network with n DGs is $M = 2^n$. The operating time of DOCR in each mode m is given by (3) as follows.

$$t = \frac{A \times TDS_{GS-k}}{\left(\frac{I_f}{I_{p,GS-k}}\right)^B - 1} \quad (3)$$

where I_f is fault current seen by relay, TDS is relay Time Dial Setting (TDS) and I_p is pick up current of k^{th} GS. The number of SGs in nowadays commercial DOCRs is about 3-

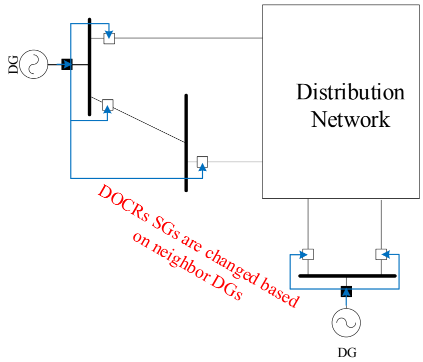

Fig. 3. Adaptive protection with SGs in some relays

6 where active GS is determined based on DGs connection status, received via binary inputs. The number of SGs is generally smaller than total statuses of DGs connection and therefore some clustering and classification techniques should be used.

A and B are DOCRs parameters which determine relays characteristic curves. To ensure the selectivity of the protection system, the operating time of backup relay should lag enough, as Coordination Time Interval (CTI). The coordination constraint is shown in (3). The typical value of CTI lies in range of 200-300 ms. j is the backup relay indices and t_{ij} is the operating time of backup relay. Ω is the near and far end fault set.

$$t_{ij}^f - t_i^f \geq CTI \quad for\ \forall\ f \in \Omega \quad (4)$$

3.2. Settings Groups Allocation

The GSs of DOCRS should be used carefully to meet with coordination requirements in different DGs connection statuses. For optimum allocation of SGs and architecture design of adaptive protection scheme two main points should be considered.

DGs contribution in faults currents is geographically limited. The DG significantly changes the fault currents in its neighborhood and no severe fault current variation is experienced in remote area relays. This concept is shown in Fig. 3 where the all relays settings are NOT adaptively changed based on the connection status of DG. Only the close relays are involved in adaptive protection design and therefore require high number of SGs. The other relays can continue to work with only one GS and increase of SGs can be avoided without any adverse effect on protection system.

SGs allocation for relays should be dealt carefully based on each DGs impact. The sensitivity matrix proposed in the previous section can be used as a main indicator for GS allocation. Depending on the operator budget, a threshold s_{th}

should be selected for adaptive protection architecture design. Based on the sensitivity matrix, following rule can be used for GS allocation and adaptive protection architecture design.

$$if|1 - S_{nm}| \geq s_{th}$$
$$add\ a\ GS\ to\ backup\ relay\ activated\ by\ mode\ m \quad (5)$$

As shown in (5), the SGs are only increased in relays with high sensitivity to DGs connection status. The number of SGs and the communication links depends on s_{th}. Lower values of threshold results in more SGs and higher number of communication links associated with lower operating times of relays.

4. Simulation Results

The proposed method for proposed adaptive protection with GS allocation is tested on modified IEEE 30 bus network. IEEE 30 bus is composed of sub-transmission and distribution networks where the distribution part is studied here which is shown in Fig. 4. Three 10 MVA DGs with X'd=0.2 pu are added to form an active distribution network. As seen, 38 DOCRs are used to isolate the faults and very inverse curve is assumed for all DOCRs. Different scenarios are simulated to present the capability of the proposed method. Genetic algorithm is used as an optimization tool for optimal protection coordination.

4.1. Prior to DGs Penetration

In this scenario, no DGs are installed and conventional protection coordination is performed for the case study grid. The genetic algorithm convergence during the optimization process is shown in Fig. 5, where the total operating time of DOCRs is 23.86 s. The optimal settings of relays are listed in Fig. 6.

Once the DGs are installed at the grid, due to DGs contribution in fault current, miss-coordination between DOCRs are experienced. The miss-coordination time for different DGs connection status is shown in Fig. 7. Once the DGs are added to network, the settings of DOCRs should be retuned for the new set of short circuit currents which is explained in next scenario

4.2. Non-adaptive Coordination for All DG's Connection Statuses

In this scenario, non-adaptive DOCRs coordination is performed for eight different modes of DGs connection. The convergence of GA for this scenario is plotted in Fig. 8 where the total operating times of relays is about 243.74 s. The relays settings are listed in Fig. 9. Due to various set of fault currents in eight modes, more coordination constraints are imposed, resulting in higher operating times of relays. The total operating time is about 10.09 times the base scenario.

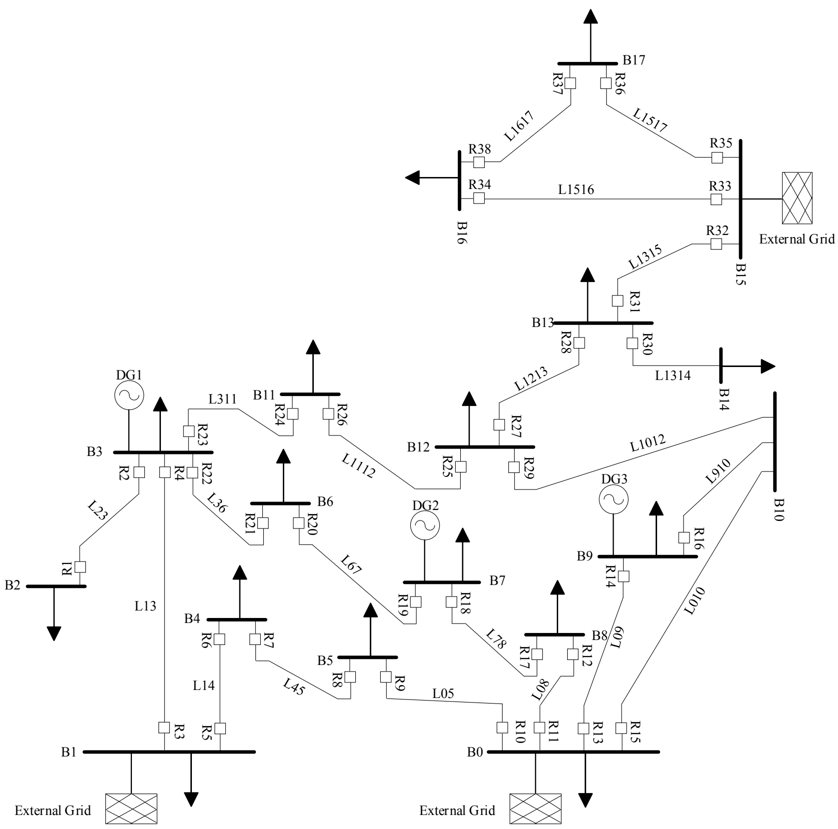

Fig. 4. Case study distribution network.

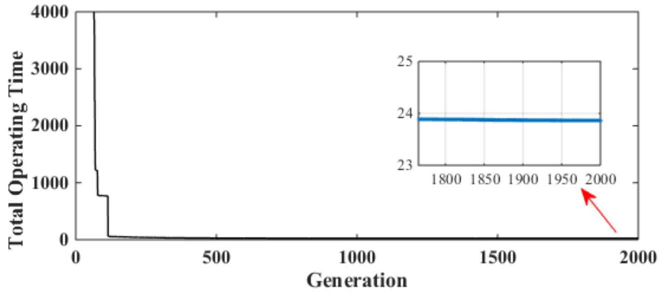

Fig. 5. Convergence of genetic algorithm for scenario 4.1.

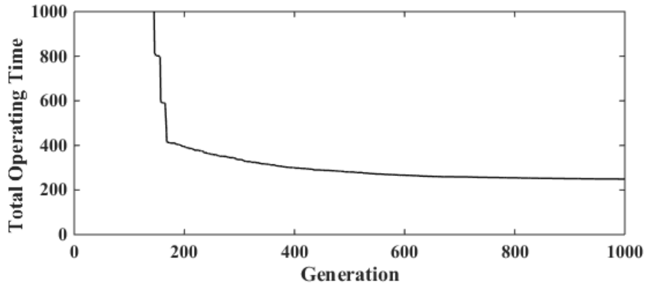

Fig. 8. GA convergence for scenario 4.2

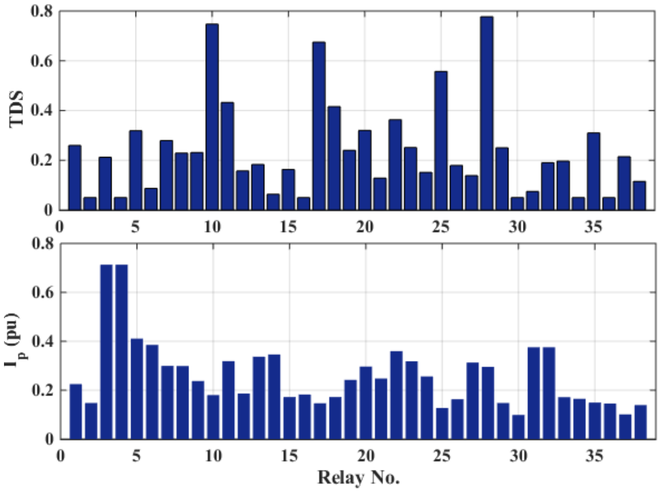

Fig. 6. Optimal settings of DOCRs for scenario 4.1

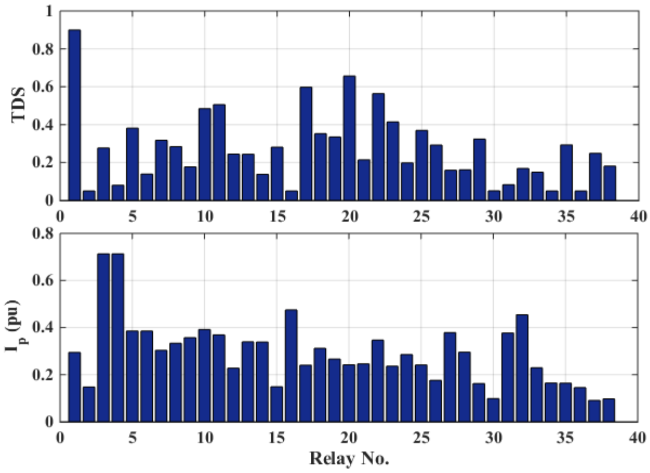

Fig. 9. GA convergence for scenario 4.2

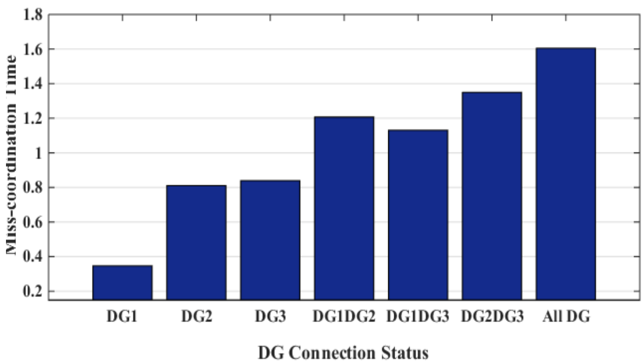

Fig. 7. Miss-coordination due to DGs penetration

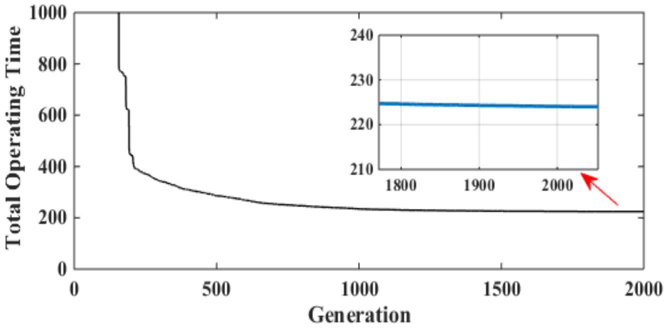

Fig. 10. GA convergence for scenario 4.3

Table 1. Sensitivity matrix

backup	Main	DG1	DG2	DG3	DG1DG2	DG1DG3	DG2DG3	DG1DG2DG3
R16	R12	1.07	1.01	1.79	1.07	1.84	1.78	1.86
R16	R13	1.07	1.04	1.78	1.11	1.86	1.83	1.91
R14	R12	1.17	1.71	0.88	1.79	1.11	1.58	1.73
R6	R7	1.59	1.30	1.17	1.85	1.73	1.46	2.00
R25	R27	0.93	1.43	1.13	1.37	1.06	1.55	1.50
R23	R25	1.02	1.28	1.07	1.3	1.09	1.35	1.37
R8	R5	1.07	1.15	1.18	1.22	1.25	1.32	1.39
R12	R10	1.06	1.10	1.14	1.10	1.14	1.18	1.21
R9	R11	1.03	1.01	1.00	1.00	0.99	1.09	1.04
R7	R9	1.03	1.01	1.00	1.04	1.03	1.01	1.04

R22	R14	1.08	1.37	1.01	1.47	1.09	1.39	1.47
R27	R30	1.09	1.04	1.01	1.13	1.1	1.05	1.14
R31	R36	1.03	1.03	1.05	1.06	1.07	1.08	1.10
R5	R27	0.91	0.97	0.99	0.87	0.9	0.96	0.87
R10	R8	1.03	1.07	1.09	1.10	1.12	1.15	1.18
R24	R22	1.07	0.79	1.01	0.86	1.09	0.8	0.87
R19	R31	1.02	1.06	1.29	1.07	1.31	1.35	1.36
R17	R31	1.01	0.98	0.91	1.07	0.92	0.96	0.98
R11	R13	1.04	1.01	0.92	1.05	0.96	0.93	0.97
R14	R15	1.15	1.62	0.98	1.76	1.13	1.61	1.60
R14	R17	1.15	1.61	0.95	1.76	1.11	1.58	1.73
R26	R24	1.08	1.00	1.01	1.09	1.11	1.02	1.10

Table 2. DOCRs with Additional SGs for scenario 4.3.

Relay No.	GS One	GS Two	GS Three
R6	DG1, DG1DG2, DG1DG3, DG1DG2DG3	DG2, DG2DG3	Other
R8	DG3, DG1DG3, DG2DG3, DG1DG2DG3	Other	N.A.
R14	DG2, DG1DG2, DG2DG3, DG1DG2DG3	Other	N.A.
R16	DG3, DG1DG3, DG2DG3, DG1DG2DG3	Other	N.A.
R19	DG3, DG1DG3, DG2DG3, DG1DG2DG3	Other	N.A.
R22	DG2, DG1DG2, DG2DG3, DG1DG2DG3	Other	N.A.
R23	DG2, DG1DG2, DG2DG3, DG1DG2DG3	Other	N.A.
R25	DG2, DG1DG2, DG2DG3, DG1DG2DG3	Other	N.A.
Additional GS No. : 9			

4.3. Adaptive Coordination with Nine Additional SGs

As seen, various constraints in different modes of operation results in higher operating time of DOCRs in non-adaptive manner. Adaptive protection can be used to cope with all eight modes where SGs allocation should be dealt carefully to for maximum potential use of SGs in relays vulnerable to high changes in short circuit currents. The sensitivity matrix for the case study grid is calculated and shown in Table 1. The data in table indicates the mode of operation effect on fault current variations. As seen, some relays are not affected by DGs connection mode and no SG is required in this relays, for example R17, R26, R11, R9, R7 and the relays which is not shown in Table 1. For other relays, depending on the adaption degree of protection system, SGs should be included.

In this scenario, a threshold of 30% is used, where the SGs are added in cases with $S\_mn \geq 1.3$ and $S\_mn \leq 0.7$. Table 2 lists DOCRs with more than one GS. As seen, the number of SGs is not same for all relays and it is dispensed based on fault current changes in different modes. As seen, the relay R16 is close to DG3 where the connection status of DG3 severely impacts the operating time of R16. Therefore, a separate SG is included in R8 to mitigate the issue. Similar situation applies to relays R22, R23, R6 being close to DGs.

The optimal coordination of relays for this scenario is also performed where the total operating times of relays is decreased to 223.02 s. Using only nine additional SGs resulted in 20.72 s reduction in fault clearance time. The GA convergence for this scenario is depicted in Fig. 10.

4.4. Adaptive Coordination with 18 Additional SGs

In this scenario, the sensitivity threshold is reduced to 15% to assign more SGs. Table 3 lists the relays with more than one GS, which are selected, based on sensitivity matrix. Since the sensitivity threshold is decreased, more SGs are included in relays as shown in Table 3. It is seen that SGs are not equally distributed between the relays. Relay R6 utilizes five SGs to maintain the sensitivity below the target value, the relay R14 includes four SGs and three SGs are dedicated to R8. The other relays shown in Table 3 have only two SGs, accounting for 18 SGs which are included to preserve the adaption degree. Therefore using same number of SGs for all relays is not an optimal and economic approach and the SGs should be dedicated based on the sensitivity of relays to DGs connection status.

The total operating time for 18 additional SGs is about 216.34 s. The convergence of GA for this scenario is shown in Fig. 11 and the optimum SGs are shown in Fig. 12. Using additional 18 SGs lead to 12% reduction in fault clearance times. Operating times of primary relays for some faults and operation mode of DGs are listed in Table 4. It can be predicted the slope of operating time reduction with an increase in SGs number is saturating and trial and error approach can be used to determine the optimal SGs number which are going to be dedicated by the sensitivity matrix.

Table 3. DOCRs with Additional SGs for scenario 4.4.

Relay No.	GS One	GS Two	GS Three	GS Four	GS Five
R6	DG1,DG1DG2, DG1DG3	DG2,DG2DG3	DG3	DG1DG2DG3	No DG
R8	DG3,DG1DG3, DG2DG3, DG1DG2DG3	DG2,DG1DG2	DG1,No DG	N.A.	N.A.
R10	DG3,DG1DG3, DG2DG3, DG1DG2DG3	Other	N.A.	N.A.	N.A.
R12	DG3,DG1DG3, DG2DG3, DG1DG2DG3	Other	N.A.	N.A.	N.A.
R14	DG2,DG1DG2, DG2DG3, DG1DG2DG3	DG1, DG1DG2	DG3	No DG	N.A.
R16	DG3,DG1DG3, DG2DG3, DG1DG2DG3	Other	N.A.	N.A.	N.A.
R19	DG3,DG1DG3, DG2DG3, DG1DG2DG3	Other	N.A.	N.A.	N.A.
R22	DG2,DG1DG2, DG2DG3, ,DG1DG2DG3	Other	N.A.	N.A.	N.A.
R23	DG2,DG1DG2, DG2DG3, DG1DG2DG3	Other	N.A.	N.A.	N.A.
R24	DG2,DG1DG2, DG2DG3, DG1DG2DG3	Other	N.A.	N.A.	N.A.
R25	DG2,DG1DG2, DG2DG3, DG1DG2DG3	Other	N.A.	N.A.	N.A.
R27	DG1,DG1DG2, DG1DG3, DG1DG2DG3	Other	N.A.	N.A.	N.A.
Additional GS No. : 18					

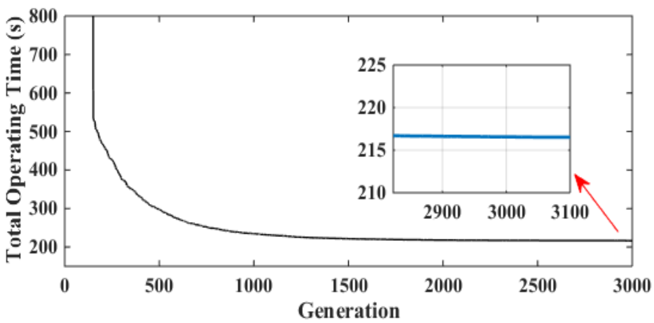

Fig. 11. GA convergence for scenario 4.4

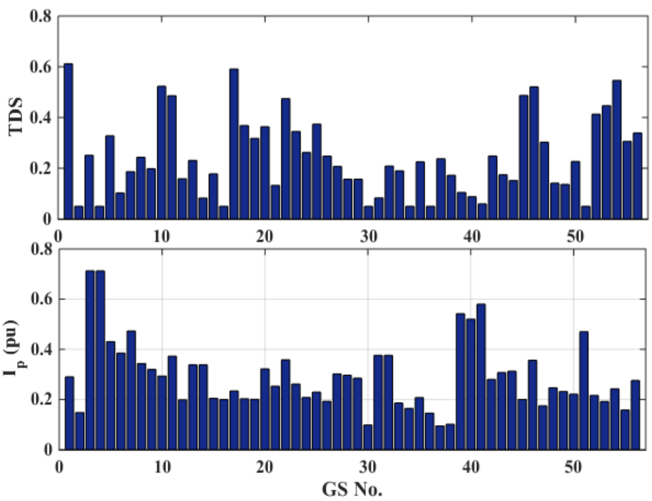

Fig. 12. Optimal SGs of DOCRs for scenario 4.4

Table 4. Operating time of DOCRs for different modes (s)

	F9	F14	F19	F23	F27
No DG	0.3583 0.5016	0.2579 0.8280	0.0364 0.3967 0.4009	0.3377 0.8497	0.2193 0.6800
DG3	0.3585 0.5023	0.2583 0.7648	0.0729 0.3938 0.3988	0.3142 0.8362	0.2151 0.6175
DG1DG2	0.3427 0.4515	0.2854 0.7999	0.0333 0.3582 0.3675	0.3286 0.8560	0.1885 0.6377
All DG	0.3427 0.7088	0.2812 0.7405	0.0671 0.3554 0.3650	0.3109 0.8431	0.1854 0.5833

5. Conclusions

In this paper, a new adaptive architecture for protection of active distribution networks is proposed. A sensitivity matrix is proposed to mirror the DGs impact on the coordination. SGs are allocated based on the sensitivity in cases with high variation in fault currents, not in all relays. As the threshold on sensitivity is decreased, more SGs are added and the operating time of relays will be decreased. The results indicate the capability of the proposed method for optimum usage of SGs in adaptive protection schemes.

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