Relay co-ordination optimization for integrated solar photo-voltaic power distribution grid

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Abstract: Distributed generation (DG) specifically from solar energy is gaining much attention. Integration of solar photo-voltaic plant (SPP) on distribution grid increases flexibility of the system but lacking behind in terms of convention protection scheme. The impact of orientation of point of common coupling (PCC) of SPP on distribution grid changes the entire power flow computation and hence, coordination of protection devices. This paper presents the power flow computation on modified IEEE 4-bus system for different integrated positions of SPP. Further analysis is carried for the fault current level with different locations and number of SPP DG. It has been found that DG integration increases the magnitudes of fault current; hence, it will have impact on relay co-ordination. A MATLAB/Simulink model is proposed for relay mis-coordination and optimal co-ordination by implementing evolutionary optimization technique. The Proposed study on IEEE 4-bus system along with three units 100 kW capacity of SPP is used to derived optimal co-ordination solution which validates the obtained results on electrical transient's analysis programming platform (ETAP).

Subjects: Electrical & Electronic Engineering; Electrical Installation; Electrical Power Industries
Keywords: relay coordination; coordination time interval (CTI); particle swarm optimization; solar PV distribution grid

1. Introduction
Distributed renewable energy generation is small power-generating unit clubbed with modern technologies and present diverse challenges while integrating with utility grid. Most of the renewable energy sources (RESs) shall be located near load centre on distribution grid. RES introduces both positive and negative effects on system operation (Brahma & Girgis, 2003; El-Khattam, Bhattacharya, Hegazy, & Salama, 2004; El-Khattam & Sidhu, 2008; Girgis & Brahma, 2001). One of the negative impacts is relay coordination and extensive voltage variation. These variations caused by power flow value and direction, which alter the operating conditions. Also, the power flow depends on health of solar photo-voltaic plant (SPP) and their placement on distribution grid. The change in value of voltage and current during transient and fault condition affect the level of fault current (Hernandez-Gonzalez & Iravani, 2006; Varier & Pindoriya, 2015). These variations create the protection issue in the distribution grid and may collapse the grid as well. Hence, it becomes mandatory to identify fault on distribution grid quickly and assure the reliability of the system (El-Khattam & Sidhu, 2008). A backup protection system plays the vital role to make the system reliable and acts as a secondary protection with the proper time delay (Sharaf, Zeineldin, Ibrahim, & El-Zahab, 2015; Zamani, Sidhu, & Yazdani, 2011). The time delay is determined according to required selectivity and this process is known as relay coordination (Birla, Maheshwari, & Gupta, 2006). Precise relay coordination is crucial for the protection and essential for reliable protection scheme (Zeineldin, Member, & Sharaf, 2015). This paper calculates time multiplier setting (TMS) and relay tripping time for integrated SPP distribution grid through predetermine value of pick up current setting.

RES interconnection on distributed grid converts simple network into complex network but increases the grid flexibility (Chowdhury, Chowdhury, Ten, & Crossley, 2008). Major consequences of interconnected RES are false tripping of feeder, blinding protection and unwanted islanding (Coster, Myrzik, Kruimer, & Kling, 2011; Khadem, Basu, & Conlon, 2010). The issue that occur often is islanding, which can be removed with the help of updating protection scheme as per number of RES interconnection. This kind of protection scheme is known as adaptive protection scheme (Brahma & Girgis, 2003; De Brito et al., 2011; Katiraei, Iravani, & Lehn, 2005; Kersting, 2001; Ohrstrom, 2003; Nthontho, Chowdhury, Winberg, & Chowdhury, 2012; Nthontho et al., 2012, Hosseini, S. A., Abyaneh, H. A., Sadeghi, S. H. H., Razavi, F., & Nasiri, A. (2016)).

In this paper, the procedure to recognize optimal TMS is shown in Figure 1. The rest of the paper is organized as follow. Section 2 presents the simulation of solar PV, including inverter, MPPT technique and parameters taken for solar PV simulation. Section 3 shows optimal relay coordination model, objective function, constraints to calculate the optimal relay settings. Particle swarm optimization (PSO) is implemented as an optimization technique to minimize the operation time of relay with respect to various constraints is illustrated in Section 4. In Section 5, the optimized value of TMS is determined by implementing PSO and comparison is carried out by using sequential quadratic programming (SQP), interior point and genetic algorithm (GA). The validation of obtained results is illustrated through electrical transient’s analysis programming platform (ETAP) software and time–current characteristics (TCC) graph in Section 6.

Calculation of optimal relay setting for various cases is clearly depicted in Figure 1. The procedure initiates with IEEE 4-bus system simulation on MATLAB platform. In step 2, recognition to voltage and current of each bus for solar PV connected cases is carried and step 3 recognized the fault current at three locations. Step 4 is selections of relay parameter for optimization process. Step 5 calculates the TMS/TDS for relay with respect to coordination time interval (CTI) and fault current at different locations.

2. Modelling of solar photo-voltaic integrated IEEE 4-bus system
The simulation model of SPP integrated IEEE 4-bus system on MATLAB platform is shown in Figure 2. The 32 cases have been taken for study and shown in Table 1, where “0” denotes the “not connected”
mode and “1” denotes the connected mode of SPP on grid, e.g. “000” shows that no SPP is integrated over grid and “111” indicates that all three SPP are integrated over grid. In Figure 2, the simulation of IEEE 4-bus distribution feeder on MATLAB Simulink model (De Brito et al., 2011; Katiraei et al., 2005; Kersting, 2001) is shown with location of three various fault cases indicated by “A,B,C”. The placement of directional over current relay (DORC) (R1, R2, R3, R4, R5) at various positions on IEEE 4-bus feeder
3. Optimal relay co-ordination model

The main aim of the proposed solution is to identify TMS relay with respect to pick up current. TMS and plug-setting multiplier (PSM) decide the operating time of implemented relay. RES-integrated system needs updation of protection relay parameters as per dynamic changes in system behaviour. Most important constraint in relay coordination is CTI. CTI is a difference between operating time of primary and secondary relay in protection network and defined if operating time of primary is high as compared with secondary this called as miscoordination. Miscoordination is occurred due to a sudden increase in fault current level moreover, proper coordination needs to be set up for a reliable protection scheme. DOCR relay’s plug setting (PS) is set to the value ranging from 50 to 200 % in steps of 25%. The PS defines the current setting of the relay, while the TMS defines the operating time of relay in steps of
For any over current relay, the PS is defined by two parameters: the fault current during the unsymmetrical fault and the pick-up current of the relay current (Varier & Pindoriya, 2015). Inverse definite minimum time relay (IDMT) operates when the current exceeds a normal value and follows an inverse characteristic between operating time and PSM. The main feature of the IDMT relay is that it takes least time to operate based on the value of fault current. (Hernandez-Gonzalez & Iravani, 2006; Ntontho et al., 2012; Solati Alkaran, Vatani, Sanjari, Gharehpetian, & Naderi, 2016; Varier & Pindoriya, 2015) To find out the optimized operating time of the relay (backup relay), an objective function is desired. $\alpha$ and $\beta$ are the two constants for determining the shape of the curve between operating time and PSM given by IEEE standard. The standard value of $\alpha$ is 0.02 and value of $\beta$ is 0.14. PSM is defined as the ratio of fault current ($I_f$) and pick-up current ($I_p$). The operation time of relays is calculated through PSM and ($\alpha$, $\beta$) constants and optimized operating time of the relay is calculated through optimizing the main function of the relay with respect to various constraints. (Castillo, Conde, & Shih, 2018; Damchi, Dolatabadi, Mashhadi, & Sadeh, 2018; Javadi, Esmaeel Nezhad, Anvari-Moghaddam, & Guerrero, 2018; Sharma & Panigrahi, 2018; Anagnostopoulos & Mamanis, 2011).

### 3.1. Objective function

The protection method must find faults as soon as possible and separate the unhealthy region of the network. The main objective of relay coordination is to reduce functioning times under

| Solar PV parameters | Values |
|---------------------|--------|
| Cell in module      | 96     |
| Module short-circuit current (Isc) | 5.96 A |
| Module open-circuit voltage (Voc)     | 64.2 V |
| Module voltage and current at maximum power (Vmp, Imp) | 54.7 V, 5.58 A |
| Sun irradiance (MAX) | 1000 W/m^2 |
| DC–DC boost converter     | 273 V to 500-volt DC |
| 3-phase inverter       | 500 v DC to 260 V AC |
| No. of series connected string | 5     |
| No. of parallel connected string | 66    |
| Transformer rating     | 100 KVA, (260 V to 12.47, 4.16 KV) |

SPP, solar power plant.

Figure 3. Simulation of solar photo-voltaic plant (SPP) with include MPPT.
coordination regulations. The operating time period of the backup relays must become higher than the operating time period of primary relays by CTI. The protection coordination issue can be designed as follows (Zeineldin et al., 2015):

\[
F_{\text{Min}} = \sum_{i=1}^{N} T_i
\]

\[
T_i = \frac{\beta}{(I_{sc}/I_p)^\alpha - 1} \text{TMS}
\]

where

- \(T_i\) is the operation time of the \(i\)th relay,
- \(N\) is the number of relays associated in the network,
- \(\alpha\), \(\beta\) are relay coefficients, \(I_{sc}\) is the short-circuit current, \(I_p\) is the pickup current and \(\text{TMS}\) is the time multiplier setting.

subjected to:

\[
\text{TMS}_{\text{min}} \leq \text{TMS} \leq \text{TMS}_{\text{max}}
\]

The value of TMS minimum and maximum is predefined. The value of the relay TMS should lie between max and min value of predefined TMS:

\[
I_p^{\text{max}} \leq I_p \leq I_p^{\text{min}}
\]

where \(I_p^{\text{max}}\) is the maximum pick up current max\((\_), I_p^{\text{min}}\) is the minimum pick up current which is predefined on the relay, and \(I_p^{\text{max}} = \min\left(\text{I}_{\text{fault}}, \text{I}_{\text{set}}\right)\) is the main pick up current. It means relay will smoothly operate when the pickup current lies between the minimum and maximum value of pickup current

\[
t_b - t_p \geq \text{CTI}
\]

where \(t_b\) is the operating time of the backup relay, \(t_p\) is operating time interval of the primary relay, and CTI is co-ordination time interval.

4. Particle swarm optimization

PSO was introduced by Kennedy and Eberhart (1995). This algorithm is inspired by the social activities of birds. In this PSO, each individual particle is search best solution in a search space by succeeding the previous best position of the neighbours and best position of own. Every particle is characterised by its own velocity and position as

\[
S_i^{k+1} = S_i^k + V_i^k
\]

\[
V_i^{k+1} = wV_i^k + c_1 \times \text{rand}_1 \times (P_{\text{best}_i} - S_i^k) + c_2 \times \text{rand}_2 \times (G_{\text{best}} - S_i^k)
\]

where \(S_i^k\) & \(S_i^{k+1}\) represent the previous and current position of “I” particle, \(V_i^k\) & \(V_i^{k+1}\) are the previous and current velocity of particle of “i.th” particle, and \(P_{\text{best}_i}\) & \(G_{\text{best}}\) are individual best positions and best global best position identified in the whole swarm. \(C_1\) & \(C_2\) are the acceleration constants, \(W\) is inertia weight of PSO which lies between 0 and 1 & defined that how much previous velocity is preserved. Each particle of PSO share information with neighbours, updated Equation (6) & (7) show PSO associate the cognition component of every particle with social component of every particle in group. The social component advises that individuals overlook their own experience and alter their behaviour according to the prior best particle in the neighbourhood of the group.
In Equation (7), $k, w$ and $c_1, c_2$ show the weighting operator and weighting factor (acceleration factor) correspondingly. $Rand$ represents a uniformly distributed random range between zero and one. In Equation (8), “iter” represents the rate of $i_{th}$ individual at iteration. Weight operates varies iteratively in PSO. Here, $w_1$ and $w_2$ are 0.9 and 0.4, respectively. Weight operates of the matter is

$$w = (w_1 - w_2) \times \frac{(\maxit - \text{iter})}{\maxit} + w_2$$

(8)

where $w_1$ and $w_2$ represent first and last weight, respectively, and $\maxit$ and $\text{iter}$ show largest current iteration number. The procedure of optimizing the objective function using PSO is shown in Figure 4.
5. Results and discussions

5.1. Grid voltage deviation when solar photo-voltaic source is connected

A single SPP is connected on grid as tabulated in Table 3. For case 2, a seemingly negligible deviation in voltage has been noticed. For case 3, authors observed the 1.5% voltage dropped at load bus for phase c. Similarly, for case 6 voltage has dropped by 1.1%, as shown in Table 3. Analysis of the variation in grid voltage is considered only for the grid integration SPP (see Figure 5).

CTI in Equation (5) is taken from the literature (Sharaf et al., 2015), which means that the difference between backup relay tripping and primary relay tripping should always be more than and equal to 0.3 s. The fault created on three locations A, B, C are shown in Figure 2. As can be seen from Table 5, fault has been created on phase C to ground on three different buses and maximum magnitude of fault. When fault occurs at site A, then maximum current flows in case 16 (110) and second maximum for case 6 (111). A similar result has been recorded for fault location B and C (Figure 2).

5.2. Frequency calculation of solar photo-voltaic connected cases

Figures 6–8 show the frequency variation after SPP integration with grid and it has been observed the frequency deviation stay in limits, i.e. ±1%. The standard frequency for system is 60 Hz.

5.3. Current calculation of solar photo-voltaic connected cases

Table 4 Shows the current calculation for each bus along with SPP integrated cases for no fault conditions. Table 5 shows the fault current calculation for various fault locations. The results show that when the solar is connected, the level of the current at buses increase to certain level and it also reflects when fault occurs in the case of solar connected circumstances, the level of fault current also increased (shown in Table 5). Due to this reason, system needs different setting for each case.

6. Optimal relay setting

For optimal relay setting, an objective function has been modelled (Equation (1)) to minimize the operating time of the relay while satisfying CTI of the relay (Equation (5)). The issue of relay mal operation happens for integrated SPP-DG grid because unstable SPP increases the fault current level. To analyse and overcome above-mentioned issue, the present paper uses the PSO algorithm to optimize the single-objective nonlinear constrained function. Figure 2 shows the single-line diagram of IEEE 4-bus system and R1—R5 are the locations of five relays. Coordination of these relays is desired according to the fault current and state of connected SPP. For fault location “A”, R2 behaves as a primary relay and R1 as a working backup relay. For fault location, “B”, R3 acts as a primary relay and R2, R1 as a backup relays. Similarly, for fault location “C”, R4 is primary relay and R3, R2 are backup relays. Limit of TMS is taken 0.01 to 1 for relay setting (0.01 ≤ TMS ≤ 1). Tables 6 and 7 show the optimal relay tripping time and TMS for the primary as well as for backup relay. Coordination of relay setting is justified through the CTI calculation which is more than or equal to 0.3. It has been found that in case number 32 when a fault occurs at C location, backup relay takes more time to clear fault but satisfied the CTI constraint (Sharma & Panigrahi, 2018). Table 6 shows that relay setting is changed as per the condition because SPP never generates power for 24 h, so as per the conditions relay setting will be changed and that change decision has decided by using PSO. In Table 7, the tripping time of relay for the fault occurrence at various location is depicted and indicates that the tripping time of relay satisfied all the constraints.

The flow chart of relay setting is shown in Figure 9. This flow chart defines the process of relay setting variation. Here, SPV is continuously observed; this observation process is carried out on matlab platform with the help of function block. The decision of changing setting of relay is taken as per SPV status. The setting of relay as per SPV status is given in Table 6. Table 8 shows the results as compared with GA, interior point, SQP technique and it has been found that PSO gives better-optimized tripping time for the primary and backup relays. The convergence graph of relevant optimization algorithm is
Table 3. Voltages of each bus for IEEE 4-bus system in various cases (RMS)

| CASE NUMBER | CASE TYPE | Va1 (Volts) | Vb1 (Volts) | Vc1 (Volts) | Va2 (Volts) | Vb2 (Volts) | Vc2 (Volts) | Va3 (Volts) | Vb3 (Volts) | Vc3 (Volts) | Va4 (Volts) | Vb4 (Volts) | Vc4 (Volts) |
|-------------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 1)          | 000       | 7157.382    | 7159.601    | 7153.6176   | 7083.495    | 7085.692    | 7079.7392   | 2305.7988   | 2306.043    | 2305.0755   | 2051.4036   | 2051.7116   | 2050.7948   |
| 2)          | 100       | 7156.08     | 7158.296    | 7152.3098   | 7082.394    | 7084.558    | 7078.6506   | 2305.422    | 2305.6676   | 2304.7008   | 2051.0132   | 2051.3228   | 2050.406    |
| 3)          | 010       | 7157.5815   | 7159.8497   | 7153.7371   | 7077.6883   | 7080.1865   | 7073.9816   | 2298.2932   | 2298.8577   | 2297.7295   | 2020.665    | 2022.2039   | 2020.7811   |
| 4)          | 001       | 7157.5573   | 7159.7769   | 7153.7918   | 7083.9464   | 7086.1489   | 7080.1931   | 2306.4      | 2306.6495   | 2305.6827   | 2058.3899   | 2058.7268   | 2057.836    |
| 5)          | 011       | 7157.717    | 7159.7208   | 7153.6796   | 7077.8345   | 7080.0766   | 7073.4553   | 2298.5968   | 2299.1647   | 2297.4296   | 2027.2775   | 2029.1556   | 2025.2306   |
| 6)          | 111       | 7156.5675   | 7158.6283   | 7152.7747   | 7077.5504   | 7079.3029   | 7073.4323   | 2298.9998   | 2298.9477   | 2297.8807   | 2029.5925   | 2028.9573   | 2027.4881   |
| 7)          | 101       | 7156.273    | 7158.4816   | 7152.5294   | 7082.8692   | 7085.0878   | 7079.218    | 2305.9921   | 2306.3327   | 2305.3521   | 2057.891    | 2058.5653   | 2057.4058   |
| 8)          | 110       | 7156.199    | 7158.392    | 7152.4632   | 7076.5334   | 7078.5735   | 7072.77     | 2297.9399   | 2298.0514   | 2297.1604   | 2020.4985   | 2020.298    | 2019.6572   |
| CASE NUMBER | CASE TYPE | Ia1 (Ampere) | Ib1 (Ampere) | Ic1 (Ampere) | Ia2 (Ampere) | Ib2 (Ampere) | Ic2 (Ampere) | Ia3 (Ampere) | Ib3 (Ampere) | Ic3 (Ampere) | Ia4 (Ampere) | Ib4 (Ampere) | Ic4 (Ampere) |
|-------------|-----------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| 1) 000      | 000       | 239.440      | 239.4786     | 239.3519     | 239.4157     | 239.4938     | 239.3636     | 711.3819     | 711.4033     | 711.0269     | 711.185      | 711.4072     | 711.0308     |
| 2) 100      | 100       | 245.215      | 245.3050     | 245.1732     | 239.3562     | 239.4312     | 239.3043     | 711.0049     | 711.2274     | 710.8508     | 711.008      | 711.2313     | 710.8547     |
| 3) 010      | 010       | 254.019      | 252.9440     | 252.6363     | 254.0324     | 252.9566     | 252.648      | 755.1349     | 751.9382     | 751.0443     | 700.5210     | 701.1724     | 700.6287     |
| 4) 001      | 001       | 238.589      | 238.6589     | 238.5357     | 238.6018     | 238.6708     | 238.5476     | 708.7413     | 708.9460     | 708.5804     | 708.7451     | 708.9498     | 708.5842     |
| 5) 011      | 011       | 255.623      | 254.0766     | 255.7258     | 255.6364     | 254.0893     | 255.7386     | 760.177      | 755.3371     | 760.3194     | 697.7052     | 698.4608     | 697.0274     |
| 6) 111      | 111       | 257.949      | 256.8355     | 257.2302     | 252.6768     | 251.4210     | 251.9214     | 751.3651     | 747.3316     | 748.8347     | 698.4414     | 698.3549     | 697.6963     |
| 7) 101      | 101       | 244.094      | 244.4603     | 244.1121     | 238.5231     | 238.6769     | 238.4536     | 708.5071     | 708.9656     | 708.2999     | 708.5109     | 708.9694     | 708.3037     |
| 8) 110      | 110       | 259.1673     | 260.22446    | 260.06861    | 253.8183     | 254.8491     | 254.73995    | 754.53472    | 757.58557    | 757.33313    | 700.42092    | 700.47033    | 700.18662    |
shown in Figure 10 and it is been found that PSO takes 35 iterations to reach best value. Similarly GA and interior point algorithm takes 20 and 11 iteration, respectively.

7. Results validation

Tables 9 and 10 show the difference between the result of ETAP and MATLAB. Table 9 shows the results of bus current on each bus for case 1 when no SPP connected and ETAP results validate that...
Table 6. TMS values for various cases (PSO)

| S.no | Type | R1      | R2     | R3       | R4    | R5 |
|------|------|---------|--------|----------|-------|----|
| 1    | 000  | 0.99    | 0.7653 | 0.5257   | 0.2534| 0.01|
| 2    | 100  | 0.99    | 0.7435 | 0.4854   | 0.2373| 0.0104|
| 3    | 010  | 0.99    | 0.7589 | 0.5048   | 0.2621| 0.01|
| 4    | 001  | 0.99    | 0.7505 | 0.4935   | 0.232 | 0.01|
| 5    | 011  | 0.99    | 0.7562 | 0.4921   | 0.2376| 0.01|
| 6    | 111  | 0.99    | 0.749  | 0.4928   | 0.2621| 0.01|
| 7    | 101  | 0.99    | 0.7503 | 0.5161   | 0.2764| 0.01|
| 8    | 110  | 0.99    | 0.7519 | 0.4939   | 0.2539| 0.01|
Table 7. Results of primary and backup relay tripping time for various cases

| Cases | F_L | P_R | B_R1 | B_R2 | Tripping time (PR) (sec) | Tripping time (BR1) (sec) | Tripping time (BR2) (sec) |
|-------|-----|-----|------|------|------------------------|------------------------|------------------------|
| 9     | A   | R2  | R1   | –    | 1.0049                 | 1.3131                 | –                      |
| 10    | A   | R2  | R1   | –    | 0.9756                 | 1.3122                 | –                      |
| 11    | A   | R2  | R1   | –    | 0.9964                 | 1.313                 | –                      |
| 12    | A   | R2  | R1   | –    | 0.9855                 | 1.3131                 | –                      |
| 13    | A   | R2  | R1   | –    | 0.9828                 | 1.3121                 | –                      |
| 14    | A   | R2  | R1   | –    | 0.9945                 | 1.3122                 | –                      |
| 15    | A   | R2  | R1   | –    | 0.9997                 | 1.3295                 | –                      |
| 16    | A   | R2  | R1   | –    | 0.9997                 | 1.3295                 | –                      |
| 17    | B   | R3  | R2   | R1   | 0.6954                 | 1.0175                 | 1.3295                 |
| 18    | B   | R3  | R2   | R1   | 0.6421                 | 0.9886                 | 1.3296                 |
| 19    | B   | R3  | R2   | R1   | 0.6687                 | 1.0097                 | 1.3305                 |
| 20    | B   | R3  | R2   | R1   | 0.6537                 | 0.9985                 | 1.3305                 |
| 21    | B   | R3  | R2   | R1   | 0.6524                 | 1.0025                 | 1.3258                 |
| 22    | B   | R3  | R2   | R1   | 0.6504                 | 0.9936                 | 1.3265                 |
| 23    | B   | R3  | R2   | R1   | 0.6734                 | 0.9845                 | 1.3122                 |
| 24    | B   | R3  | R2   | R1   | 0.6533                 | 0.9997                 | 1.3295                 |
| 25    | C   | R4  | R3   | R2   | 0.7901                 | 1.6432                 | 2.3921                 |
| 26    | C   | R4  | R3   | R2   | 0.74                  | 1.5174                 | 2.3414                 |
| 27    | C   | R4  | R3   | R2   | 0.8248                 | 1.5921                 | 2.3935                 |
| 28    | C   | R4  | R3   | R2   | 0.7131                 | 1.5209                 | 2.3129                 |
| 29    | C   | R4  | R3   | R2   | 0.7384                 | 1.5327                 | 2.3553                 |
| 30    | C   | R4  | R3   | R2   | 0.809                 | 1.5246                 | 2.3339                 |
| 31    | C   | R4  | R3   | R2   | 0.8496                 | 1.5904                 | 2.33                   |
| 32    | C   | R4  | R3   | R2   | 0.8218                 | 1.5631                 | 2.3955                 |

(cases 1–8 have no fault cases as shown in Table 1).

(F_L = fault location, P_R = primary relay, B_R = backup relay).

Figure 9. Flow chart for relay setting selection.
MATLAB simulations are practicable within (0.079 to 1.01)% deviation. Similarly, Table 10 shows the bus voltage variation for case 6 when all three SPVs are connected and % variation of simulation results is within 0.073 to 1.3%.

Figure 11 shows that for case (111) CTI constraint is not satisfying when relay setting is the same. CTI for that case between relay 1 and 2 is 0.274 and this CTI should higher then equal to 0.3.

Table 8. Result comparison with PSO, GA, SQP, interior point algorithms

| algorithm                                      | Relay | R1  | R2  | R3  | R4  | R5  | Iteration taken to reach optimal result |
|-----------------------------------------------|-------|-----|-----|-----|-----|-----|----------------------------------------|
| PSO (Li, Liu, Zhou, Kang, & Wang)             |       | 0.990 | 0.7562 | 0.4921 | 0.2376 | 0.01 | 35                                     |
| GA (Sachdev & Ow, 1996)                       |       | 0.997 | 0.708 | 0.434 | 0.349 | 0.081 | 20                                     |
| Interior point (Darvay & Rigó, 2018)          |       | 0.9273 | 0.7011 | 0.4774 | 0.1069 | 0.0100 | 11                                     |
| SQP (Gill, Murray, & Saunders, 2005)          |       | 0.9272 | 0.7010 | 0.4773 | 0.1069 | 0.0100 | 4                                      |

Table 9. Result comparison with ETAP for case 1

| Bus     | Phase | MATLAB RESULTS (current in RMS) (Ampere) | ETAP RESULTS (current in RMS) (Ampere) | Difference in % |
|---------|-------|------------------------------------------|----------------------------------------|-----------------|
| Bus 1   | A     | 239.40 \pm 34.115                        | 239.6 \pm 29.6                         | 0.083           |
|         | B     | 239.40 \pm 154.17                       | 239.6 \pm 149.6                       | 0.083           |
|         | C     | 239.40 \pm 85.83                        | 239.6 \pm 90.4                        | 0.083           |
| Bus 2   | A     | 239.41 \pm 34.16                        | 239.6 \pm 29.6                        | 0.079           |
|         | B     | 239.46 \pm 154.18                       | 239.6 \pm 149.6                       | 0.079           |
|         | C     | 239.36 \pm 85.82                        | 239.6 \pm 90.4                        | 0.079           |
| Bus 3   | A     | 711.18 \pm 34.04                        | 718.3 \pm 29.6                        | 1.01            |
|         | B     | 711.18 \pm 154.06                       | 718.3 \pm 149.6                       | 1.01            |
|         | C     | 711.03 \pm 85.94                        | 718.3 \pm 90.4                        | 1.01            |
| Bus 4   | A     | 711.18 \pm 34.04                        | 718.3 \pm 29.6                        | 0.991           |
|         | B     | 711.18 \pm 154.06                       | 718.3 \pm 149.6                       | 0.991           |
|         | C     | 711.18 \pm 85.94                        | 718.3 \pm 90.4                        | 0.990           |

Figure 10. Comparison of all optimization algorithms (GA, PSO, interior point, SQP).

Figure 11 shows that for case (111) CTI constraint is not satisfying when relay setting is the same. CTI for that case between relay 1 and 2 is 0.274 and this CTI should higher then equal to 0.3.
Table 10. Comparison of results with ETAP for case 6

| Phase | MATLAB voltage RMS | ETAP voltage RMS | Difference in % |
|-------|-------------------|-----------------|----------------|
| Bus 1 |                   |                 |                |
| A     | 7156.55 ± 0.21    | 7200 ± 0        | 0.603,472      |
| B     | 7159.55 ± 119.79  | 7200 ± 120      | 0.561,806      |
| C     | 7155.56 ± 120.21  | 7200 ± 120      | 0.645          |
| Bus 2 |                   |                 |                |
| A     | 7077.5504 ± 0.27  | 7122 ± 0.257    | 0.624,117      |
| B     | 7079.3029 ± 120.27| 7139 ± 120.3    | 0.836,211      |
| C     | 7073.4323 ± 119.72| 7132 ± 119.65   | 0.821,196      |
| Bus 3 |                   |                 |                |
| A     | 2298.9986 ± 1.77  | 2269 ± 3.16     | 1.32,216       |
| B     | 2298.9477 ± 121.80| 2275 ± 123.19   | 1.052646       |
| C     | 2297.8807 ± 118.20| 2272 ± 116.75   | 1.139,115      |
| Bus 4 |                   |                 |                |
| A     | 2029.5925 ± 8.22  | 2023 ± 7.82     | 0.325,877      |
| B     | 2028.9573 ± 128.24| 2030 ± 127      | 0.051365       |
| C     | 2027.4881 ± 111.76| 2026 ± 112.13   | 0.07345        |

Figure 11. TCC graph for solar connected case (111) with old setting of relay.
This CTI variation could be the chances of mal-operation of relays. Therefore, the relay co-ordination needs adjustment as per SPP integration. This modification is done through the PSO technique by identifying the optimized TMS/TDS value.

shows the TCC graph for ground fault, occur at load side, which validates that result for relay setting, derived through PSO is quite correct. In Figure 13, relay coordination is shown when fault occurs at B location and relay satisfied the CTI constraint. The difference between ETAP and MATLAB results for ground fault occurred at location B has been found to deviate by 10%.

8. Conclusion
The present paper shows the simulation of IEEE node test model along with three solar PV plants and verified the results by comparing ETAP results. . Table 5 shows that bus voltages are dropped when all three SPP contributed for grid, variation of voltage regulation between case 1 and case 6 is 1.149% and for current regulation in fault case is 20.94%. These variations demand that relay setting needs to be changed as per DG connected in systems. The coordination of relay is identified through the PSO, GA, SQP, interior point algorithms and which found that SQP takes less time to converge the results. The results of Table 8 prove that PSO is capable to found optimized
results for “Optimal relay coordination model”. The result of PSO validated on electrical transient analysis programming platform through time-coordination curve is shown in Figure 12.

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