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Optimal Coordination of DOCRs Considering Transient States of Fault Current in Interconnected DG Systems using User-Defined Dynamic Model of Relays

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Abstract- In real networks, short circuit (SC) current doesn't have a fixed value but it has time variable values. So that, to avoid possible miscoordination between directional overcurrent relays (DOCRs), transient states of fault current must be considered during coordination. In this paper, a user-defined dynamic model of DOCRs - optimally select the relays four parameters (time multiplying setting (TMS), pickup current (IP) and constant coefficients (α and β)) - is presented to consider the transient states of SC current - from both the utility and synchronous based distributed generators (DGs)- in coordination problem. The coordination problem is solved by three techniques; two hybrid meta-heuristic techniques: gravitational search algorithm- sequential quadratic programming (GSASQP) and particle swarm optimization- gravitational search algorithm (PSOGSA) and one mathematical method: find minimum constraints (FMINCON). Each one of the presented techniques is applied to three different test systems- IEEE 3, 9 and 14 bus systems- in four different models for each system- to show the efficiency of the proposed user-defined dynamic model technique. Each system four models are (model 1: conventional steady-state model, model 2: user-defined steady-state model, model 3: conventional dynamic model considering transient and model 4: proposed method (user-defined dynamic model considering transient). The results show a superiority of the meta-heuristic techniques over the mathematical method also show that the presented user-defined dynamic model technique is the most efficient method for DOCRs coordination in presence of transient fault. MATLAP program is used to obtain the transient SC current and to apply the proposed techniques.

Keywords Dynamic model of over current relays, Directional overcurrent relays; User-defined relay characteristics; Transient short circuit current; Optimal Protection Coordination.

1. Introduction

Despite the numerous advantages obtained by connecting Distributed generators (DGs) to the distribution networks, DGs connection to these networks leads to bi-direction power flow in the systems and change in short circuit current levels [1], [2], [3] and [4]. Many researches have studied the effects of DGs on the protection coordination of overcurrent (OC) relays [5], [6] and [7]. Most of these researches considered only the steady-state value of the short circuit currents like [8], [9], [10], [11], [12] and [13].

On the other hand, less researchers tackled the problem of DOCRs coordination in presence of DGs considering the transient fault current, which will be briefly mentioned in the following sentences. In [7], a coordination strategy based on the dynamic model of the overcurrent relays is presented to take-over the transient behavior of DGs and fault current limiters (FCLs). The dynamic model of FCL and synchronous based DGs are implemented in PSCAD program to get the transient fault current of the DGs then the genetic algorithm (GA) optimization technique is used to calculate the optimal time multiplying setting (TMS) of the relays. The drawbacks of this solution are the long processing time and the optimal selection of only one setting; TMS; while the pickup current (I_p) is not selected optimally. In [14], the authors present a linear programing (LP) based algorithm integrated with the GA technique for solving the optimal coordination of DOCRS where both the TMS and I_p have been optimally selected. Although both settings have been optimally calculated, the long processing time continued to be a challenge, as it takes 235 min. for the IEEE 14 bus test system and 283 min. for the IEEE 39 bus test system. In [15], an optimization method based on adapted particle swarm optimization (PSO) algorithm is presented to optimally select TSM, I_p and curve type from the standard curve types shown in Table 1. Two strategies were presented in this research: the conventional method based on fixed short circuit current values and the proposed method based on transient short circuit current values. The study concluded that by selecting I_p and the curve type in addition to TMS through the optimization algorithm; the summation of relays operating times are get minimized from 14.8099 s to 13.81 s for 19 bus radial system of Sirjan-Iran and from 40.02 s to 12.14 s for IEEE 8 bus meshed system when using the proposed method based on transient fault current. Also for both test systems, the proposed method could resolve all the miscoordination cases obtained by the conventional method. The main drawback of the presented method in [15] is the large number of constraints which may restrict the optimization technique to find optimal solution due to narrow search space. In [16], the authors present an optimization method based on GA and dynamic model of non- directional overcurrent relays (OC) relays for optimal coordination of non-directional OC relays, taking into account the transient fault current contributed from induction motor during short circuit states in the industrial power networks. The study added a new set of constraints in order to accommodate the transient response of induction motors in SC states. In [17], an optimization method based on the dynamic model of OC relays is presented to incorporate the momentary SC of two types of wind turbine generator (WTG): synchronous based and doubly fed inverter interfaced DG (IIDG) for both far- end and near- end faults. The proposed technique coordinates the protection devices in the power system like OC relays, fuses, FCL and reclosers in two stages. In the first stage; DOCRs used to protect the main feeder in the high voltage level are coordinated with each other. In the second stage; reclosers and fuses which used in the lower voltage level to protect lateral are coordinated with the above level DOCRs, by identifying each pair of protective devices involved in a certain fault location. To resolve the contribution of WTG DGs in fault current, FCL is connected between DG and its point of common coupling (PCC) with the network. It is worth mentioning that considering the transient fault current in coordination problem magnifies the size of FCL needed by 29-65 % and the price of the FCL by 20-35% compared to FCL size and cost used in case of steady-state (SS) based coordination. In [18], an optimization method for coordinating DOCRs based on LP and the dynamic model of OC relays is presented. The presented solution intended to consider the effect of topology change on the SC current level due to the operation of the relay on the other side of transmission line (TL). The study concluded that, faster operation of one of the main relays of a TL leads to topology change which in turn, change the fault current level seen by the main relay on the other side of TL and its back up, which finally, can lead to miscoordination between them. The same problem of [18] is discussed also in [19] but with a different optimization technique which is teaching learned- based optimization (TLBO) technique.

Table 1 Standard relay characteristic based on IEC 60255

Relay Characteristic	IEC 60255 Characteristics curves constants	
	A	β
Standard Inverse (SI)	0.14	0.02
Very Inverse (VI)	13.5	1
Extremely Inverse (EI)	80	2

In this paper, three optimization techniques based on the user-defined dynamic model of OC relay are presented to solve the coordination problem taking into consideration the transient fault current. The used techniques are gravitational search algorithm- sequential quadratic programming (GSASQP), particle swarm optimization- gravitational search algorithm (PSOGSA) which are two hybrid heuristic optimization techniques and find minimum constraints (FMINCON) which is a MATLAB mathematical function that solves the constrained optimization problems with SQP algorithm. Actually, each proposed technique is applied to three test systems in four different models to verify its effectiveness. In model 1, conventional steady-state model, (TMS, I_p) are optimally selected based on steady-state fault current, while in model 2, user-defined steady-state model, (TMS, I_p, α and β) are optimally selected based on steady-state fault current, on the other hand in model 3, conventional dynamic model considering transient, (TMS, I_p) are optimally selected considering transient fault current, finally in model 4, the proposed method (user-defined dynamic model considering transient), (TMS, I_p, α and β) are optimally selected considering transient fault current. It worth to mention that, through all the presented techniques, the DOCRs four parameters are considered to have continuous values not restricted to certain specified values like the common standard values of (α and β) in Table 1, also the transient fault considered in this paper is representing the transient response of both the utility and synchronous DGs due to three phase SC at the mid-point of TL.

The main contribution in this paper can be concluded in the following points:

- It presents a comparison between mathematical based solution techniques and the meta-heuristic techniques in DOCRs coordination filed with the consideration of transient fault current. Sections (5) and (6) in this paper show this.
- It proves that considering the transient states of the fault currents in the optimal coordination studies reduces the total relays' operating times. This effect doesn't obviously appear in small test systems like IEEE 3 bus systems, but could be clearly observed in larger systems like IEEE 9 bus and 14 bus systems. Previous published references don't explore the effect of transient fault on relays coordination in such small systems, as the smallest test system studied in previous references are 8 bus system. So that, this paper fills this research gap.
- The main contribution of this paper is the introducing of an optimal coordination strategy based on a user-defined dynamic model for overcurrent relays. The proposed strategy gets use of the great flexibility and evolution of the digital relays while considering the transient fault current contributions from both the DGs and the main utility. The proposed coordination strategy optimally selects different values of (α and β) resulting in optimally user-defined relay characteristics rather than the traditional standard values shown in Table 1 of this paper. The obtained results show that this presented user-defined non-standard characteristic of DOCRs has a great effect in reducing relays operating times when considering the transient fault currents in the coordination study.
- The validity of the proposed strategy has been proved by extensive simulation case studies using different test systems and different optimization techniques.

2. Problem Statement

The fault current is a signal with a dynamic nature which has a transient response that can be notable for a period extended from 0.2 to 0.5 s from the fault inception time. Neglecting the transient component of the fault current during protection coordination studies may lead to miscoordination incidents among the protective devices as discussed in [20], [21] and [22].

For the sample network shown in Fig.1, if the operating time of the relay (R_4) is 0.1s calculated based on transient fault current, the relay will have an operating time of 0.13 s calculated based on fixed SC, with an error of 13% for the VI characteristic curve, as shown from Fig.2 [15]. This error can lead to miscoordination among protective devices in the system.

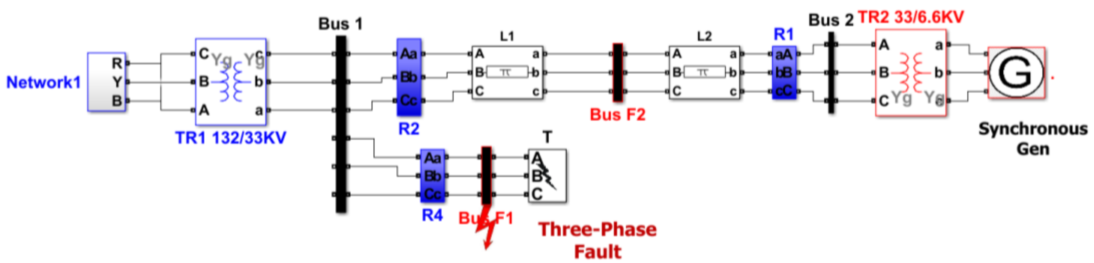

Fig. 1. Sample network

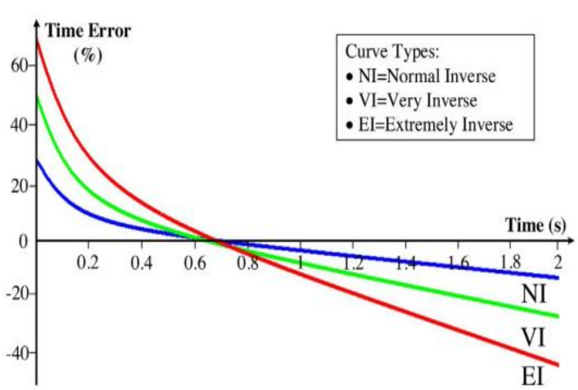

Fig. 2. Error in calculating OC relay operating time for different relay characteristics as in [15]

So that, the traditional relay operating shown in Eq. (1) cannot be used for calculating relays operating time under fault level change situations.

$$t = TMS\ x\ \frac{\alpha}{(\frac{I}{I_p})^{\beta}-1} \quad (1)$$

Where t is the relay operating time, TMS, I_p, α and β are the relay four parameters and I is the steady-state SC. So that, the transient fault current must be considered when calculating the operating time of OC relays which require the usage of the dynamic model of OC relays.

2.1 Overcurrent relays dynamic model

According to IEEE standard C37.112-1996 [22], The dynamic model for inverse-time OC relays is presented as shown in Eq. (2).

$$\frac{1}{TMS}\int_{t_0}^{t_x}\left(\frac{1}{F_2(I)}-\frac{1}{F_1(I)}\right)=1 \quad (2)$$

Where t_0 is the time at which the relay starts to sense the SC current and t_x is the operating time of the relay. While $F_2(I)$ and $F_1(I)$ are the trip and reset characteristics of the relay, respectively, as shown in Eq. (3) and Eq. (4).

$$f_2(I_{sc})=\frac{\alpha}{((\frac{I_{sc}}{I_P})^{\beta}-1)}, \quad where \ (\frac{I_{sc}}{I_P})>1 \quad (3)$$

$$f_1(I_{sc})=\frac{t_r}{(1-(\frac{I_{sc}}{I_P})^2)}, \quad where \ 0<\left(\frac{I_{sc}}{I_P}\right)<1 \quad (4)$$

$f_2(I_{sc})$ is activated when $I_{SC}>I_p$ whereas, $f_1(I_{sc})$ is activated when $I_{sc}<I_p$. I_p is the pickup setting of OC relay and parameters α, β and t_r are constant factors. I_{SC} is the momentary SC current so it contains the transient states of SC currents. If the value of integration in Eq. (2) reaches 1, the relay will send a trip command, so Eqn. (2) can be called relay operating status (ROS).

3. Proposed Formulation for DOCRs Coordination Problem Considering Transient Fault Current

In this paper, an optimal coordination method based on user-defined dynamic model of OC relays is presented in order to consider the transient states of SC current in DOCRs coordination problems. In the user-defined dynamic model of the OC relay, α and β; which define the characteristics of the relay; are optimally selected along with the two traditional settings TMS and I_p. It worth to mention that, through all the presented techniques in this paper, the OC relay four parameters are considered to have continuous values not restricted to certain discrete values, like the common standard values for α and β in Table 1. The four optimized settings of the relay with the representation of the transient short circuit current will formulate the user-defined dynamic model of the DOCRs to be used while solving the optimal coordination problem.

3.1 Linearization-based method

In this study, a multi-level linearization method based on the user-defined dynamic model of OC relays is presented for DOCRs coordination in the presence of transient fault current. The presented method is inspired from [14] and can be described in the following steps:
- For each fault location, identify the primary/backup relay pairs.
- For each fault location, get the transient fault current (sub-transient, transient and steady-state) seen by the involved relays of this fault.
- The resulted fault waves from the previous step are linearized.
- Divide the fault waves after the linearization into P-levels, based on the selected time step (0.05 s), and calculate the average current value in each level, as shown in Fig. 3.

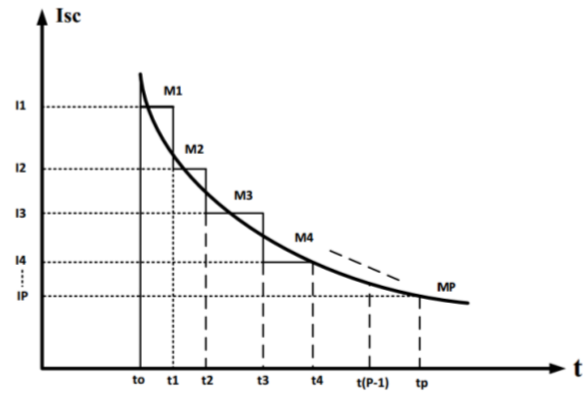

Fig. 3 Linearized transient fault current divided into P-levels

Actually, linearization is a must step pre the step of dividing and average. Because if the average in each level is got before linearization, the average of a certain level, especially the first levels after fault, may have a negative value due to the greater negative peak compared to the positive peak in these first levels as shown in Fig. 4. Based on the comparison presented in [23] and [24] between the linearization based on the upper envelope of the wave and the RMS of the wave, it can be concluded that; the consideration of RMS values gives more accurate results in different application compared to the envelope, as the envelope is obtained by passing along the outer contour of the SC wave so it contains multiple spikes and outliers. On the other hand, RMS samples are much smoother as shown in Fig. 5 and Fig. 6 which explain that the envelope wave has much more ripples compared to RMS wave which have very limited range of ripples. So that, the linearization in this paper is based on RMS values of the SC wave.

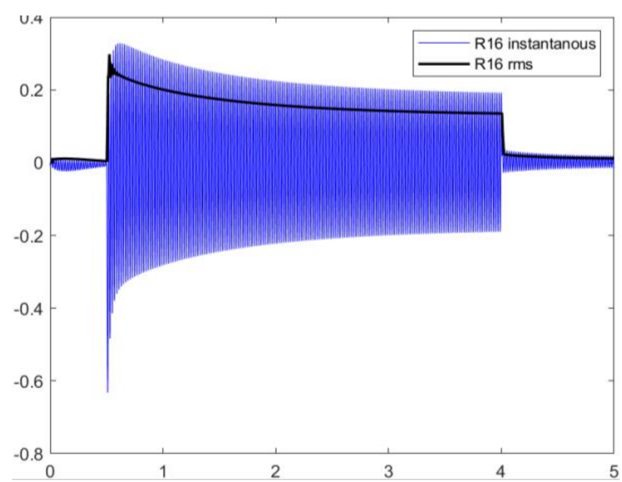

Fig. 4. Instantaneous and linearized fault wave

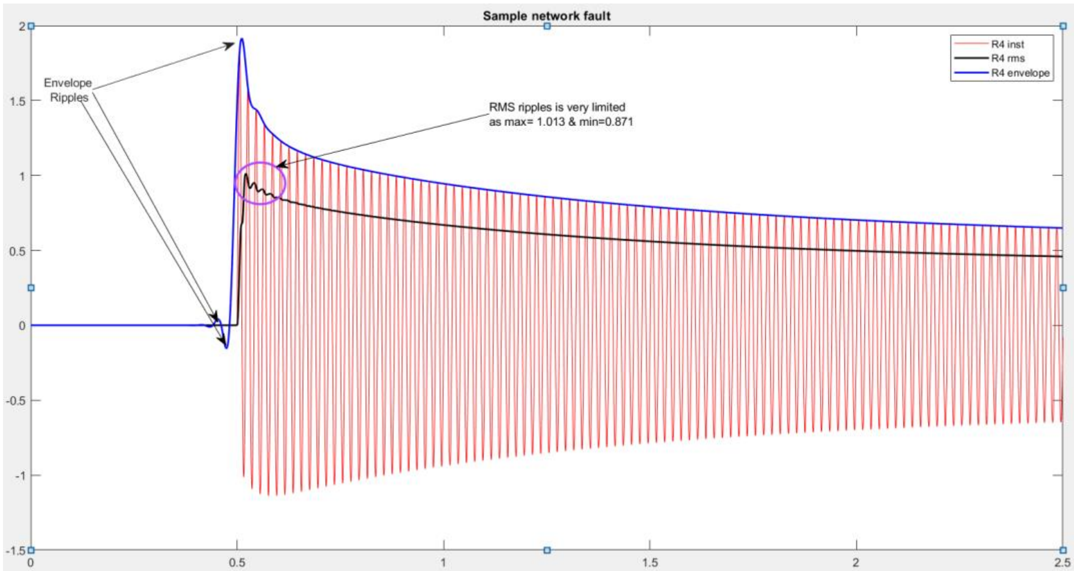

Fig. 5 Instantaneous, rms and envelope values of the SC current for the sample network

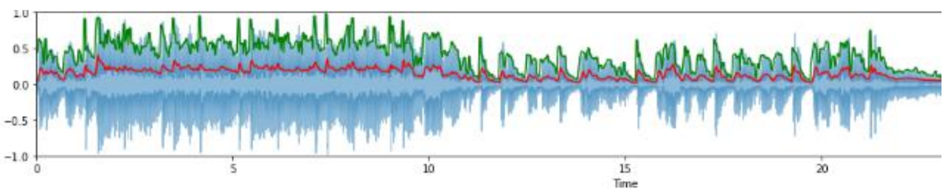

Fig. 6 Envelope (green wave) against RMS (red wave) as from [23]

From Fig.3, M value for each level is calculated based on the average current in the same level as in equations (5), (6) and (7).

$$M_1=\frac{\alpha}{\left(\left(\frac{I_{f1}}{I_p}\right)^{\beta}-1\right)} \quad (5)$$

$$M_2=\frac{\alpha}{\left(\left(\frac{I_{f2}}{I_p}\right)^{\beta}-1\right)} \quad (6)$$

$$M_p=\frac{\alpha}{\left(\left(\frac{I_{fp}}{I_p}\right)^{\beta}-1\right)} \quad (7)$$

Substituting by equations (5), (6) and (7) in the trip part of Eq. (2), Eq. (8) is obtained.

$$\int_{t_0}^{t_1}\frac{dt}{M1\,TMS}+\int_{t_1}^{t_2}\frac{dt}{M2\,TMS}+\cdots+\int_{t_{p-1}}^{t_x}\frac{dt}{Mp\,TMS}=1 \quad (8)$$

The previous equation can be reformulated as follows:

$$\frac{t_1-t_0}{M_1}+\frac{t_2-t_1}{M_2}+\cdots+\frac{t_x-t_{p-1}}{M_P}=TMS \quad (9)$$

$$t_x = M_p\,TMS+\sum_{i=1}^{p-1}t_i\left(\frac{M_p}{M_{i+1}}-\frac{M_p}{M_i}\right)+t_0\left(\frac{M_p}{M_1}\right) \quad (10)$$

Where t_0 is the time at which relay start to sense the fault, P is the number of levels and t_x is the relay operating time under transient SC.

3.2 Objective function and constraints

In this paper, the objective function aims to minimize the operating time of both primary and backup relays involved in a certain fault to reach the optimal coordination of DOCRs, utilizing the dynamic-model relay operating equation presented in Eq. (10), which can be represented as in Eq. (11).

$$Minimized\ OF = \sum_{i=1}^{N_r}[t_{xi-pr}+t_{xi-bk}] \quad (11)$$

Where i is the relay number, t_{xi-pr} is the primary relay operating time for mid-point 3-phase SC, , t_{xi-bk} is the primary relay operating time for mid-point 3-phase SC and N_r is total number of relays in the system. The constraints applied to the objective function Eq. (11) are as following:

$$t_b-t_m \geq CTI^{\,min} \quad \forall(m\ and\ b)\in\ \Omega \quad (12)$$

$$TMS_i^{min}\leq TMS_i\leq TMS_i^{max} \quad (13)$$

$$I_{pi}^{min}\leq I_{pi}\leq I_{pi}^{max} \quad (14)$$

$$\alpha_i^{min}\leq\alpha_i\leq\alpha_i^{max} \quad (15)$$

$$\beta_i^{min}\leq\beta_i\leq\beta_i^{max} \quad (16)$$

$$t_{imin}\leq t_i\leq t_{imax} \quad (17)$$

Where Ω is the primary/ backup relays pair and the minimum coordination time interval (CTI_{min}) is taken to be 0.2s, TMS_{min}= 0.1 PU and TMS_{max}= 3 PU, I_{pmin}= 1. 5 *FLA and I_{pmax}= 0.9 * minimum SC current seen by the relay, α_{min} = 0.14 PU and α_{max}= 10 PU, β_{min}=0.01 PU and β_{max} = 1 PU and the relay operating time limits are t_{imin} = 0.1s and t_{imax} = 2.5 s.

3.3 Optimization Techniques used

3.3.1-Gravitational Search Algorithm-Sequential Quadratic Programming (GSASQP)

GSA is a population based metaheuristic technique; it has multiple solutions in each iteration and it is more exploration than exploitation. GSA searches a wide area of solutions with excellent approach to a global optimum solution but it may not be the best global due to multi-points in the large search space. On the other hand, SQP is a single solution based technique, it has one solution in each iteration and it is more exploitation than exploration. As long as SQP is a single point search technique, it may be trapped to a local solution, if the initial point isn't selected properly. To overcome the drawback of each method and get use of its advantage, a hybrid GSA-SQP method is presented where SQP is added to GSA to improve its convergence. GSA is normally executed and in each iteration the best fitness is selected, the corresponding agent to this best fitness is transferred to SQP to be used as the initial values for the variables to be optimized. After that, SQP is run to enhance the best fitness obtained by GSA, at the end the hybrid GSA-SQP reaches the global optimum solution [25].

3.3.2 Particle Swarm Optimization- Gravitational Search Algorithm (PSOGSA)

PSO and GSA are two population based metaheuristic techniques, they have multiple solution in each iteration. Although both of them are population based techniques, PSO has more abilities in exploitation and GSA has more abilities in exploration. The power of this technique is that it is a co-evolutionary method as the two algorithms are run in parallel not in sequence [26]. GSA is a physical type algorithm and PSO is a swarm intelligent type algorithm. In PSO, each candidate solution (particle) try to find the best solution in its certain path, and all the particles are communicated to update their positions and velocities to find the best solution so far i.e. the global best. In GSA, each agent (mass) represent a solution which is evaluated as a best or worst solution based on its force calculated by Newton gravitational law. According to the law of motion, the acceleration of each particle is calculated and evaluated through the fitness function. Using the optimal position and velocity obtained by PSO and the optimal acceleration obtained by GSA, the hybrid PSO-GSA can converge to a global optimum solution [25].

3.3.3 Find Minimum Constraints (Fmincon)

Fmincon is a non-linear multi-variable optimization solver, which is a built-in function in MATLAB software which depends on the gradient-based method. The fmincon algorithm starts the iteration process by an initial suppose and stops when all constraints are satisfied. If the last iteration satisfies the optimization problem constraints, it is considered a local minimum solution. Fmincon is a gradient based optimization tool which can be used for minimized based objective function. Fmincon main solvers are interior-point, SQP and active-set methods [27] and [28].

The previous proposed technique presented in the above section can be better clarified from the next logic algorithm shown in Fig.7.

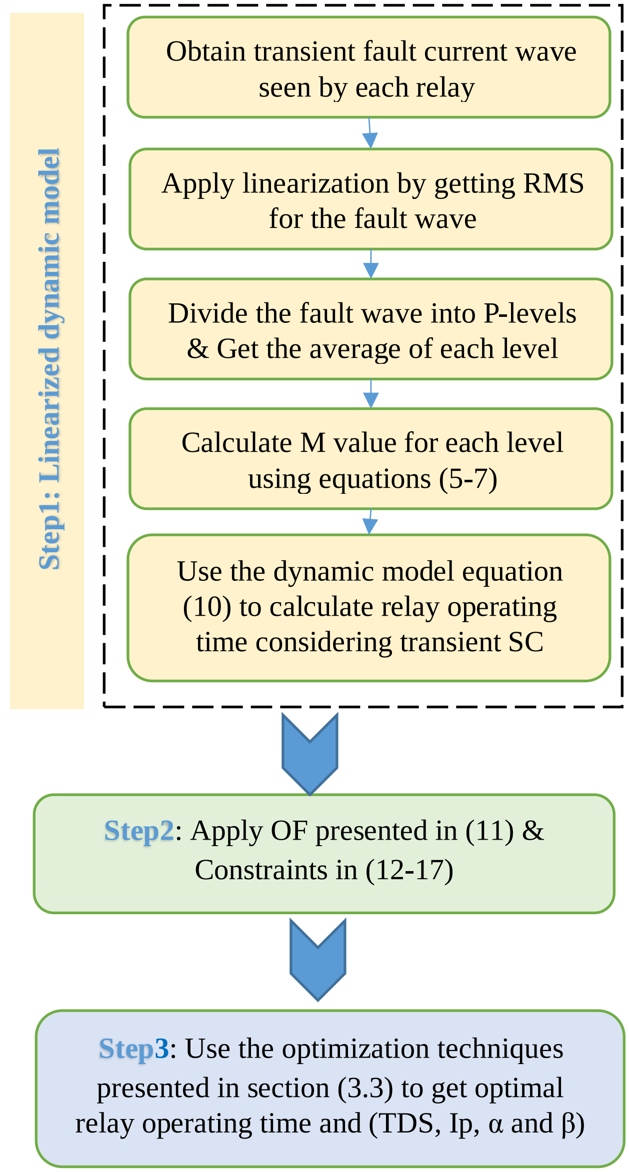

Fig.7 Proposed algorithm for the solution steps

4. Test Systems

Three test systems are used to validate the proposed solutions including; IEEE 3 bus system, IEEE 9 bus system and IEEE 14 bus system as shown in figures Fig.8, Fig.9 and Fig.10 respectively.

The IEEE 3 bus system consists of 3 buses rated at 33 kV, 6 DOCRs installed at both ends of all feeders, one main utility with a transformer rated at a 60 MVA, 13.8/33 kV rated with a percentage impedance equal to 3% at bus 1 and one synchronous based DG with a transformer at bus 2. The DG technology used is chosen to be a synchronous type. Each DG is practically connected to the network through a transformer with 5MVA, 6.6/33 kV and a percentage impedance of 5%. The dynamic parameter of DG is as shown in Table 2. The feeders characteristics and length, load values, utility data and the terminal conditions are as mentioned in [29].

The IEEE 9 bus system consists of 9 buses rated at 33 kV, 12 DOCRs installed at both ends of all feeders, one main utility with a transformer rated at a 60 MVA, 13.8/33 kV with a percentage impedance equal to 3% at bus 1 and two synchronous based DGs at buses 2 and 3 each with a suitable transformer. The DG technology used is chosen to be a synchronous type. Each DG is practically connected to the network through a transformer with 5MVA, 6.6/33 kV and a percentage impedance of 5%. The dynamic parameter of DG is as shown in Table 2. The feeder characteristics and length, load values, utility data and the terminal conditions are as mentioned in [29].

The IEEE 14 bus system consists of 14 buses rated at 33 kV, 16 DOCRs installed at both ends of all feeders, two main utilities with suitable two transformers at buses 1 and 2 each utility transformer is rated at a 60 MVA, 13.8/33 kV with a percentage impedance equal to 3% and two synchronous based DGs at buses 3 and 5 with suitable two transformers. The DG technology used is chosen to be a synchronous type. Each DG is practically connected to the network through a transformer with 5MVA, 6.6/33 kV and a percentage impedance of 5%. The dynamic parameter of DG is as shown in Table 2. The feeder characteristics and length, load values and utilities data and terminal conditions are as mentioned in [30].

Table 2 Synchronous DG dynamic parameter

S_n = 5MVA	V_n = 6.6kV	F = 50 Hz	R_A = 0.004 pu	X_0 = 0.046 pu
X_d=1.8 pu	X_d'=0.166 pu	X_d" = 0.119 pu	T_{d0}' =1.754 s	T_{d0}" = 0.019 s
X_q=1.793 pu	X_q'=0.98 pu	X_q" = 0.17 pu	T_{q0}' =0 s	T_{q0}" = 0.164 s
X_L= 0.1 pu	P = 4 poles			

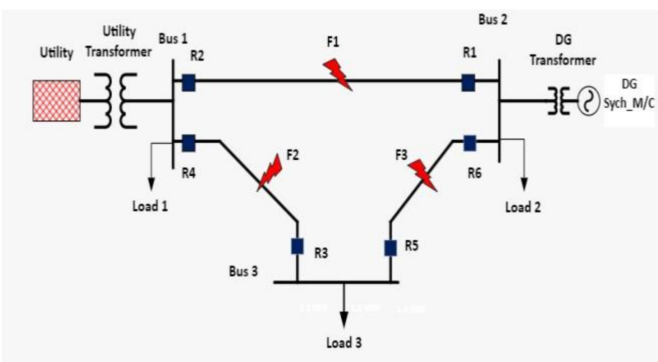

Fig.8 IEEE 3 bus system

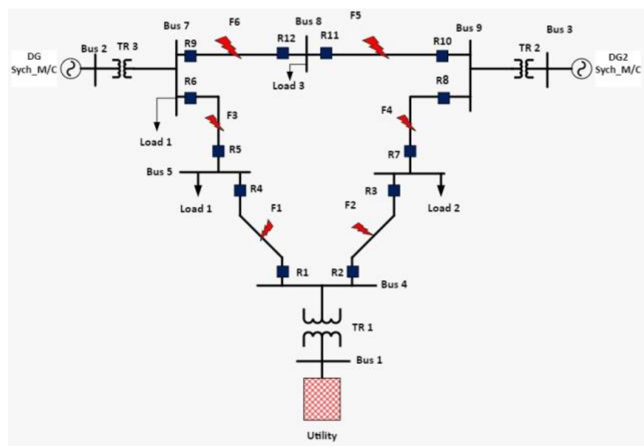

Fig.9 IEEE 9 bus system

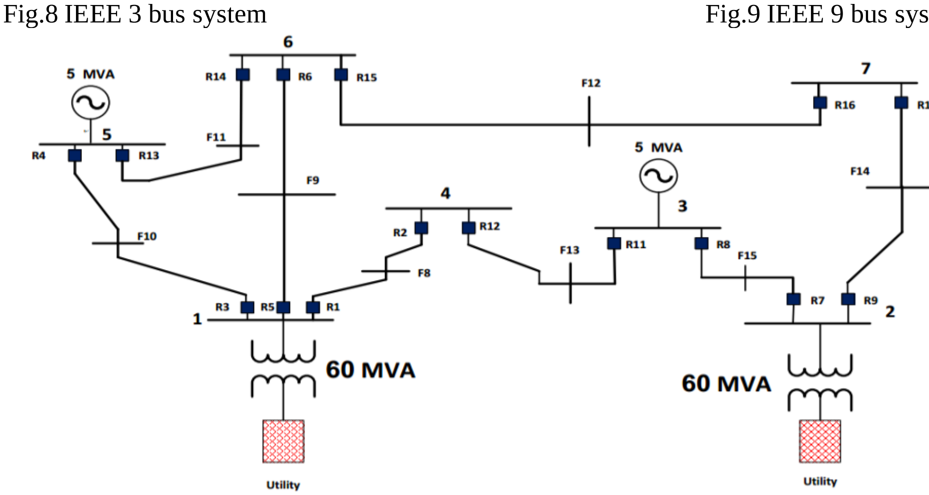

Fig.10 IEEE 14 bus system

5. Simulation Results and Analyses

In order to evaluate the proposed solution methods presented in section 3.2, each system is solved by each solution technique in four different models to make a comparison between them and to find the best technique for solving optimal coordination problem in the presence of DGs with considering transient fault current. The four models are as follow:

- Model 1: Conventional steady-state model of OC relays; optimally select (TMS, I_p) considering steady-state fault current, while α and β are fixed values equal to normally inverse characteristic values shown in Table 1.
- Model 2: User-defined steady-state model of OC relays; optimally select (TMS, I_p, α and β) considering steady-state fault current.
- Model 3: Conventional dynamic model of OC relays; optimally select (TMS, I_p) considering transient states of fault current, while α and β are chosen to be equal to normally inverse characteristic values shown in Table 1.
- Model 4: Proposed method: User-defined dynamic model of OC relays; optimally select (TMS, Ip, α and β) considering transient states of fault current.

Samples of relays operating times for IEEE 3 bus system and the CTI between primary/backup relays pair are as shown in Table 3.

Table 3 Relays operating time of 3 bus system

Relay Number		Optimization technique used								
		GSASQP			PSOGSA			Fmincon		
Primary	Backup	Primary t_{op} (s)	Backup t_{ob} (s)	CTI (s)	Primary t_{op} (s)	Backup t_{ob} (s)	CTI (s)	Primary t_{op} (s)	Backup t_{ob} (s)	CTI (s)
Model 1 (Conventional steady-state model considering SS fault current)										
1	5	1.6969	1.8969	0.2000	1.1349	1.3349	0.2000	0.6985	1.1686	0.4701
4	1	0.8382	2.3431	1.5049	0.5712	1.5661	0.9950	0.6929	0.9641	0.2712
5	4	0.9380	1.2355	0.2976	0.5896	0.8385	0.2489	0.6966	1.0173	0.3207
All relays sum (s)		20.4517			15.9104			13.7489		
Model 2 (User-defined steady-state model considering SS fault current)										
1	5	0.8740	1.0740	0.2000	1.6752	2.4669	0.7917	1.1845	1.4863	0.3018
4	1	0.2240	1.4623	1.2383	2.0908	2.3260	0.2352	0.4815	1.0893	0.6078
5	4	0.3326	0.5326	0.2000	0.9593	1.9586	0.9993	0.4026	1.3081	0.9055
All relays sum (s)		12.1913			18.0674			9.3680		
Model 3 (Conventional dynamic model considering transient SC current)										
1	5	1.0734	1.2734	0.2000	1.0736	1.2927	0.2191	1.0734	1.2734	0.200
4	1	0.9981	1.2292	0.2311	0.9744	1.2298	0.2554	0.9237	1.2292	0.200
5	4	0.9644	1.1699	0.2055	1.0272	1.2372	0.2100	0.9265	1.1265	0.200
All relays sum (s)		14.0482			16.1384			13.6273		
Model 4 (User-defined dynamic model considering transient SC current)										
1	5	0.9688	1.1721	0.203	1.1263	1.3334	0.207	0.9501	1.1501	0.200
4	1	0.7291	0.9293	0.200	1.0103	1.2105	0.200	0.7258	0.9258	0.200
5	4	0.7631	0.9684	0.205	0.9886	1.2899	0.301	0.7541	0.9541	0.200
All relays sum (s)		11.8853			13.8849			11.9027		

For the 3 bus system among the four cases, it can be concluded that

- For GSASQP, relays operating times get in the proposed method (user-defined dynamic model of OC relays considering transient) are the best.
- For PSOGSA, relays operating times get in the proposed method (user-defined dynamic model of OC relays considering transient) are the best.
- For Fmincon, relays operating times get in Model 2 (User-defined steady-state model considering SS fault current) are the best.
- The best results so far are those obtained from model 2 using fmincon which is slightly decrease than those from proposed method (model 4) using GSASQP. So that, for 3 bus system the mathematical method is better than the hybrid-metaheuristic techniques.
- From the above results it can be concluded that, for IEEE 3 bus system, considering the transient SC fault current during coordination is a good solution but not the best.

Whenever samples of the relays settings in IEEE 3 bus system using the three presented techniques in the different models are as shown in Table 4.

Table 4 IEEE 3 bus system optimal relays settings

Relay NO.	GSASQP TMS (PU)	GSASQP I_p (PU)	GSASQP α	GSASQP β	PSOGSA TMS (PU)	PSOGSA I_p (PU)	PSOGSA α	PSOGSA β	Fmincon TMS (PU)	Fmincon I_p (PU)	Fmincon α	Fmincon β
Model 1 (Conventional steady-state model considering SS fault current)												
R1	0.300	0.0306	0.14	0.02	0.201	0.0306	0.14	0.02	0.1236	0.0306	0.14	0.02
R4	0.300	0.0440	0.14	0.02	0.206	0.0431	0.14	0.02	0.2502	0.0431	0.14	0.02
R5	0.300	0.0260	0.14	0.02	0.170	0.0321	0.14	0.02	0.2824	0.0148	0.14	0.02
Model 2 (User-defined steady-state model considering SS fault current)												
R1	0.700	0.0306	3.0000	1.0000	0.777	0.0306	5.0370	0.9839	0.100	0.1030	0.1400	1.000
R4	0.706	0.0439	3.0160	0.9609	1.379	0.0431	6.1540	0.5891	1.7004	0.0751	1.6309	0.999
R5	0.956	0.0169	3.2614	0.8917	0.512	0.0147	9.3769	0.6495	0.7512	0.0202	5.6381	0.999
Model 3 (Conventional dynamic model considering transient SC current)												
R1	0.100	0.0306	0.14	0.02	0.100	0.0306	0.14	0.02	0.100	0.0306	0.14	0.02
R4	0.164	0.0495	0.14	0.02	0.100	0.1092	0.14	0.02	0.100	0.0846	0.14	0.02
R5	0.134	0.0282	0.14	0.02	0.203	0.0162	0.14	0.02	0.100	0.0382	0.14	0.02
Model 4 (User-defined dynamic model considering transient SC current)												
R1	0.262	0.0310	0.1658	0.1158	0.1001	0.0306	3.3616	0.4078	0.1000	0.0306	0.1400	0.0383
R4	0.100	0.1370	0.1400	0.2315	2.8224	0.0431	1.5763	1.0000	0.1000	0.1335	0.1400	0.2172
R5	0.100	0.0618	0.1400	0.2838	0.1000	0.0425	9.8452	0.9919	0.1000	0.0609	0.1400	0.1815

It is seen from Table 4, that all the relays variables are within limits as in section 3.2.

For IEEE 9 bus system, a set of relays operating times and the CTI between primary/backup relays pair are as shown in Table 5.

Table 5 Relays operating time of 9 bus system

Primary	Backup	GSASQP Primary t_{op} (s)	GSASQP Backup t_{ob} (s)	GSASQP CTI (s)	PSOGSA Primary t_{op} (s)	PSOGSA Backup t_{ob} (s)	PSOGSA CTI (s)	Fmincon Primary t_{op} (s)	Fmincon Backup t_{ob} (s)	Fmincon CTI (s)
Model 1 (Conventional steady-state model considering SS fault current)										
3	8	0.543	0.743	0.2	0.543	0.902	0.359	0.780	1.602	0.822
6	12	0.888	1.088	0.2	0.892	1.171	0.279	1.255	2.089	0.833
11	9	0.492	0.692	0.2	0.492	0.692	0.2	1.569	1.863	0.293
All relays sum (s)		17.372			21.561			37.65137		
Model 2 (User-defined steady-state model considering SS fault current)										
3	8	0.543	0.743	0.2	0.543	0.856	0.313	0.689	2.208	1.518
6	12	0.888	1.088	0.2	0.888	1.088	0.2	1.532	2.080	0.548
11	9	0.492	0.692	0.2	0.492	0.692	0.2	0.904	1.476	0.571
All relays sum (s)		17.372			21.188			36.8748		
Model 3 (Conventional dynamic model considering transient SC current)										
3	8	0.1	0.3	0.2	0.1	0.301	0.201	1.606	1.807	0.201
6	12	0.1	0.3	0.2	0.1	0.303	0.203	1.327	1.476	0.149
11	9	0.1	0.3	0.2	0.1	0.415	0.315	1.608	1.781	0.172
All relays sum (s)		4.8			12.907			36.05217		
Model 4 (User-defined dynamic model considering transient SC current)										
3	8	0.1	0.308	0.208	0.103	0.31	0.207	1.081	1.281	0.200
6	12	0.1	0.309	0.201	0.827	1.084	0.257	1.093	1.293	0.200
11	9	0.1	0.3	0.200	0.1	0.3	0.200	0.971	1.171	0.200
All relays sum (s)		4.8			6.873			29.109		

From the above results it can be concluded that, for IEEE 9 bus system, considering the transient SC fault current during coordination leads to the best solution using any solution method from the three proposed methods in this paper. Moreover, using the proposed method (user-defined dynamic model considering transient) with fmincon solver technique can overcome the miscoordination states appeared when using fmincon with the conventional transient method. Furthermore, the hybrid meta-heuristic techniques are better than the mathematical method for any model or study case.

A comparison of the optimized settings for set of relays in the IEEE 9 bus system obtained by the three presented techniques in the different models are presented in Table 6.

Table 6 IEEE 9 bus system optimal relays settings

Relay NO.	Optimization technique used											
	GSASQP				PSOGSA				Fmincon			
	TMS (PU)	I_p (PU)	A	β	TMS (PU)	I_p (PU)	α	β	TMS (PU)	I_p (PU)	α	β
Model 1 (Conventional steady-state model considering SS fault current)												
2	3	0.2940	0.14	0.02	1.5235	0.2890	0.14	0.02	0.1445	0.0807	0.14	0.02
7	0.1	0.2170	0.14	0.02	0.4785	0.0760	0.14	0.02	1.102	0.0906	0.14	0.02
12	3	0.1460	0.14	0.02	0.1	0.0530	0.14	0.02	0.1001	0.0709	0.14	0.02
Model 2 (User-defined steady-state model considering SS fault current)												
2	1.803	0.137	8.431	0.669	2.881	0.261	0.344	0.554	1.997	0.139	0.400	0.678
7	2.132	0.120	4.975	0.526	1.313	0.163	0.150	0.583	2.540	0.104	0.140	0.125
12	1.152	0.117	3.463	0.611	0.784	0.055	6.886	0.999	2.502	0.053	0.410	0.205
Model 3 (Conventional dynamic model considering transient SC current)												
2	3	0.2070	0.14	0.02	2.716	0.2070	0.14	0.02	2.382	0.1418	0.14	0.02
7	0.2341	0.2170	0.14	0.02	2.950	0.0760	0.14	0.02	1.1	0.0888	0.14	0.02
12	0.1	0.0540	0.14	0.02	2.014	0.1170	0.14	0.02	0.1	0.0699	0.14	0.02
Model 4 (User-defined dynamic model considering transient SC current)												
2	2.289	0.148	4.328	0.734	0.101	0.053	9.773	0.361	2.0015	0.154	0.14	0.133
7	1.524	0.130	4.132	0.546	0.424	0.117	0.242	0.031	1.481	0.109	0.14	0.141
12	1.693	0.114	7.977	0.042	0.126	0.068	10.000	0.969	0.1	0.116	0.14	0.061

It is seen from Table 6, that all the relays variables are within limits as in section 3.2.

Table 7 shows the operating times of a set of primary/backup relays in IEEE14 bus system and the CTI between them.

Table 7 Relays operating time of 14 bus system

Relay Number		Optimization technique used								
		GSASQP			PSOGSA			Fmincon		
Primary	Backup	Primary t_{op} (s)	Backup t_{ob} (s)	CTI (s)	Primary t_{op} (s)	Backup t_{ob} (s)	CTI (s)	Primary t_{op} (s)	Backup t_{ob} (s)	CTI (s)
Model 1 (Conventional steady-state model considering SS fault current)										
1	4	0.529	0.830	0.301	2.089	2.289	0.200	0.335	1.467	1.132
6	13	0.742	0.942	0.200	1.142	2.343	1.201	0.340	2.051	1.711
12	1	0.706	0.906	0.200	1.920	2.267	0.347	0.379	0.956	0.577
7	10	0.621	1.292	0.671	1.666	2.327	0.661	0.396	1.436	1.040
All relays sum (s)		29.263			59.794			33.558		
Model 2 (User-defined steady-state model considering SS fault current)										
1	4	0.389	0.673	0.284	2.102	2.301	0.200	0.203	1.267	1.064
6	13	0.690	0.890	0.200	1.902	2.319	0.417	0.240	1.992	1.752
12	1	0.421	0.621	0.200	0.470	0.670	0.200	0.495	1.364	0.868
7	10	0.401	0.665	0.264	0.683	0.960	0.277	0.500	0.918	0.418
All relays sum (s)		24.2415			53.671			28.527		
Model 3 (Conventional dynamic model considering transient SC current)										
1	4	0.4719	0.6 719	0.2000	1.3160	1.5160	0.2000	Fmincon doesn't solve for any transient coordination model		
6	13	0.7319	0.9334	0.2015	0.9534	1.6348	0.7319			
12	1	0.8232	1.3122	0.4889	0.3433	1.1365	0.7933			
7	10	0.5756	1.5619	0.9864	1.7776	1.9777	0.2001			
All relays sum (s)		27.2710			56.4223					
Model 4 (User-defined dynamic model considering transient SC current)										
1	4	0.3347	0.5347	0.2	0.2170	0.4170	0.2000	Fmincon doesn't solve for any transient coordination model		
6	13	0.2975	0.6543	0.3568	2.2052	2.4651	0.2599			
12	1	0.3907	0.5922	0.2015	1.0695	2.2214	1.1519			
7	10	0.3098	0.5098	0.2000	0.6488	0.9747	0.3259			
All relays sum (s)		19.0388			32.9643					

From the above results of IEEE 14 bus system it can be concluded that, the proposed method (user-defined dynamic model considering transient SC current) leads to the best solution using any method of the hybrid meta-heuristic techniques (GSASQP and PSOGSA), while GSASQP leads to the best solution at all. However, fmincon solution method doesn't approach to any feasible solution in any transient based optimization case.

The IEEE 14 bus Relays settings samples obtained from the three proposed techniques in the different models are as shown in Table 8.

Table 8 IEEE 14 bus system optimal relays settings

Relay NO.	Optimization technique used											
	GSASQP				PSOGSA				Fmincon			
	TMS (PU)	I_p (PU)	A	B	TMS (PU)	I_p (PU)	α	β	TMS (PU)	I_p (PU)	α	β
Model 1 (Conventional steady-state model considering SS fault current)												
4	1.047	0.577	0.14	0.02	3.000	0.523	0.14	0.02	1.100	0.159	0.14	0.02
10	0.100	0.082	0.14	0.02	0.180	0.082	0.14	0.02	0.305	0.084	0.14	0.02
14	0.100	0.268	0.14	0.02	1.917	0.052	0.14	0.02	0.406	0.140	0.14	0.02
16	0.100	0.078	0.14	0.02	0.127	0.041	0.14	0.02	0.131	0.064	0.14	0.02
Model 2 (User-defined steady-state model considering SS fault current)												
4	0.867	0.181	5.434	0.460	2.885	0.335	9.686	0.021	0.777	0.122	0.183	0.606
10	0.100	0.093	1.014	1.000	0.100	0.292	0.140	1.000	1.384	0.089	0.284	0.787
14	1.014	0.222	4.766	0.749	2.995	0.103	0.366	0.619	1.042	0.058	0.683	0.458
16	1.065	0.123	6.670	0.642	1.306	0.105	9.940	0.853	1.527	0.062	0.409	0.574
Model 3 (Conventional dynamic model considering transient SC current)												
4	1.0724	0.3218	0.14	0.02	2.999	0.1361	0.14	0.02	Fmincon doesn't solve for any transient coordination model			
10	1.1391	0.2134	0.14	0.02	1.169	0.1252	0.14	0.02				
14	0.3778	0.1697	0.14	0.02	0.468	0.2681	0.14	0.02				
16	1.6948	0.2287	0.14	0.02	2.999	0.1778	0.14	0.02				
Model 4 (User-defined dynamic model considering transient SC current)												
4	1.422	0.376	5.465	0.426	0.129	0.370	0.179	0.999	Fmincon doesn't solve for any transient coordination model			
10	1.016	0.213	3.122	0.775	0.100	0.082	9.960	0.999				
14	1.769	0.176	3.741	0.406	0.280	0.105	9.637	0.999				
16	1.417	0.127	6.445	0.237	2.298	0.145	3.722	0.027				

It is seen from Table 8, that all the relays variables are within limits as in section 3.2.

The work presented in this manuscript can be concluded as in Table 9.

Table 9 Comparison of the presented solutions

Tech. Used	Test system											
	IEEE 3 bus system models				IEEE 9 bus system models				IEEE 14 bus system models			
	Model1	Model2	Model3	Model4	Model1	Model2	Model3	Model4	Model1	Model2	Model3	Model4
Fmincon	√	√	√	√	√	X^1	√	√	X^2	X^2	√	√
GSASQP	√	√	√	√	√	√	√	√	√	√	√	√
PSOGSA	√	√	√	√	√	√	√	√	√	√	√	√

√: give a feasible solution and satisfy all constraints.
X^1: Two miscoordination states.
X^2: No feasible solution.

6. Conclusion

From the above results it can be concluded that, for the 3 bus system, the hybrid meta-heuristic techniques give very good solution for relays coordination problem when considering the transient SC fault. However, for such small systems, like 3 bus system, the best solution at all is given by the mathematical method (fmincon) optimization technique in model 2 case (user-defined steady-state model). So that for such small systems, considering the transient fault current during coordination is quite efficient but is not the best. Moreover, for such small systems like 3 bus system, all the proposed three techniques solve the optimization problem for the four study.

For slightly larger system like 9 bus system, the hybrid meta-heuristic techniques like (GSASQP and PSOGSA) give much better solution than the mathematical method (fmincon) for all study cases; and GSASQP gives the best solution in the four study models. Moreover, the best results at all is obtained while using the proposed method (user-defined dynamic model considering transient) with the hybrid meta-heuristic technique (GSASQP). So that, for slightly larger systems; considering the transient fault current during coordination is most efficient. Furthermore, considering the proposed transient method i.e. model 4 is also quite efficient even with fmincon solver itself as it can overcome the miscoordination states obtained by using the same solver in model 3 (conventional dynamic model).

For 14 bus system, the hybrid meta-heuristic techniques (GSASQP and PSOGSA) are only the methods which can solve the coordination problem in the presence of transient fault current as the mathematical method (fmincon) optimization technique can't solve the problem in any case of transient based coordination methods. Moreover, the best results at all are obtained while using the proposed transient (user-defined dynamic model) method with the hybrid meta-heuristic technique (GSASQP).

From the above it can be concluded that, other than very small distribution networks like 3 bus network; considering the transient fault current during relays coordination problem is the most efficient and this requires the usage of a hybrid meta-heuristic technique to obtain the best relays operating times at all. The work presented in this manuscript is concluded as shown in Table 9.

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