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A Novel Transient Search Optimization for Optimal Directional Over Current Relay Coordination for Multi-technology Microgrid Protection

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Abstract— The directional overcurrent relays (DOCR) are a critical protection component in microgrids. Incorporating distributed generation into the microgrid can result in a breach of relay coordination within the distribution system. Variations in the magnitudes and directions of short-circuit currents can lead to erroneous tripping or failure to trip of DOCR in the system. As a consequence, the existing protection system may operate inaccurately. Hence, the failure of coordination between the primary and backup relays has a detrimental effect on the protection system. The current plug setting (CPS) and time dial setting (TDS) are key factors in determining the configuration of DOCR. Achieving proper coordination of these relays is a widely acknowledged challenging task due to the highly constrained nonlinear optimization problem it presents. Furthermore, the intricacy of this non-linearity increases as the network size grows. This paper introduces for the very first time a Transient Search optimization (TSO) based relay coordination for the protection of microgrids. Therefore, this research paper proposed a novel approach to optimize the coordination of DOCR in microgrids by employing the TSO algorithm with a modified objective function. The proposed objective function improves the relay coordination in the grid-connected and islanded mode of operation. The performance of the proposed method is assessed through testing on a multi-technology DG-connected 7-bus microgrid network. To demonstrate its effectiveness, it is compared to other popular metaheuristic optimization techniques. Moreover, the proposed algorithm successfully minimizes the total operating time while ensuring compliance with all constraints. The study validates that the proposed algorithm offers an efficient solution for the DOCR coordination problem, which holds significant benefits for microgrid protection.

Keywords- Transient search optimization, Relay coordination, directional over current relay, protection.

I. INTRODUCTION

The rising global demand for energy has spurred the widespread utilization of Distributed Generation (DG) with renewable energy sources at consumer premises. As a result, traditional electrical distribution networks are transitioning toward modern distribution networks. Microgrids present numerous advantages, such as increased flexibility, cost-effectiveness, fuel efficiency, and enhanced reliability compared to conventional distribution systems. The protection of the microgrid stands as one of the primary technical concerns during its operation. In the microgrid protection system, the DOCR carries out a fundamental role. Its precise operation is essential to ensure the network's selectivity, sensitivity, and overall reliability. The fault level in microgrids is influenced by the specific types of DG technologies integrated into the system. In microgrid, fault occurrences result in the bidirectional flow of fault currents [1,2]. Consequently, the overcurrent loses their ability to function effectively, leading to a lack of coordination among them. To address these challenges, DOCRs are introduced into the network. The goal is to minimize network outages by establishing an efficient coordination mechanism between the relays, limiting the affected area to a minimum. Specifically, the primary protection schemes must operate swiftly and effectively during their operation. However, in the event of primary relay failure, the backup relay needs to act after a predetermined time known as the coordination time interval (CTI) [3,4]. Proper coordination between primary and backup relays in DOCRs hinges on optimizing and updating two critical parameters, i.e., current plug setting (CPS) and time dial setting (TDS). These settings play a vital role in ensuring the efficient functioning of the protection scheme. The challenge of relay coordination has been formulated as a highly non-linear optimization problem, which can be addressed through conventional and heuristic methods. Numerous researchers in the field of protection system research have embraced the utilization of heuristic algorithms to tackle relay coordination issues. The conventional method involves trial and error, curve fitting technique, and graph theory. Initially, the trial-and-error approach was used to determine relay settings. However, for large network protection, this method exhibits slow convergence rates and may not yield sufficient relay settings [5-8]. A wide array of techniques for coordinating DOCRs has been documented in the available literature. The research described in [9-11] employed the graph theory approach in distribution network analysis to identify the breakpoint relays (BPS) for achieving relay coordination. Efficient BPS selection is crucial for achieving rapid convergence of the relay coordination problem. Linear programming methods were deemed a commendable optimization technique mainly suitable for optimizing the TDS value. This suitability arises from the fact that the operating time of the DOCRs exhibits a linear relationship with the TDS [12,13]. Traditional optimization techniques like linear programming [14-16], gradient-based methods [17], binary integer-based programming [18], and sequential quadratic programming [19] suffer from several limitations. These include being prone to get trapped in local minima, inability to provide an optimal global solution, and reduced convergence performance as the system size grows. Over the past few years, there has been a proliferation of population-based metaheuristic techniques aimed at addressing constrained-based optimization problems. Several other optimization techniques have also gained prominence in recent years, such as Biogeography-based optimization (BBO) [20], artificial bee colony [21], teaching–learning-based optimization (TLBO) [22], seeker optimization algorithm (SOA) [23], gravitational search algorithm (GSA) [24], and hybrid GSA-PSO [25]. In the realm of relay coordination problems, some of the latest metaheuristic techniques include Levy flight-based CSA [26], SOS [27], a comparative analysis of LINGO and metaheuristic algorithms [28], Aggrandized Class Topper Algorithm [29], and African Vultures Optimization [30]. The optimization approaches mentioned above have their disadvantages, including premature and sluggish convergence, limited accuracy, and vulnerability to being trapped in local minima. Moreover, these methods often rely on carefully calibrated weighting parameters for their designated functions. The primary motivation behind this proposed work is to develop an advanced and efficient method to address the relay coordination problem in microgrids. This paper introduces a novel TSO algorithm for the first time in the context of optimized relay coordination in microgrids. The primary contribution of this research lies in identifying the optimal TDS and CPS for proposed microgrid networks while maintaining the CTI. To enhance relay protection coordination and achieve improved CTI, an objective function is introduced. This function aims to minimize miscoordinations and improve the sensitivity between primary and backup relay pairs. The effectiveness of the TSO algorithm for the proposed objective function is evaluated through its application in grid-connected and islanded mode of 7 bus microgrid. The optimal results obtained from the TSO algorithm are compared and evaluated with different popular algorithms such as PSO, GSA, and hybrid PSOGSA to determine the most suitable algorithm for the intended task.

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II. PROBLEM FORMULATION

The primary objective of the coordination problem for DOCRs is to minimize the total weighted sum of operating times (OTs) of the primary relays, expressed as follows

$$\min_{TDS,CPS} BOF = \textstyle\sum_{i=1}^{n} \sum T_{ij}$$

(1)

The given expression represents the coordination problem, where '*n*' denotes the number of relays, '*Tij*' corresponds to the operating time of relay R_i at location *k*. The basic objective functions (BOF) (eq. 1) used in relay coordination problems have a limitation in effectively handling the intricate and dynamic characteristics of microgrids. The unique operating conditions and constantly changing system configurations of microgrids make it challenging for BOF to provide optimal and adaptable coordination solutions. This can lead to issues such as miscoordination and insensitivity to changing conditions. Consequently, BOF may not fully capture the specific requirements and complexities of microgrids, potentially resulting in suboptimal relay coordination and reliability concerns. In response to these limitations, this research paper proposed a new objective function for microgrid protection coordination that improves relay coordination and maintains the CTI constraints. The proposed objective function is given as:

$$\begin{aligned} \min\left(CPS_i, TDS_i, MOF\right) &= a_1 \sum_{i}^{n} \sum_{j} T_{ij}^2 \\ &+ a_2 \sum_{p=1}^{mp} \left[\Delta T_{mbp} \right. \\ &\left. - \beta\left(\Delta T_{mbp} - \left|\Delta T_{mbp}\right|\right)\right]^2 \end{aligned} \qquad (2)$$

$$\Delta t_{mbp} = t_{kj} - t_{ij} - CTI$$

(3)

A. *Relay setting constraints*

Minimizing the objective function described in eq. (2) involves adhering to certain predefined constraints. Initially, these constraints pertain to the configuration of the relay and involve establishing both upper and lower boundaries for TDS, and CPS, as detailed in eq. (4) and (5), respectively.

$$TDS_i^{min} \leq TDS_i \leq TDS_i^{max} \qquad i = 1,..,m \tag{4}$$

$$CPS_i^{min} \leq CPS_i \leq CPS_i^{max} \qquad i = 1,..,m \tag{5}$$

where TDS_i^{min} , TDS_i^{max} and CPS_i^{min} , CPS_i^{max} are the minimum and maximum limits of time dial setting and current plug setting respectively. Proper coordination is ensured by requiring the operating time of the backup relay to be greater than the operating time of the primary relay by the predefined CTI as described in eq. (6). The parameter CTI_{min} is typically assigned as 0.3 seconds, representing the minimum coordination time interval.

B. *Coordination constraints*

The coordination constraints guarantee that both the primary and backup relays operate in a coordinated manner, preventing any unnecessary or uncoordinated relay tripping. Proper coordination is ensured by requiring the operating time of the backup relay to be greater than the operating time of the primary relay by the predefined CTI as described in eq. (6). The parameter CTI_{min} is typically assigned as 0.3 seconds, representing the minimum coordination time interval.

$$T_{kj} - T_{ij} \geq CTI_{min} \qquad i = 1,..,m \tag{6}$$

The operating time of each relay is determined by

$$T_{ij}{}^{min} \leq T_{ij} \leq T_{ij}{}^{max} \qquad i = 1,..,m \tag{7}$$

Where $T_{ij}{}^{min}$ and $T_{ij}{}^{max}$ presents the minimum and maximum operating time of relay *i* for fault at *j*.

III. PROPOSED TSO APPROACH FOR DOCR COORDINATION

The behavior of electrical circuits, which includes elements such as resistors (R) and energy storage components like capacitors (C), inductors (L), or a combination of both (LC), encompasses both a transient response and a steady-state response (final response), as depicted in eq. (8). The solution for *x(t)* can be determined by solving the given differential equation, as depicted in Eq. (9). On the other hand, circuits incorporating two energy storage elements (RLC) are known as second-order circuits. Eq. (10) represents the differential equation used to compute the transient response of the first-order circuit [31].

$$\frac{d}{dt}x(t) + \frac{x(t)}{\tau} = K \tag{8}$$

$$x(t) = x(\infty) + (x(0) - x(\infty))e^{-t/\tau} \tag{9}$$

The transient response of the second-order circuit can be calculated using the differential equation presented in Eq. (10).

$$\frac{d^2}{dt^2}x(t) = 2\alpha\frac{d}{dt}x(t) + w_0^2x(t) = f(t) \tag{10}$$

In this context, "*t*" signifies time, and "*x(t)*" can denote either the capacitor voltage "*v(t)*" in the RC circuit or the inductor current "*i(t)*" in the RL circuit. The time constant of the circuit, represented as "τ," assumes the value of "RC" in the RC circuit and "L/R" in the RL circuit. The constant "K" is contingent upon the initial value of "*x(0)*," while "*x(∞)*" signifies the ultimate response value. This algorithm draws inspiration from the transient responses of switched electric circuits that involve storage components such as inductance and capacitance. The TSO algorithm's ability to explore and exploit was evaluated by optimizing various mathematical benchmark functions. It has been applied to many engineering design optimization problems, and the results demonstrate its effectiveness and correlation with other novel optimization algorithms [31]. The TSO algorithm is structured into three main steps:

1. Initialization of search agents within the lower and upper bounds of the search area.
2. Searching for the best solution through exploration.
3. Reaching a steady state or the best solution through exploitation.

During the first step, the search agents are randomly generated according to eq. (11).

$$Y = lb + rand \times (ub - lb) \tag{11}$$

Here, "*lb*" and "*ub*" represent the lower and upper bounds of the search region, respectively. The term "rand" indicates a consistently distributed random number. rand is a random number distributed uniformly, Next, the exploration behavior of the TSO algorithm takes inspiration from the oscillations observed in second-order RLC circuits around the zero state. However, the exploitation aspect of the TSO algorithm is inspired by the exponential decay observed in the first-order discharge process. The TSO algorithm utilizes a random number, denoted as r1, to achieve a balance between exploration (r1 ⩾ 0.5) and exploitation (r1 < 0.5). This balancing process is mathematically represented in eq. (12), drawing inspiration from Eq. (9) and eq. (10). The TSO algorithm's optimal solution (*Yl**) emulates the steady-state or final value *x(∞)* of an electrical circuit. Additionally, the equation B1 = B2 = |*Yl-C1. Yl**| is employed as part of the mathematical modeling for exploitation and exploration in the algorithm. In the TSO algorithm, the exploration phase is geared towards uncovering the best possible solution, while the exploitation phase is centered on attaining either a stable-state or the optimal solution. The TSO algorithm enhances its exploratory process by leveraging oscillations inherent in second-order circuits centered around the null point. Consequently, during the exploitation phase of TSO, it harnesses the exponential decay observed in electrical circuits during the first-order discharge of storage components. The computational model encapsulating the interplay between exploitation and exploration within the TSO algorithm is mathematically expressed in equation (12), drawing inspiration from the combined response (comprising transient and steady-state) of first and second-order electrical networks, as illustrated in equation (13) [31].

$$X_{J+1} = \begin{cases} X_j^* + (X_J - C_1 \times X_j^*)e^{-T} & \mathrm{r}_1 < 0.5 \\ X_j^* + e^{-T}[cos(2\pi T) + sin(2\pi T)]\left|X_j - C_1 \times X_j^*\right|, & \mathrm{r}_1 \geq 0.5 \end{cases} \quad \dots (12)$$

$$C_1 = k \times z \times r_3 + 1 \quad (13)$$

$$z = 2 - 2(J/J_{max}) \quad (14)$$

The variable "z" represents a changing parameter that ranges from 2 to 0, as indicated in eq. (14). The constant "k" takes values from 0, 1, 2, and so on. Additionally, "J_{max}" represents the total number of iterations in the given context. The initialization process is represented using *O(N)*, where *N* denotes the number of search agents.

Following this, the search agents commence a while loop with a predefined maximum iteration limit, denoted as "Jmax." The computational complexity for all search agents' function evaluations is characterized as $O(N*J_{max})$. Furthermore, the complexity associated with updating all search agents, considering a dimension *(D)* and total iterations (J_{max}), is represented as $O(N \times J_{max} \times D)$. Consequently, the overall computational complexity of the TSO algorithm is succinctly expressed as $O\ (N \times (J_{max}\ D + J_{max} + 1))$. The tuning parameter relevant to this problem is provided in Table I.

TABLE I. TUNING PARAMETER OF TSO

Parameter	**Value**
No. of search agents(N)	30
No. of maximum iteration (J_{max})	100
No. of independent run	30

IV. RESULT & DISCUSSION

The efficacy and appropriateness of a microgrid suggested protection coordination strategy have been examined using a 7-bus test system, as shown in Fig 1. This test configuration represents the low-voltage (LV) portion of the IEEE 14-bus system, encompassing eight lines. To ensure comprehensive safeguarding of this configuration, a total of sixteen DOCRs are essential, involving the installation of two relays on each line. The coordination settings for protection have been derived for two distinct scenarios which are outlined as follows:

(1) Grid-connected mode

(2) Islanded mode

Figure 1 illustrates the 7-bus microgrid, which is energized by a Synchronous based Generator (SBDG) linked to bus 1, along with two inverter-interfaced Distributed Generators (IIDG) connected to buses 2 and 7. Furthermore, in its grid-connected configuration, this system is designed to receive power through two specific buses (bus 3 and bus 6). The original system details can be found in [32]. In Figure 1, all 16 DOCRs necessary for the protection of this system are depicted, corresponding to each line in the network. Within this setup, there exists a total of 22 primary and backup relay pairs among these totals of 16 relays. Details about the various primary and backup relay pairs and the fault current traversing through them are outlined in Table II. It is important to highlight that a three-phase fault was applied at the midpoint of each line to compute the diverse fault currents listed in Table II.

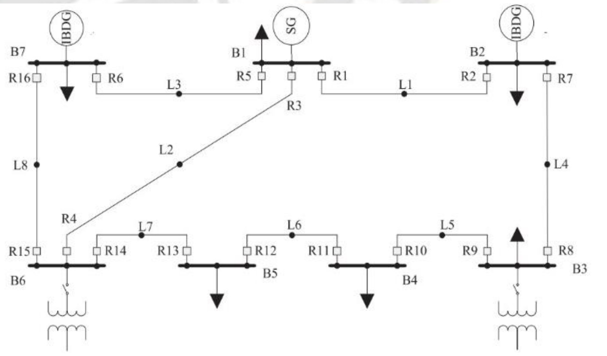

Figure 1. Single line diagram of 7 bus distribution system with DOCRs

A. *Grid Connected mode:*

The optimal settings of TDS & CPS were determined using a newly developed optimization technique, i.e., Transient Search Optimization (TSO), and depicted in Table III.

Additionally, Table IV displays the operational timings of primary relays using PSO, GSA, PSOGSA, and TSO. The total operating times for DOCRs with PSO, GSA, PSOGSA, and TSO is determined as 15.6 sec, 13.5 sec, 12.8 sec, and 10.2 sec, respectively. Notably, it led to a remarkable reduction of up to 35% in PSO, 24 % in GSA, and 12.8 % in hybrid PSOGSA with the overall relay operating time compared to TSO. The comparative statistical analysis of operating time is shown in Fig. 3. Furthermore, these findings reveal that, among all the optimization techniques in grid-connected mode, the operating time using TSO for different fault locations and fault current is consistently lower than all others. Comparing with alternative methods, Fig. 3 displays the operating time of primary relays in grid-connected mode achieved by the proposed TSO approach in the context of the 7-bus system. Notably, the TSO algorithm outperforms other established techniques, offering not only improved results but also a more favorable net gain in terms of operating time.

Similarly, employing the value of modified objective function, it is lower in all cases. The convergence behavior of the TSO algorithm during simulation is depicted in Fig. 2. The minimum value of MOF obtained in PSO, GSA, PSOGSA and TSO is given as 39.15, 32.65, 28.79 and 13.82 respectively. When comparing convergence characteristics, the value of MOF with TSO, the net reduction of 65% with PSO, 58 % with GSA and 52 % with PSOGSA is achieved. It's evident that the TSO consistently converges to a significantly optimized value when compared to other algorithms. The proposed TSO technique exhibits a notably swift convergence rate, attaining its optimal value under 15 % of maximum iterations. At the same time, the other method requires more iterations to reach the minimal value of the objective function evidently given in Fig. 2.

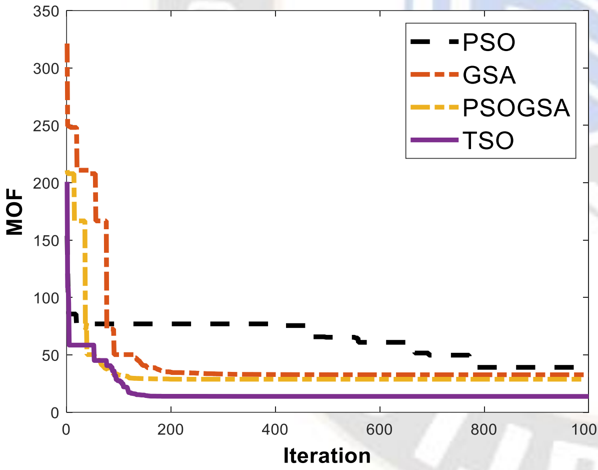

Figure 2 Convergence Curve for grid connected mode

The evident superiority of the TSO algorithm in terms of overall net time gain, when compared to alternate methods, underscores its effectiveness and superior results. Additionally, Fig. 4 presents the Critical Time Interval (CTI) for all 22 pairs of primary and backup relays. The graph in Fig.4 highlights that the CTI between relay pairs consistently remains above 0.3 seconds in TSO. While in other methods, there are some miscoordinations. It's important to note that the optimal relay configurations were established under peak load conditions. Consequently, these configurations ensure effective coordination among all relays. The optimal results successfully adhere to all relevant constraints formulated in the relay coordination problem in grid connected mode.

B. Islanded mode

Table V provides the optimal configurations achieved for the given microgrid system in its islanded mode. The associated response times of primary relays are shown in Table VI. The corresponding CTI for each pair is visually depicted in Figure 6. Upon analyzing the data in Table VI for the islanded operation of the 7-bus test microgrid, it's evident that the total operating time for all 16 primary relays using TSO is 12.21sec.

TABLE II. VARIOUS FAULT CURRENTS AND PRIMARY-BACKUP RELAY PAIRS

Fault Point	**Relay Pair no.**	**Primary Relay**	**Grid Connected Mode I_{fault_prim} (kA)**	**Islanded mode I_{fault_prim} (kA)**	**Back up Relay**	**Grid Connected Mode I_{fault_back} (kA)**	**Islanded mode I_{fault_back} (kA)**
F1	1	1	4.83	3.61	4	1.91	0.38
	2	1	4.83	3.61	6	0.81	0.56
	3	2	3.43	2.3	8	2.06	0.72
F2	4	3	5.73	4.84	2	1.64	0.96
	5	3	5.73	4.84	6	0.69	0.33
	6	4	6.43	2.14	13	1.58	0.95
	7	4	6.43	2.14	16	0.54	1.05

F3	8	5	5.5	3.96	2	1.30	0.92
	9	5	5.5	3.96	4	1.6	0.32
	10	6	3.35	2.34	15	1.98	0.83
F4	11	7	3.51	3.08	1	1.98	1.46
	12	8	5.37	1.96	10	1.17	1.40
F5	13	9	8.01	2.67	7	1.94	2.08
	14	10	2.79	2.07	12	2.60	1.88
F6	15	11	4.77	2.19	9	4.64	2.0
	16	12	3.59	2.47	14	3.54	2.41
F7	17	13	2.92	1.54	11	2.87	1.48
	18	14	6.62	3.86	3	2.20	2.54
	19	14	6.62	3.86	16	0.96	1.17
F8	20	15	5.67	3.04	3	1.21	2.09
	21	15	5.67	3.04	13	1.24	0.86
	22	16	3.11	2.60	5	1.82	1.23

TABLE III. OPTIMUM SETTING OF TDS & CPS FOR THE RELAYS IN GRID-CONNECTED MODE

Relay No.	**TDS (s)**	**PSO**	**GSA**	**PSO-GSA**	**TSO**	**CPS (A)**	**PSO**	**GSA**	**PSO-GSA**	**TSO**
1	TDS1	0.500	0.427	0.447	0.297	CPS1	0.289	0.427	0.693	1
2	TDS2	0.623	0.396	0.880	0.318	CPS2	0.238	0.666	0.231	0.867
3	TDS3	0.433	0.336	0.750	0.296	CPS3	0.408	0.588	0.129	1
4	TDS4	0.396	0.447	0.952	0.304	CPS4	0.464	0.314	0.292	1
5	TDS5	0.362	0.478	0.651	0.304	CPS5	0.575	0.321	0.795	0.869
6	TDS6	0.394	0.334	0.566	0.304	CPS6	0.413	0.556	0.137	0.847
7	TDS7	0.360	0.393	0.333	0.363	CPS7	0.503	0.413	0.725	0.865
8	TDS8	0.392	0.501	0.700	0.337	CPS8	0.75	0.28	0.629	0.856
9	TDS9	0.460	0.469	0.384	0.367	CPS9	0.607	0.568	0.383	0.864
10	TDS10	0.520	0.503	0.233	0.303	CPS10	0.202	0.205	0.928	1
11	TDS11	0.477	0.438	0.949	0.375	CPS11	0.571	0.73	0.662	1
12	TDS12	0.532	0.385	0.497	0.304	CPS12	0.215	0.464	0.321	0.845
13	TDS13	0.387	0.394	0.978	0.314	CPS13	0.691	0.703	0.83	0.868
14	TDS14	0.585	0.532	0.450	0.304	CPS14	0.277	0.303	0.377	1
15	TDS15	0.340	0.413	0.214	0.314	CPS15	0.635	0.324	0.841	0.856
16	TDS16	0.310	0.406	0.833	0.304	CPS16	0.641	0.352	0.408	0.858

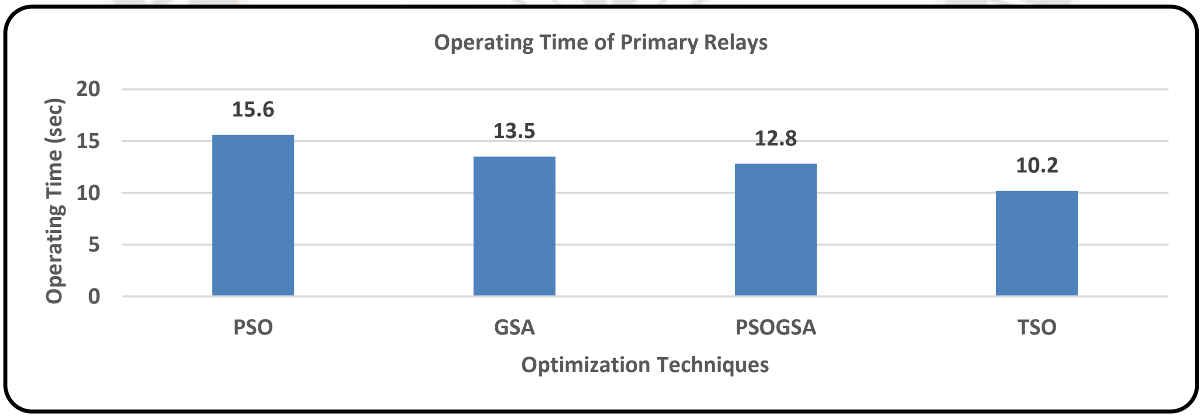

Figure. 3 Statistical analyses of various algorithms in grid connected mode

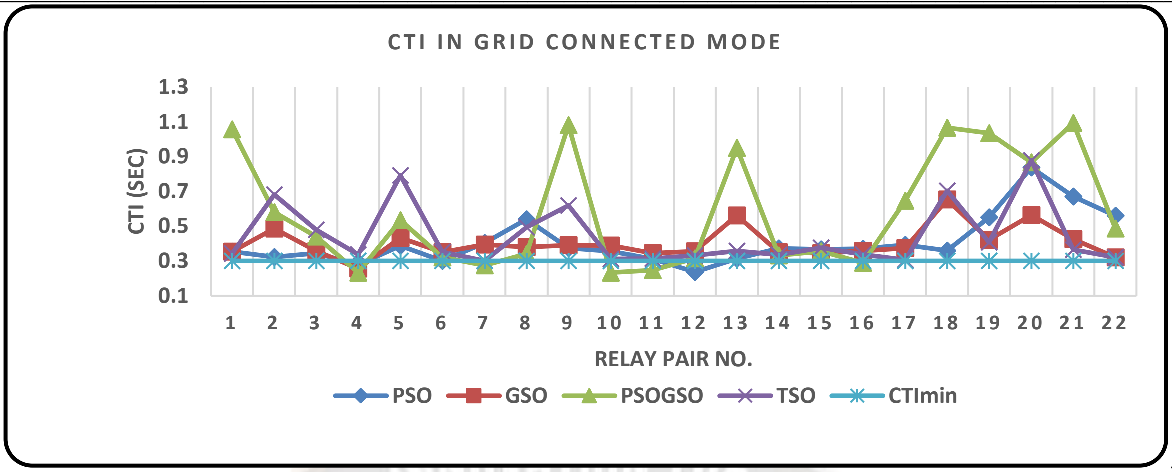

Figure 4. CTI in Grid connected mode

TABLE IV. RELAY OPERATING TIME IN GRID CONNECTED MODE

Relay No.	PSO	GSA	PSOGSA	TSO
1	0.957	0.864	1.121	0.715
2	1.077	0.826	0.572	0.654
3	1.024	0.821	0.906	0.596
4	0.887	0.764	1.377	0.685
5	1.004	0.807	0.851	0.57
6	0.687	0.662	0.689	0.433
7	1.136	0.943	1.442	0.663
8	0.93	0.822	0.494	0.412
9	1.208	0.95	0.742	0.899
10	0.855	0.838	0.523	0.767
11	1.165	0.897	1.131	0.851
12	1.039	0.958	0.141	0.539
13	0.954	0.819	1.097	0.735
14	1.125	0.998	0.379	0.665
15	0.643	0.693	0.474	0.484
16	0.96	0.829	0.862	0.533
OT_P	15.6 sec	13.5 sec	12.8 sec	10.2 sec
Net operating time gain(sec)	5.4 sec	3.3 sec	2.6 sec	--

The net gain in operating time compared to PSO, GSA and PSOGSA is 7.84 sec, 4.79 sec, and 4.34 sec respectively. Moreover, an observation from Table V underscores that the optimal settings aligned with the relays yield the most favorable outcome, resulting in the shortest cumulative operating time across all 16 DOCRs in the islanded mode. The minimum MOF values obtained through PSO, GSA, PSOGSA, and TSO are 45.77, 40.36, 33.55, and 17.37. Regarding convergence profile, TSO achieves the most remarkable performance, with a substantial reduction of 62% compared to the value obtained from PSO, 57 % reduction against GSA and 48 % reduction obtained from PSOGSA.

Clearly, the TSO method consistently converges to an exceptionally optimized value, surpassing the convergence performance of other algorithms. The proposed TSO technique demonstrates an impressive swift convergence rate, reaching its optimal value within just 10% of the maximum iterations. In contrast, the alternative method necessitates more iterations to attain the minimum value of the objective function also in islanded mode, as clearly demonstrated in Figure 5.

Subsequently, Figure 6 illustrates that the CTI consistently surpasses the minimum value. PSO, GSA and PSOGSA exhibits instances of two miscoordination occurrences, whereas TSO stands out by not having any instances of miscoordination. In summary, the findings strongly suggest that the relay operating time and MOF value is consistently lower in proposed TSO when compared to alternative methods in islanded mode. Table VI provides a statistical representation of the primary DOCRs operating times achieved through PSO, GSA, PSOGSA and TSO in the islanded operating mode.

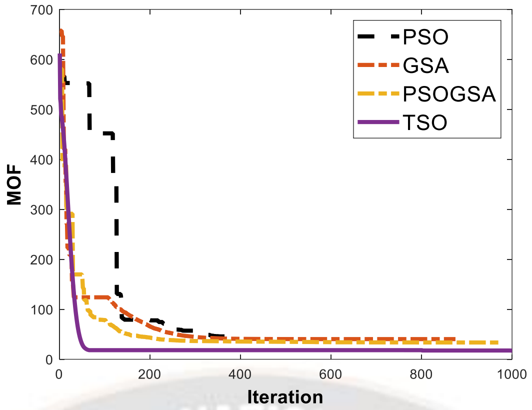

Figure. 5 Convergence characteristics in islanded mode

TABLE V. OPTIMUM SETTING OF TDS & CPS FOR THE RELAYS IN ISLANDED MODE

Relay No	TDS (s)	PSO	GSA	PSO-GSA	TSO	CPS (A)	PSO	GSA	PSO-GSA	TSO
1	TDS1	0.550	0.665	0.559	0.322	CPS1	0.372	0.336	0.251	0.826
2	TDS2	0.606	0.495	0.281	0.359	CPS2	0.321	0.675	0.969	0.810
3	TDS3	0.506	0.805	0.432	0.369	CPS3	0.473	0.183	0.326	0.767
4	TDS4	0.201	0.571	0.108	0.305	CPS4	0.385	0.100	0.551	0.536
5	TDS5	0.493	0.476	0.512	0.367	CPS5	0.369	0.613	0.251	0.962
6	TDS6	0.495	0.778	0.242	0.406	CPS6	0.305	0.145	0.815	0.756
7	TDS7	0.462	0.511	0.688	0.306	CPS7	0.593	0.659	0.104	0.962
8	TDS8	0.446	0.306	0.127	0.402	CPS8	0.291	0.550	1.000	0.271
9	TDS9	0.524	0.529	0.573	0.361	CPS9	0.329	0.559	0.100	0.644
10	TDS10	0.516	0.495	0.265	0.361	CPS10	0.389	0.434	0.571	0.712
11	TDS11	0.625	0.522	0.505	0.381	CPS11	0.193	0.663	0.106	0.820
12	TDS12	0.415	0.816	0.230	0.361	CPS12	0.531	0.100	0.736	0.669
13	TDS13	0.473	0.558	0.184	0.368	CPS13	0.247	0.405	0.969	0.755
14	TDS14	0.485	0.654	0.244	0.400	CPS14	0.490	0.296	0.905	0.655
15	TDS15	0.330	0.492	0.170	0.369	CPS15	0.418	0.377	0.716	0.759
16	TDS16	0.441	0.560	0.640	0.360	CPS16	0.556	0.406	0.100	0.875

TABLE VI. RELAY OPERATING TIME IN ISLANDED MODE

Relay No.	PSO	GSA	PSOGSA	TSO
1	1.367	1.169	0.921	1.054
2	1.186	1.143	0.921	0.774
3	1.433	1.214	1.071	0.912
4	0.965	0.521	0.907	0.324
5	1.075	0.947	0.98	0.883
6	1.187	0.916	1.008	0.617
7	1.564	1.348	1.132	1.132
8	0.866	0.993	0.874	0.48
9	1.602	1.278	1.167	0.969
10	1.124	1.129	0.986	0.663
11	1.356	1.09	1.079	0.759
12	1.408	1.274	1.237	0.829
13	1.192	0.87	0.985	0.547
14	1.44	1.285	1.196	0.852
15	1.032	0.715	0.996	0.449
16	1.269	1.121	1.105	0.974
OT_P	20.066 sec	17.013 sec	16.565 sec	12.218 sec
Net operating time gain (sec)	7.84 sec	4.79 sec	4.34 sec	-

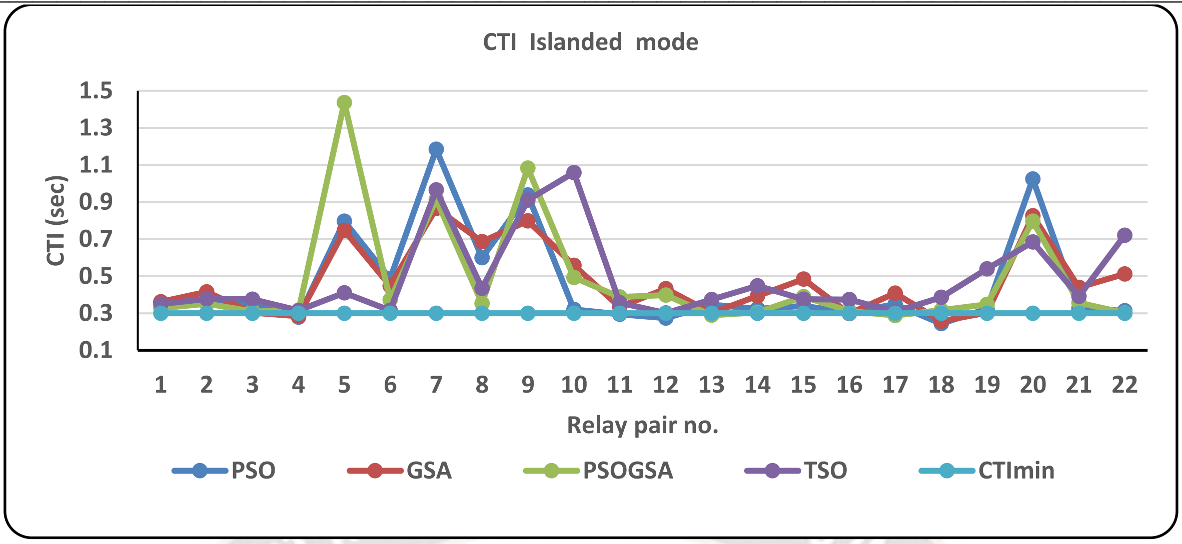

Fig 6. CTI in islanded mode

CONCLUSION

This research paper introduces a new physical-based meta-heuristic optimization algorithm method called Transient Search Optimization to tackle the challenge of coordinating DOCRs in microgrid operation. The efficacy of the TSO is validated through the distribution part of the IEEE-14 bus system i.e., 7-bus microgrid in grid-connected and islanded mode. The statistical analysis and convergence profile of various optimization algorithms, including the proposed TSO are depicted in various figures and tables in the result and discussion section. The TSO metaheuristic algorithm exhibits superior performance compared to popular existing methods such as PSO, GSA, and hybrid PSOGSA in terms of relay operating time. Furthermore, the TSO displays quicker convergence with fewer iterations and lower computational demands than its counterparts. This highlights its potential to effectively address intricate optimization challenges within microgrid protection. Based on these findings, it asserts that the TSO holds promise as an optimization technique for DOCR coordination in microgrid operating modes. The versatility of the TSO extends to various domains within the microgrid realm, offering efficient solutions with reduced computational burden. Future research can refine and expand the TSO's capabilities to address other intricate optimization problems within microgrids.

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