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Fractional Order Darwinian PSO with Constraint Threshold for Load Flow Optimization of Energy Transmission System

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Abstract

This paper present an effective optimization algorithm for Optimal Power Flow (OPF) in electrical power systems. Fractional Order Darwinian Particle Swarm Optimization (FODPSO) algorithm is modified with constraint threshold limitation mechanism to acheive OPF. Results of the proposed method are compared on a part of 13 bus-bar 154 kV Eastern Anatolia Transmission System and on a 14 bus-bar IEEE test system. In addition, the transmission system is modeled by DigSilent software to analyse without taking any risk that may occur in real systems. Thus, optimal parameter settings can be recommended for real time transmission system.

1. INTRODUCTION

Energy is still a prominent agenda of all countries with today's increasing population and fast developing industry. Power losses are gradually increasing due to reasons such as the increasing demand for energy over the world, the increase of malfunctions due to overloaded power system equipment, failure to optimize load flow due to variable supply/demand, lack of the necessary engineering works in power system equipment and adequate maintenance [1]. Due to such problems, the tendency towards alternative and new energy sources has increased. In addition, it is essential to do revisions in current energy systems to operate efficiently and ensure energy continuity. In these revisions, the most serious one is to rearrange the system to make good load flow analysis. In electrical energy systems, OPF is a serious issue for power system engineers. OPF ensures that the power system is stable by choosing the optimum parameters for total energy cost, active power losses, and voltage limit values in bus-bars.

Solution of the OPF problem includes the minimization of the active power loss under constraint of the electrical power systems [2]. Several optimization techniques have been using for OPF in the literature [3]. Some of them can be summarized as; Aderyani and Karami used artificial bee colony algorithm for OPF [4]. Bouchekara studied on using black-hole-based optimization approach [5]. Some others have used different meta-heuristic optimization algorithms for the solution of different electrical power system problems [6-9].

One of the most promising meta-heuristic optimization algorithms, PSO, is suitable for further improvement. Thus, many optimization techniques based on PSO were reported so far. FODPSO algorithm is the most recent one that is used for several engineering solutions [10-12]. FODPSO, benefits from evolutionary concept of Darwinian and distinct features of fractional calculus that is mostly used in engineering area in the last decades. This paper proposes to combine FODPSO algorithm with constraint

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threshold mechanism that is vital in high power electrical systems. So, the proposed algorithm provides better results.

In this paper, power flow optimization has been studied using the modified FODPSO and VPSO algorithms for a part of east Anatolian 154 kV energy transmission system. The results are used to reduce power loses by conducting reactive power compensation. In addition, the result of optimization is used in the virtual model of the power system, obtained by DigSilent software, to simulate the real time system. In the virtual model, load flow analyses were carried on for two scenarios and results are discussed. Then the proposed optimization algorithms were utilized on standard 14 bus-bars IEEE test system to show the effectiveness of the proposed algorithm over the existing ones in the literature and results were discussed. Further sections of the paper are organized as follows;

Section 2 provides the model of the part of East Anatolian 154 kV transmission system and 14 bus-bars IEEE test system. Section 3 and 4 introduces FODPSO algorithm with constraint threshold mechanism and VPSO algorithm respectively. In Section 5, formulation of optimal power flow is given and the constraints for the objective function are described. Section 6 gives a case study and finally section 7 provides some concluding remarks.

2. MODEL OF ELECTRICAL OF SYSTEM

This section presents models of a real time system and a test system that is widely used for power transmission analysis.

2.1. A part of East Anatolian 154 kV Transmission System

Single line scheme of a part of east Anatolian 154 kV energy transmission system is shown in Figure 1. Real time data of the transmission system is listed in Table 1. Generation/consumption data of the bus-bars are obtained from the average values of Table 1, as shown in Table 2. One can see from Figure 1 that the bus-bars, 1, 3, 6, 10, 11, 13 are connected to power generation centers. System is modeled with the assumption that all bus-bars include power consumptions.

2.2. IEEE 14 Bus-bars Test System

In order to show the effectiveness of the proposed FODPSO approach, standard 14 bus-bars IEEE test system is used [13]. In the test system, the limits of the voltage is assumed in between 0.95 – 1.05 pu and the voltage angle limits are in between -45 ° and + 45° as in Fig 2.

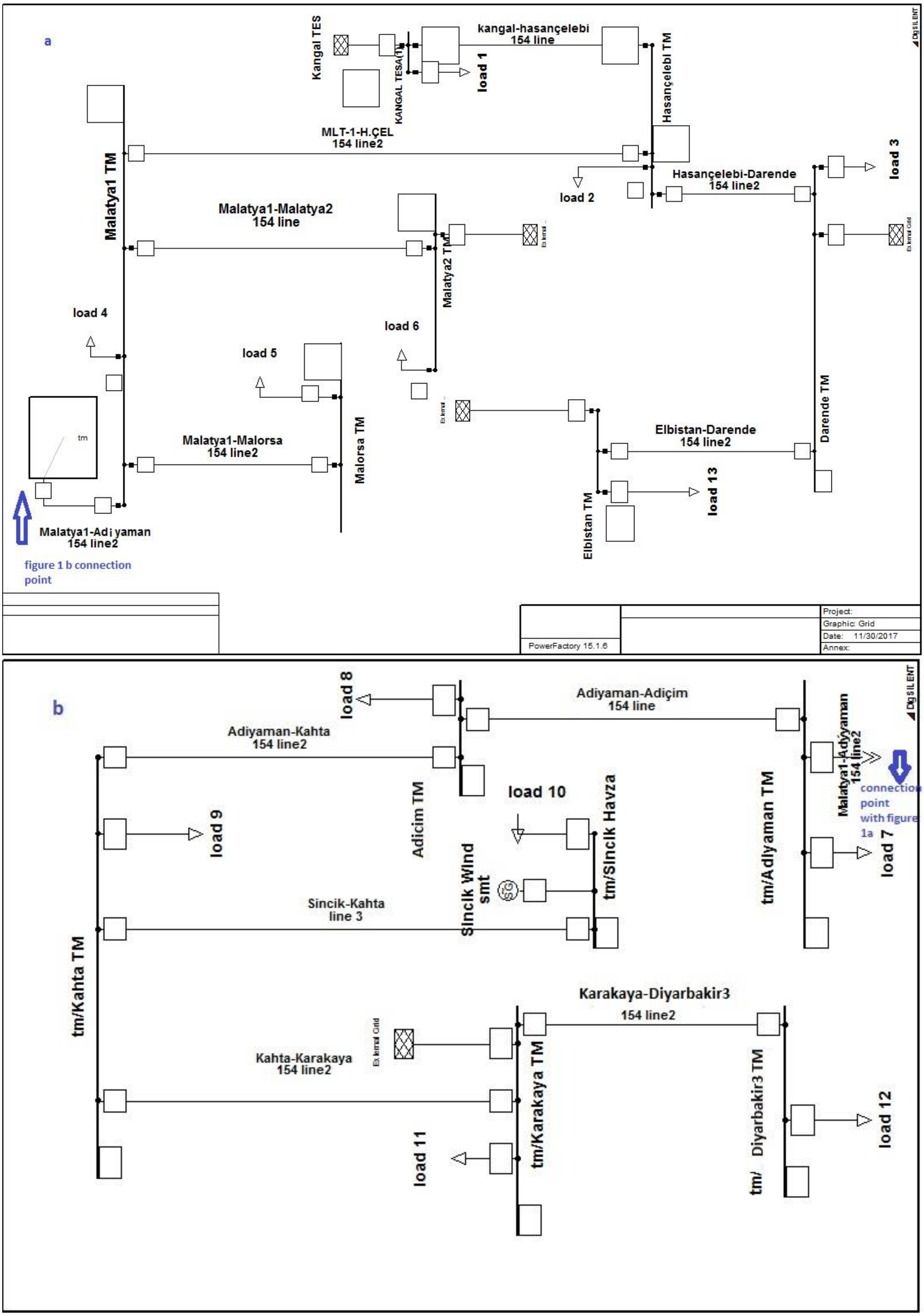

Figure 1. *Single line scheme of power system*

Table 1. *Data for 154 kV single line scheme of power system*

		Load		Generator		Generator	
Bus No	Bus Code	P	Q	P(min)	P(max)	Q(min)	Q(max)
1	1	14 MW	4 MVAR	-	-	-	-
2	0	10 MW	3 MVAR	0 MW	0 MW	0 MVAR	0 MVAR
3	2	15 MW	3 MVAR	0 MW	17 MW	-4 MVAR	4 MVAR
4	0	40MW	4 MVAR	0 MW	0 MW	0 MVAR	0 MVAR
5	0	44 MW	4 MVAR	0 MW	0 MW	0 MVAR	0 MVAR
6	2	38 MW	2 MVAR	0 MW	40 MW	-20 MVAR	20 MVAR
7	0	40 MW	7 MVAR	0 MW	0 MW	0 MVAR	0 MVAR
8	0	5 MW	0.5 MVAR	0 MW	0 MW	0 MVAR	0 MVAR
9	0	30 MW	4 MVAR	0 MW	0 MW	0 MVAR	0 MVAR
10	2	10 MW	2 MVAR	0 MW	30 MW	-10 MVAR	20 MVAR
11	2	30 MW	6 MVAR	100 MW	140 MW	-50 MVAR	18 MVAR
12	0	70 MW	5 MVAR	0 MW	0 MW	0 MVAR	0 MVAR
13	2	15 MW	5 MVAR	65 MW	200 MW	20 MVAR	40 MVAR

** Bus code 1= slack buses, 2= generation buses, 0= load buses*

Table 2. *Data for 154 kV transmission system*

nl	nr	R pu	X pu	½ B pu	Tap
1	2	0.0292 pu	0.0871 pu	0.01730 pu	1
2	3	0.0356 pu	0.1142 pu	0.01955 pu	1
2	4	0.0493 pu	0.1583 pu	0.02710 pu	1
3	13	0.0308 pu	0.0921 pu	0.01825 pu	1
4	5	0.0121 pu	0.0389 pu	0.00667 pu	1
4	6	0.0102 pu	0.0312 pu	0.00593 pu	1
4	7	0.0422 pu	0.1354 pu	0.06579 pu	1
7	8	0.0088 pu	0.0255 pu	0.00485 pu	1
7	9	0.0179 pu	0.0477 pu	0.00985 pu	1
9	10	0.0050 pu	0.0423 pu	0.01400 pu	1
9	11	0.0445 pu	0.1427 pu	0.02440 pu	1
11	12	0.0538 pu	0.1727 pu	0.0296 pu	1

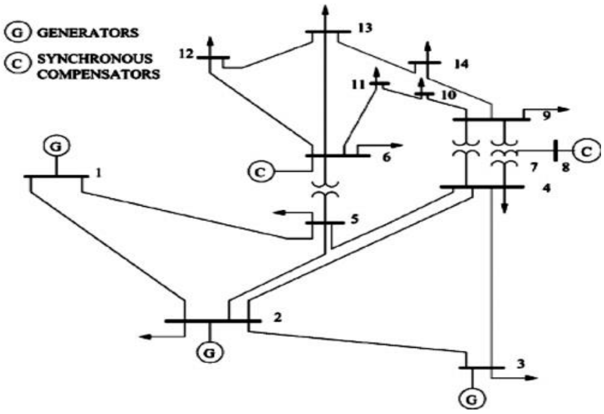

Figure 2. *Single line scheme of 14 bus-bars IEEE test system [13]*

3. FODPSO ALGORITHM WITH CONSTRAINT THRESHOLD MECHANISM

Particle Swarm Optimization (PSO), well-known algorithm for decades [14], has been utilized in many engineering area. PSO basically benefits from the concept of swarm intelligence. It forms a system in which non-native, interacting agents of complex characteristics form coherent, global and functional patterns of common behavior [15]. In traditional PSO, candidate solutions are called particles. These particles get the best solution by circulating the search field and interacting with neighboring particles. In the PSO algorithm the best global solution, obtained in the whole swarm, is updated in each iteration. All of the particles use this information to recognize the position of the particle and try to approximate it. In order to model the particle, each particle in t^{th} iteration, moves in a multidimensional space according to the position ($\boldsymbol{x_n^s}$) and velocity ($\boldsymbol{v_n^s}$). These values vary depending on $\boldsymbol{x_{1_n}^s}$, known as local best, and $\boldsymbol{x_{2_n}^s}$, known as global best. This dependence is expressed as,

$$v_n^s[t+1] = wv_n^s[t] + \sum_{i=0}^{2} p_i r_i \left(x_{i_n}^s[t] - x_n^s[t]\right) \tag{1}$$

$$x_n[t+1] = x_n[t] + \ v_n[t+1] \tag{2}$$

Where, w is weight of inertia, p is the local best and r is the global best.

Darwinian PSO (DPSO), presented by Tillett et al. in [16], is an evolutionary algorithm that expands the PSO by natural selection or by surviving those with high fitness values in order to increase its ability to escape from the local optimum. Although the DPSO performs better than the PSO, the computational complexity appears as a disadvantage. Pires et al. combines the advantages of fractional order computation concept with DPSO to improve convergence ability of DPSO algorithm and they propose Fractional Order DPSO (FODPSO) in [17].

Nowadays, Fractional Order Calculus (FOC) is widely used in many engineering problems due to long memory and heredity effect [18]. Riemann-Liouville, Caputo and Grünwald-Letnikov integro-differential equations are the most famous expressions used for the application of fractional order concept in many engineering solutions. The Grünwald-Letnikov fractional order differential equation, can be expressed as [19],

$$D^{\alpha}[x(t)] = \lim_{h\to 0}\left[\frac{1}{h^{\alpha}}\sum_{k=0}^{\infty}\frac{(-1)^k \Gamma(\alpha+1)x(t-kh)}{\Gamma(k+1)\Gamma(\alpha-k+1)}\right] \tag{3}$$

Where, α is the order of fractional derivative, h is sampling interval and $\Gamma(.)$ defines Euler's Gamma function. FODPSO seeks a solution to the problem of early convergence of swarms in traditional PSO. Similar to the DPSO, the FODPSO algorithm also wipes out swarms from the solution pool, which is optimal before time. It also creates new swarm groups from particles with the best solution to provide an environment in which information is inherently shared. Couceiro and Ghamisi [18] compared FODPSO with conventional PSO and DPSO and clearly demonstrated its superiority in many respect. The main feature that distinguishes FODPSO from the DPSO algorithm is that the velocity is determined by fractional order computation. When the weight of inertia is assumed as $w = 1$ for speed computation in Eq. (1), the following equation can be obtained,

$$v_n^s[t+1] = v_n^s[t] + \sum_{i=0}^{2} p_i r_i \left(x_{i_n}^s[t] - x_n^s[t]\right) \tag{4}$$

The Eq. (4) can be reorganized as,

$$v_n^s[t+1] - v_n^s[t] = \sum_{i=0}^{2} p_i r_i \left(x_{i_n}^s[t] - x_n^s[t]\right) \tag{5}$$

One can easily see that the expression $v_n[t+1] - v_n[t]$ defines a derivative in discrete form. If one define the order of fractional derivative in Eq. 3 as $\alpha = 1$, following equation can be obtained.

$$D^{\alpha}[v_n^s[t+1]] = \sum_{i=0}^{2} p_i r_i \left(x_{i_n}^s[t] - x_n^s[t]\right) \tag{6}$$

Based on the concept of the fractional derivative, the derivation of the velocity specified in the DPSO can be generalized to a real number between 0 and 1. Thus, a smoother variation and longer memory effect can be obtained. Therefore, when using the fractional approach in Eq. (3), the Eq. (6) can be rewritten as,

$$v_n^s[t+1] = -\sum_{k=0}^{\infty} \frac{(-1)^k \Gamma(\alpha+1) v_n^s[t+1-kT]}{\Gamma(k+1)\Gamma(\alpha-k+1)} + \sum_{i=0}^{2} p_i r_i \left(x_{i_n}^s[t] - x_n^s[t]\right) \tag{7}$$

As seen, DPSO is a special form of FODPSO for α = 1 (no memory).

This paper aims to achieve better solution for the load flow analysis under strict constraints of the electrical power system. Because, constraints in high power electrical energy systems are very seriously affecting the system performance, hazards and malfunctions. In order to eliminate negative effects of exceeding limits in constraints, this paper combines the FODPSO algorithm with constraint threshold mechanism and proposes FODPSO with Constraint Threshold (FODPSO-CT) algorithm. FODPSO-CT algorithm eliminates particles that do not satisfy fitness function within the specified threshold of the constraints. This constraint threshold mechanism increases the reliability of the solutions. The algorithm assumes the objective function, constraint functions and minimum-maximum values as variables. Random swarm and swarm groups are created in between the minimum and maximum values for each variable in the objective and constraint functions. Constraints need to be tested to ensure the reliability of the result obtained for an objective function with constraints. To ensure confidence testing, the constraint function value of each particle in the swarm groups, created in between the minimum and maximum values for each variable, is measured. If the value is not in the desired range, the particle is removed from the group. The fitness value for each particle remaining in the group is calculated. If the group has the best local solution, the best solution is updated. If the group has not reached to the best solution, the group is penalized and removed from the solution pool. This process results in producing a group and particle with the best value. Pseudo code and flow chart of FODPSO-CT algorithm is provided in Figure 3 and Figure 4 respectively. The constraint threshold mechanism is given in green color in both pseudo code and in flowchart.

4. VECTOR PSO ALGORITHM

VPSO algorithm is a modified form of PSO, in which each swarm adjusts its own position according to the other swarm groups. It is assumed that swarms ($S_{1,}$ $S_{2,\ldots,}S_M$) intend to optimize fitness functions at the same time. Velocity and the position functions of VPSO algorithms can be defined respectively as following [20],

$$V_{\dot{\imath}}^{[j]}(t+1) = k^{[j]} * \left[w_i^{[j]} * V_i^{[j]}(t) + c_p^{[j]} * r_1 * \left\{P_{\dot{\imath}}^{[j]} - S_i^{[j]}(t)\right\} + c_g^{[j]} * r_2 + \left\{P_{gb}^{[k]} - S_i^{[j]}(t)\right\}\right] \tag{8}$$

$$S_i^{[j]}(t+1) = S_i^{[j]}(t) + V_i^{[j]}(t+1) \tag{9}$$

Where, $S_i^j(t)$ is current position, $V_i^j(t)$ is velocity, $P_i^j(t)$ is the first best position, $P_{gb}(t)$ is the global best, c_p is cognitive learning coefficient, c_g is social learning coefficient, r_1 and r_2 are random numbers in between (0-1) [20]. This paper uses VPSO algorithm to verify and compare the result of proposed FODPSO-CT algorithm.

```
Initialize List[S]  (Swarm Groups).  (Set default values =>$v_n^s[1], x_n^s[1], X_1^s[1], X_2^s[1]$ )
Loop (Main Program)
For each S in List [S]
Initialize swarms in S (Go to Initialize Swarms)
Calculate group (Go to Calculate Swarm Group Function )
Spawn new groups from the group
Kill 'failed' groups
End
Until iteration
Function (Calculate Swarm Group)
For each particle n in S
Calculate and sum the constraints of n
If sum of the constraints value doesn't get better
Kill 'failed' swarm
End
For each particle n in S
Calculate the fitness of n
Find out the best distribution of fitness
        Update $X_1^s[t], X_2^s[t]$
        Update $v_n^s[t+1]$ with fractional calculate
        Update $x_n^s[t+1]$
If group S gets better
Reward group by extending its life and spawning new groups
         Else
Punish group by reduce its life and possibly killing particle
End
Return
Function (Initialize Swarm)
For 1 to N    (N = Population )
For 1 to N_PAR  (N_PAR = Swarm count)
Swarms [i] = rand(1,1) * ( $X_{MAX} - X_{MIN}$ ) + $X_{MIN}$
End
End
Return Swarms
```

Figure 3. *Pseudocode of FODPSO-CT algorithm*

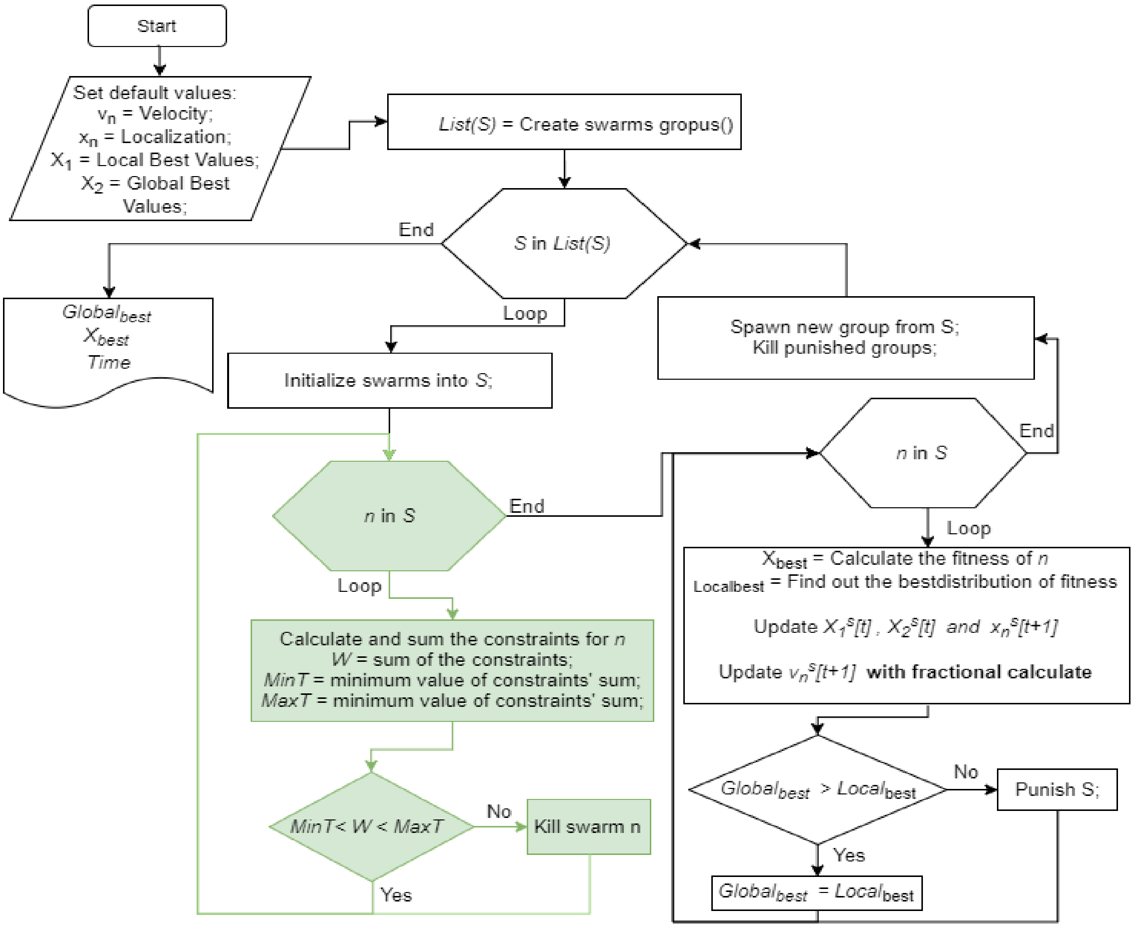

Figure 4. *Flowchart of FODPSO-CT algorithm*

5. FORMULATION OF OPTIMAL POWER FLOW

Load flow analysis gives information about amplitude, phase angle, active and reactive power of bus-bars in a power system. Thus, stability, loading, power loss, supply/demand balance of the power system can be analyzed. Therefore, OPF in the power system is critical. One can generalize OPF problem under the constraints of the power system as following [21],

$$Minimize\ p\ (x,u) \tag{10}$$

$$Subject\ to\ r(x,u)=0 \tag{11}$$

$$and\ s(x,u)\leq 0 \tag{12}$$

Where, $p\ (x,u)$ is the cost function of OPF, $r\ (x,u)$ is equality constraints, $s\ (x,u)$ is inequality constraints, u is control variable and x is state variable. The control and state variable can be defined as in Eqs. 13 and 14, respectively.

$$u_T=[P_{Gy}\ldots P_{GNG}\ ,V_{G1}\ldots V_{GNG}\ ,Q_{C1}\ldots Q_{CNC}] \tag{13}$$

Where, P_G is active power generation in production bus-bars, V_G is voltage of the bus-bars in the power system, Q_C is shunt capacitors in the power system, N_G and N_C represents number of generators and Volt Ampere Reactive (VAR) compensators, respectively.

$$x_T=[P_{Gx},V_{L1}\cdots V_{LNL},Q_{G1}\cdots Q_{QNG}] \tag{14}$$

Where, N_L is loading bus-bars. The objective function to be minimized in this study is as given in Eqs. 15 and 16. These equations express the minimization of active power loses. In the study, the minimization of the active power loss is repeated by adding capacitor banks and the two cases are compared [21].

$$p = f_i \tag{15}$$

$$fi = \sum_{k=1}^{Ni}[g_k\left(V_i^2 + V_j^2 - 2V_i.V_j.cos\big(\theta_{(i,j)}\big)\right)] \tag{16}$$

Where, N_i is number of lines, g_k is conductivity of line k, V_i and V_j is the amplitude of voltages of the bus-bars i and j, respectively located at the end of line k. $\theta_{(i,j)}$ is voltage angle between bus-bars i and j. The problem is to minimize Eq. 16 satisfying the equality constraints in Eqs. 17, 18 and, inequality constraints in Eqs. 19-22 [4, 6, 21].

The equality constraints $r\ (x,u)$ can be defined as following,

$$P_{G,i} - P_{load,i} - V_i\sum_{j=1}^{Nb}[V_j\big(g_{h(i,j)}.cos\big(\theta_{(i,j)}\big) + b_{h(i,j)}.sin\big(\theta_{(i,j)}\big)\big)] = 0 \tag{17}$$

$$Q_{G,i} + Q_{ci} - Q_{load,i} - V_i\sum_{j=1}^{Nb}[V_j\big(g_{h(i,j)}.sin\big(\theta_{(i,j)}\big) - b_{h(i,j)}.cos\big(\theta_{(i,j)}\big)\big)] = 0 \tag{18}$$

The inequality constraints $s(x,u)$ can be defined as following,

$$V_i^{min} \le V_i \le V_i^{max} \quad i = 1,2,\dots N_b \tag{19}$$

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \quad i = 1,2,\dots N_g \tag{20}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \quad i = 1,2,\dots N_g \tag{21}$$

$$Q_{ci}^{min} \le Q_{ci} \le Q_{ci}^{\mathrm{max.}} \quad i = 1,2,\dots N_C \tag{22}$$

Where, N_g is the number of voltage controlled bus-bars, N_C is the number of shunt capacitors, N_b is the number of bus-bars, P_{Gi} is the active power in the *i*th bus-bar, Q_{Gi} is the reactive power in the *i*th bus-bars, f_i is the total active power loss, $P_{load,i}$ is the active power at the bus-bar *i*, $Q_{load,i}$ is the reactive power at the bus-bars *i*, Q_{ci} is the shunt capacitor value to be added to bus-bar *i*, where loads are located, V_i is the voltage of bus-bars *i*, V_j is the voltage of bus-bars *j*, $g_{h(i,j)}$ is the conductance value between *i* and *j* bus-bars, $b_{h(i,j)}$ is the admittance value between *i* and *j* bus-bars, $\theta_{(i,j)}$ is the phase difference between *i* and *j* bus-bars.

6. CASE STUDY

In this study, two cases have been studied to demonstrate the effectiveness of the FODPSO-CT algorithm for OPF. In the first case, a section of the 13 bus-bars east Anatolian transmission system is studied, while 14 bus-bars IEEE test system is used for reliability testing in the second case. In order to see the effectiveness of the proposed OPF solution, the result of two cases are used in the virtual model and simulated. Both of FODPSO-CT and VPSO algorithms are used for case studies. Simulation results are discussed and commentated for application on a real time power system.

6.1. Case 1: Load Flow Analysis of 154 kV East Anatolia Transmission System

For this case, the proposed FODPSO-CT and VPSO algorithms are used for OPF in a part of 154 kV east Anatolia transmission systems given in Figure 1. In the figure, the bus-bars 3, 6, 10, 11, 13 are generation bus-bars, while bus-bars 1 is slack bus-bars. Other bus-bars are used as consumption bus-bars. Voltages in all bus-bars are limited in between 0.95 pu and 1.05 pu. The aim of the optimization algorithms is to achieve OPF by minimizing power loses. The active and reactive power values of the generation bus-bars are obtained using FODPSO-CT and VPSO algorithms in a power system. Reactive Power Compensation (RPC) can further reduce active power losses. Values of active power lose before and after RPC are listed in Tables 3. The virtual model represents the real power system, given in Figure 1, as a whole. Thus, Results of optimization for OPF can be correctly simulated on the virtual model. Values in Tables 1 and 2 are used in the virtual model, obtained by DigSilent software, to simulate real time behavior of the power system and results are given in Table 3. Bus-bar added capacitor bank values are as shown in Table 4. As seen from Table 3, the active power loss of the real time system is 30.92 MW. As one can see from Tables 3 that active power loss before RPC is found as 23.33 MW for the proposed FODPSO-CT, while 24.39 MW for VPSO algorithm. In VPSO, an improvement was observed from active power losses of 30.92 MW (real time) to 24.39 MW. In FODPSO-CT, an improvement from 30.92 MW to 23.33 MW was observed. The FODPSO-CT algorithm provides a further improvement of 1.06 MW according to VPSO. Then, RPC was performed by adding capacitor banks to bus-bars to increase voltage stability. In this case, the value of the power loss after RPC is 28.55 MW in virtual model of the real system. The power loss was decreased from 28.55 MW to 21.87 MW for FODPSO-CT algorithm while 22.93 MW was observed for VPSO algorithm. In this case FODPSO-CT algorithm also performs better results. As seen from Table 3, voltage values of the bus-bars are in between the desired voltage limits for FODPSO-CT algorithm. Thus, the voltage stability of the power system is ensured by OPF.

Table 3. Optimization results for OPF values of 154kV power system before and after RPC

OPF values before RPC				OPF values after RPC		
	FODPSO-CT	DigSilent	VPSO	FODPSO-CT	DigSilent	VPSO
P_{1Ge}	16,862 MW	7.6 MW	14.98 MW	10.722 MW	5.2 MW	14.989 MW
P_{3Ge}	17 MW	17 MW	17 MW	17 MW	17 MW	17 MW
P_{6Ge}	40 MW	40 MW	39.99 MW	40 MW	40 MW	40 MW
P_{10Ge}	30 MW	30 MW	30 MW	30 MW	30 MW	30 MW
P_{11Ge}	117.39 MW	117.39 MW	135.33 MW	122 MW	117.4 MW	140 MW
P_{13Ge}	163.068 MW	179.93 MW	148.08 MW	162.95 MW	179.9 MW	141.96 MW
Q_{1Ge}	3.7657 MVAR	54 MVAR	14.74 MVAR	0 MVAR	21.1 MVAR	14.268 MVAR
Q_{3Ge}	19.379 MVAR	19.37 MVAR	4 MVAR	3.57 MVAR	19.4 MVAR	1.762 MVAR
Q_{6Ge}	4.3407 MVAR	4.340 MVAR	9.09 MVAR	6.6 MVAR	4.3 MVAR	8.45 MVAR
Q_{10Ge}	17.267 MVAR	17.26 MVAR	12.75 MVAR	10.69 MVAR	17.3 MVAR	12.6487 MVAR
Q_{11Ge}	12.578 MVAR	12.57 MVAR	7.37 MVAR	-37.13 MVAR	12.6 MVAR	7.214 MVAR
Q_{13Ge}	3.7657 MVAR	3.765 MVAR	-1.36 MVAR	13 MVAR	3.8 MVAR	-10.35 MVAR
V_1	0.98909 pu	1 pu	1 pu	1.0393 pu	1pu	1 pu
V_2	0.99073 pu	0.98 pu	0.9833 pu	1.016 pu	0.99pu	0.9837 pu
V_3	0.95363 pu	1.02 pu	0.98 pu	1.0118 pu	1.03 pu	0.99 pu
V_4	0.9823 pu	0.9 pu	0.98 pu	1.0061 pu	0.96 pu	0.98 pu
V_5	1.0294 pu	0.89 pu	0.973 pu	1.006 pu	0.95 pu	0.973 pu
V_6	0.99504 pu	0.9 pu	0.99 pu	1.0008 pu	0.96 pu	0.99 pu
V_7	1.0055 pu	0.89 pu	0.9839 pu	0.98962 pu	0.96 pu	0.983 pu
V_8	0.99744 pu	0.89 pu	0.9834 pu	1.0037 pu	0.97 pu	0.983 pu
V_9	0.99294 pu	0.89 pu	0.9926 pu	1.0083 pu	0.98 pu	0.992 pu
V_{10}	0.9935 pu	0.91 pu	1 pu	1.0473 pu	0.99 pu	1 pu
V_{11}	0.99001 pu	0.89 pu	1 pu	0.97635 pu	0.99 pu	1 pu
V_{12}	1.0144 pu	0.84 pu	0.948 pu	0.98705 pu	0.95 pu	0.946 pu
V_{13}	0.95449 pu	1.056 pu	1.01 pu	0.98903 pu	1.06 pu	1.01 pu
P_{demand}	361 MW	361 MW	361 MW	361 MW	361 MW	361 MW
$P_{total\ loss}$	23.33 MW	30.92 MW	24.39 MW	21.87 MW	28.55 MW	22.93 MW

**Ge= Generator*

Table 4. *Bus-bars added capacitor bank values*

Bus-bars added capacitor bank values			
Bus-bars no	INJ FODPSO-CT	INJ Digsilent	INJ VPSO
1			
2	-3.7 MVAR	0 MVAR	-1 MVAR
3			
4	6.36 MVAR	0 MVAR	0.2 MVAR
5	6.85 MVAR	-7.1 MVAR	-0.5 MVAR
6			
7	8.74 MVAR	-3.7 MVAR	-1 MVAR
8	7.7 MVAR	-6.4 MVAR	-0.05 MVAR
9	3.75 MVAR	-1.6 MVAR	1 MVAR
10			
11			
12	7.74 MVAR	-4 MVAR	-1 MVAR
13			

Table 4 shows the values of the capacitors to be added to the load bus-bars (2, 4, 5, 7, 8, 9, 12). Reactive power consumption, which can be regulated by adding capacitor banks, is essential for efficiency of load flow in the transmission system. In this study, active power losses in the power system have been reduced by adding capacitor banks.

Figure 5 demonstrates the decrease of cost function of the proposed FODPSO-CT and VPSO algorithms for OPF. Figure 5 shows that the FODPSO-CT algorithm reaches to the optimal solution nearly at 70th iteration. Figure 6 shows the results of FODPSO-CT and VPSO algorithms for 20 trials. Standard deviation of 20 trials for FODPSO-CT, which is 1.43, reveals that the algorithm produces consistent results. However FODPSO-CT algorithm presents better results than VPSO algorithm for the decrease of cost function and average total power loss values in 20 trial in the Figs. 5 and 6.

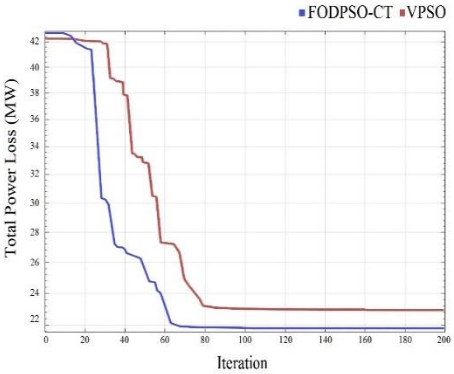

Figure 5*. Cost function of FODPSO-CT and VPSO*

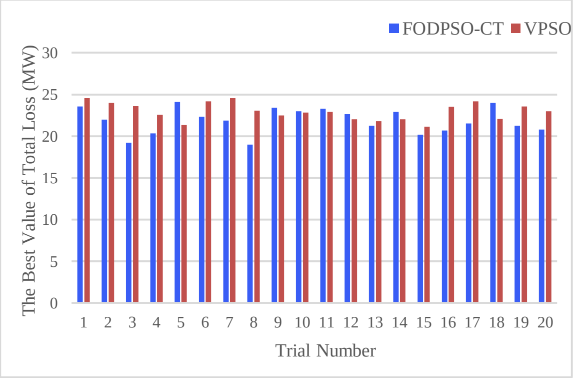

Figure 6. *20 trials of FODPSO-CT and VPSO*

6.2. Case2: Load Flow Analysis of 14 Bus-Bars IEEE Test System

In this case study, the effectiveness of the proposed FODPSO-CT algorithm is demonstrated by comparing with the algorithms in the literature, using standard 14 bus-bars IEEE Test System. All values of the test system coincide with the literature [22]. Table 5 gives the results of commonly used optimization algorithms and the proposed FODPSO-CT algorithm. As seen, the FODPSO-CT algorithm achieves 2.96 MW power loss that is the best result in Table 5. The FODPSO-CT algorithm also keeps the voltage profiles within the specified thresholds that result in minimizing active and reactive power loses. More stable power distribution will be provided in the power system when the losses are minimized.

Table 5. *Result of OPF for 14-Bus-bars IEEE Test System*

	FODPSO-CT	VPSO	PSO[22]	MPSO[22]	ABC[22]	FSS[22]	GSA[22]
V_1	1.06 pu	1.06 pu	1.06 pu	1.06 pu	1.06 pu	1.06 pu	1.06 pu
V_2	1.045 pu	1.045 pu	1.045 pu	1.044 pu	1.044 pu	1.044 pu	1.04 pu
V_3	1.01 pu	1.01 pu	1.01 pu	1.011 pu	1.011 pu	1.011 pu	1.01 pu
V_4	1.0129 pu	1.0035 pu	0.979 pu	0.956 pu	0.996 pu	0.977 pu	0.926 pu
V_5	1.0282 pu	1.0066 pu	0.9653 pu	1.004 pu	0.971 pu	0.932 pu	0.98 pu
V_6	1.07 pu	1.025 pu	1.07 pu	1.072 pu	1.07 pu	1.07 pu	1.07 pu
V_7	0.99007 pu	1.017 pu	0.969 pu	0.982 pu	0.99 pu	0.95 pu	0.974 pu
V_8	1.09 pu	1.017 pu	1.09 pu	1.09 pu	1.09 pu	1.09 pu	1.09 pu
V_9	1.0365 pu	1.0136 pu	0.953 pu	0.912 pu	0.941 pu	0.976 pu	1.007 pu
V_{10}	1.0248 pu	1.0079 pu	0.952 pu	0.941 pu	0.925 pu	0.969 pu	1.001 pu
V_{11}	1.0047 pu	1.0128 pu	0.952 pu	0.954 pu	1.003 pu	0.93 pu	1.004 pu
V_{12}	1.0222 pu	1.0097 pu	0.981 pu	0.94 pu	0.917 pu	0.938 pu	0.973 pu
V_{13}	1.03 pu	1.005 pu	0.919 pu	0.933 pu	0.912 pu	0.937 pu	0.964 pu
V_{14}	0.99405 pu	0.991 pu	0.96 pu	0.945 pu	0.985 pu	0.995 pu	1.006 pu
$P_{totalloss}$	2.96 MW	6.25 MW	9.91 MW	8.5 MW	6.46 MW	7.84 MW	3.27 MW

7. RESULTS and CONCLUSIONS

In power systems, threshold values of the voltage and power is vitally important. In this study, the FODPSO-CT algorithm is proposed by modifying the FODPSO algorithm for the optimal solution of the engineering problems, such as the power system, where the threshold values are vital. The paper demonstrates that the FODPSO-CT algorithm gives satisfactory results for the system that is highly dependent to strictly specified constraints. This algorithm has been successfully applied to the OPF study. Then the proposed algorithm is compared with VPSO and some other algorithms in the literature that are widely preferred for OPF solutions. The algorithm is applied to a part of 13 bus-bar east Anatolian power system and 14 bus-bar IEEE test system. The optimization results are also used in virtual model of the transmission systems that is obtained by using DigSilent power systems modeling software and the power flow was simulated.

As a result of the optimization with the proposed FODPSO-CT algorithm, an active power loss of 21.87 MW was obtained in the power system. This value is 22.93 MW for VPSO algorithm. Furthermore, the optimization result with FODPSO-CT in 14 bus-bar IEEE test system is compared with other optimization algorithms in the literature. The proposed FODPSO-CT algorithm performed a load flow with an active power loss of less than 0,31 MW from the GSA algorithm which gives the closest result to the proposed algorithm, as given in Table 5. As a result, a more optimal power flow was obtained with FODPSO-CT in both cases.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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