Optimal Power Flow Using Artificial Bee Colony, Wind Driven Optimization and Gravitational Search Algorithms

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***Abstract*—In this study, artificial bee colony, wind driven optimization and gravitational search algorithms are employed in order to solve the optimal power flow problem. The proposed optimization approaches are tested on the standard IEEE 9-bus power system with the objective functions of voltage deviation reduction, active power loss minimization and fuel cost minimization. In addition, the calculation time spent is compared. The simulation results show that, on the one hand, the proposed optimization approaches have the similar potentials in the minimization of active power losses and fuel costs. On the other hand, wind driven optimization algorithm ensures more consistent results than the other ones in the reduction of voltage deviation and in terms of the calculation time spent.**

Keywords—optimal power flow; metaheuristic algorithms; voltage deviation; active power loss; fuel cost; minimization

I. INTRODUCTION

The solution of optimal power flow problem in power systems has a great importance for security, timing, economy, operation and planning purposes. It is utilized for making the optimal settings of control variables considering one or more determined objective functions. By creating various inequality and equality constraints, it leads to improve the voltage profile, to enhance the voltage stability, and to decrease the active power losses and fuel costs [1].

Many mathematical approaches such as linear programming [2], nonlinear programming [3], Newton-Raphson method [4], etc. have been used for the solution of optimal power flow problem. These mathematical methods are based on the differential, analytical and convex objective functions, and they may not able to identify the optimal results [5]. In order to eliminate such drawbacks and challenges, many population-based algorithms have been implemented for solving the optimal power flow problem in recent years. Some of them are the studies applying genetic algorithm [6], ant colony algorithm [7], particle swarm algorithm [8], evolutionary programming [9], etc.

In addition to these studies, simulated annealing and shuffle frog leaping algorithm were hybridized for the optimal power flow solution, including non-convex and non-smooth characteristics of fuel cost. The validation of the hybridized model was made in the standard IEEE 30-bus power system, effectively [10]. Chaotic invasive weed optimization approaches were presented for the large-scale nonlinear non-smooth environmental optimal power flow solution. The proposed chaotic approaches produced the high quality solutions in the standard IEEE 30-bus power system [11]. Gravitational search algorithm and moth swarm algorithm were integrated for solving the problem of fuel cost deterioration. The simulation process was successfully conducted in the standard IEEE 118-, 57- and 30-bus power systems [12]. Shuffle frog leaping algorithm and particle swarm optimization algorithm were combined for the optimal power flow solution, containing all constraints related to the generators. The suitability of the combined approach on the basis of convergence speed and consistency was verified in the standard IEEE 118-, 57- and 30-bus power systems [13]. For the standard IEEE 30-bus power system, a hybrid algorithm consisting of dragonfly algorithm and enhanced grey wolf optimizer was presented in order to solve the optimal power flow issues. The presented hybrid approach minimized voltage deviations, power losses and fuel costs in a fast and efficient manner [14]. In the standard IEEE 30-bus power system, a symbiotic organisms approach was tested considering prohibited generating zones and valve-point effect. The proposed algorithm was found to be effective to accomplish the optimal power flow solution according to the Wilcoxon signed-rank statistical test [15].

In this study, in the standard IEEE 9-bus power system, the compatibilities of artificial bee colony, wind driven optimization and gravitational search algorithms are consistently validated for the optimal power flow solution. In addition to the calculation time spent, many reasonable comparisons are made for the objective functions of voltage deviation reduction, active power loss minimization and fuel cost minimization. In the following sections, initially, optimization algorithms and problem formulation are described. Afterwards, simulation results are depicted and evaluated. Lastly, the conclusions are provided.

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II. Optimization Algorithms

A. Artificial Bee Colony Algorithm

The ABC (Artificial Bee Colony) algorithm is a swarm-based optimization approach developed by *Karaboga* in 2005 [16]. It is inspired from the food seeking behavior of honey bee swarm in nature. In this optimization algorithm, there are three types of bees: scout, onlooker and employed bees. The bees leave their hive for the purpose of finding a new food source. They perform the initial searches randomly and look for new food sources when the food amount they find starts to decrease. During the food search between sources, information transfer between bee colonies continues [16, 17]. The fundamental processing stages of the ABC algorithm are given below:

- Start
- Determination of random food sources
- Sending bees to food sources
- Probability calculation of the food sources for the selection task
- Sending the bees to the food sources selected depending on their probability values
- Determination of the food source to be abandoned and exploring new food sources
- Termination

B. Wind Driven Optimization Algorithm

The WDO (Wind Driven Optimization) algorithm was developed as a population-based and nature-inspired global optimization approach by *Bayraktar et al.* in 2013 [18]. It is based on the atmospheric motion's physical equations, which is modeled by the Lagrangian description. In the Lagrangian description, in accordance with the Newton's second law of motion, the atmosphere is characterized as a collection of many infinitesimal small air parcels. In addition, a simplification, assuming that the air parcel is a cuboid in a rectangular coordinate system, is made. The fundamental processing stages of the WDO algorithm are given below:

- Start
- Assignment of position and velocity randomly
- Evaluation of the pressure function
- Velocity update and checking its limits
- Position update and checking its boundaries
- Finish

C. Gravitational Search Algorithm

The GSA (Gravitational Search Algorithm) is a meta-heuristic optimization approach developed by *Rashedi et al.* in 2009 [19, 20]. It is inspired from the Newtonian laws of motion and gravitation. In this optimization approach, objects are regarded as the agents, and agents' masses are utilized for computing the performance. By means of the gravity force, all objects attract each other and so, this force allows all objects to move towards to the ones with heavier masses. In addition, a direct form of communication is used in order to cooperate the masses. The fundamental processing stages of the GSA algorithm are given below:

- Randomized initialization
- Evaluation of the fitness values of agents
- Updating the gravitational constant
- Calculation of velocity and acceleration of objects
- Updating the agents' positions
- Meeting the stopping criteria

III. Problem Formulation

The optimal power flow method aims to obtain the optimal results with one or more objective functions depending on the selected control variables along with various inequality and equality constraints [21]. The optimal power flow can be expressed as below. In this equation, F denotes the objective function to be minimized, and it is the vector of dependent variable x and control variable u.

$$min\, F(x,u) \quad (1)$$

$$g(x,u) = 0 \quad (2)$$

$$h(x,u) \leq 0 \quad (3)$$

x indicates the vector of dependent variables of transmission line load (S_l), load bus voltage (V_L), generator reactive power output (Q_G) and generator active power output (P_{G1}) at the slack bus. Accordingly, x is expressed with (4), where NG is the number of generators, NTL is the number of transmission lines and NL is the number of load buses.

$$x^T = [P_{G1},\, V_{L1} \dots V_{LNL},\, Q_{G1} \dots Q_{GNG},\, S_{l1} \dots S_{lNTL}] \quad (4)$$

u denotes the vector of control variables of parallel reactive power compensator values (Q_c), transformer tap settings (T), generator bus voltages (V_G) and generator active power output (P_G) except at the slack bus. Accordingly, u is expressed with (5), where NT is the number of regulatory transformers and NC is the number of parallel reactive power compensators.

$$u^T = [P_{G2} \dots P_{GNG},\, V_{G1} \dots V_{GNG},\, Q_{C1} \dots Q_{CNC},\, T_1 \dots T_{NT}] \quad (5)$$

g, which represents the equality constraints for the typical load, and h, which represents the inequality constraints for generators, transformers and parallel reactive power compensators have been defined as in [21]. In addition to the calculation time comparison, three objectives have been determined for the optimum power flow analysis. These are reduced voltage deviation, minimized active power losses and minimized fuel costs [21, 22].

The minimization of fuel costs for all generators is expressed as the objective function $minF_{COST}$, where a_i, b_i and c_i are the cost coefficients of ith generator, and f_i is the quadratic cost function of ith generator.

$$minF_{COST} = \sum_{i=1}^{NG} f_i = \sum_{i=1}^{NG} (a_i + b_i \,.\, P_{Gi} + c_i \,.\, P_{Gi}^2) \quad (6)$$

The minimization of active power losses is expressed as the objective function $minP_{LOSS}$, where g_k is the conductivity of the line k connected between ith and jth buses, N_{TL} is the number of transmission lines, δ_{ij} is the voltage phase difference between ith and jth buses, and V_i and V_j are the voltage magnitudes of ith and jth buses, respectively.

$$minP_{LOSS} = \sum_{k=1}^{N_{TL}} g_k\left(V_i^2 + V_j^2 - 2V_iV_jcos\delta_{ij}\right) \quad (7)$$

The minimization of voltage deviations is expressed as the objective function $minV_d$, where V_y^{ref} is the desired voltage magnitude value (usually 1.0 p.u.) at the yth load bus, V_y is the voltage magnitude at the yth load bus, N_y is the number of load buses and V_d is the total voltage deviation of load buses.

$$minV_d = \sum_{y=1}^{N_y}\left|V_y - V_y^{ref}\right| \quad (8)$$

IV. Simulation Results

Artificial bee colony algorithm, wind driven optimization algorithm and gravitational search algorithm employed in this paper are tested using the standard IEEE 9-bus power system. Figure 1 shows the single line diagram of it. The minimum and maximum limit values of the generators in the power system are given in Table I. It should be noted that the mentioned optimization approaches were executed 30 times, and the total number of iterations was assigned as 100. In the IEEE 9-bus power system, three different scenarios were implemented according to different load conditions. These scenarios are *Case 1* with the total load value of 453.6 MW, *Case 2* with the total load value of 544.32 MW and *Case 3* with the total load value of 783.821 MW. The load values were identified in the way of not exceeding the total active power generation values of the generators. *Case 1* was considered as the base case. The load was increased 20% and 60% in *Case 2* and *Case 3*, respectively. The optimal power flow analysis results of the employed optimization approaches for the mentioned scenarios are listed in Table II.

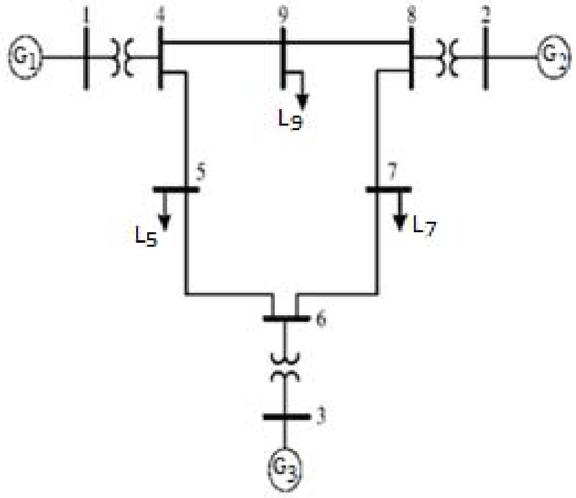

Fig. 1. Single line diagram of IEEE 9-bus power system

TABLE I. Minimum and Maximum Limit Values of the Generators

NG	V_{Gmin}	V_{Gmax}	P_{Gmin}	P_{Gmax}	Q_{Gmin}	Q_{Gmax}	a	b	c
G_1	0.90	1.10	0.10	2.50	-3.00	3.00	150	5	0.11
G_2	0.90	1.10	0.10	3.00	-3.00	3.00	600	1.2	0.085
G_3	0.90	1.10	0.10	2.70	-3.00	3.00	335	1	0.1225

TABLE II. The Optimal Power Flow Analysis Results of ABC, WDO and GSA for Different Scenarios

	Case 1			Case 2			Case 3		
	ABC	**WDO**	**GSA**	**ABC**	**WDO**	**GSA**	**ABC**	**WDO**	**GSA**
Objective Function	9660.953	9661.439	9660.940	13242.743	13243.703	13242.726	26014.058	26019.187	26022.666
P_{LOSS} (MW)	7.539	7.601	7.543	10.026	10.207	10.013	22.133	22.230	22.237
F_{COST} ($/h)	9474.170	9476.140	9474.230	12957.160	12963.550	12956.710	25501.020	25507.160	25509.330
VD (p.u.)	0.199	0.185	0.198	0.450	0.406	0.454	0.400	0.387	0.389
Standard Deviation	0.045	0.307	0.007	0.097	0.800	1.170	9.440	63.270	NAN
Calculation Time (s)	5.605	2.777	2.998	6.024	2.880	3.312	15.107	3.667	9.074
P_{G1}	139.573	139.390	139.542	170.222	169.955	170.249	250.051	250.069	249.974
P_{G2}	188.991	188.200	189.022	225.728	226.849	225.796	300.000	300.000	299.879
P_{G3}	132.575	133.611	132.579	158.398	157.724	158.289	255.903	255.983	256.205
P_{GTOTAL}	461.139	461.201	461.143	554.347	554.527	554.334	805.954	806.051	806.058
P_{LOAD}	453.600	453.600	453.600	544.32	544.32	544.32	783.821	783.821	783.821
V_1	1.005	1.000	1.064	1.100	1.026	1.054	1.100	1.064	1.091
V_2	1.029	1.051	1.032	1.040	1.070	1.085	1.065	1.095	1.061
V_3	1.085	1.008	1.056	1.043	1.033	1.085	1.081	1.054	1.040
V_4	1.045	1.043	1.045	1.087	1.077	1.088	1.101	1.095	1.101
V_5	1.018	1.015	1.018	1.056	1.047	1.057	1.037	1.033	1.037
V_6	1.051	1.047	1.050	1.100	1.096	1.100	1.101	1.101	1.101
V_7	1.031	1.028	1.032	1.074	1.069	1.075	1.058	1.058	1.055
V_8	1.054	1.051	1.055	1.100	1.094	1.100	1.100	1.100	1.094
V_9	1.000	0.997	1.000	1.034	1.024	1.034	1.003	0.999	1.001

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Figures 2 to 5 compare the values of total active power loss, fuel cost, voltage deviation and calculation time according to the load conditions, respectively. As the load increases, fuel costs and active power losses also increase. On the basis of fuel costs and total active power losses, similar values are achieved by ABC, WDO and GSA in almost all cases. On the basis of voltage deviations, WDO provides better values than ABC and GSA. On the basis of calculation time, the minimum value is produced by WDO, while the maximum one is caused by ABC.

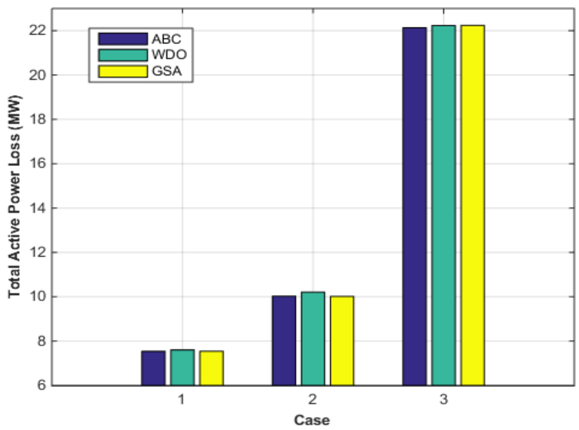

Fig. 2. Evaluation in terms of total active power losses

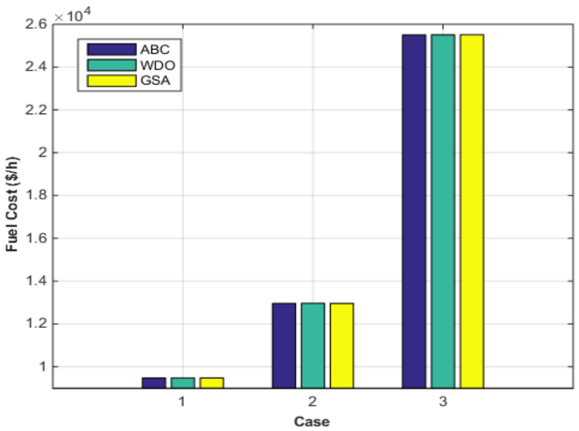

Fig. 3. Evaluation in terms of fuel costs

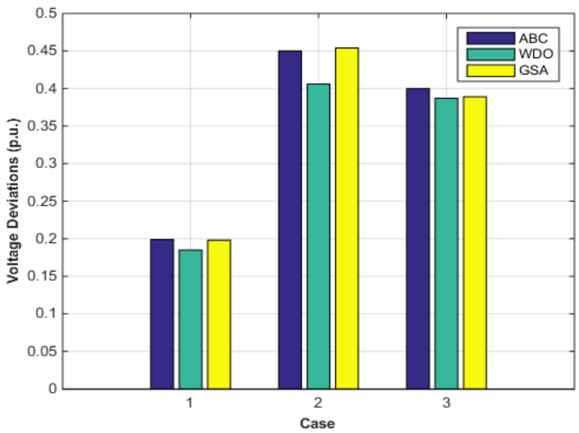

Fig. 4. Evaluation in terms of voltage deviations

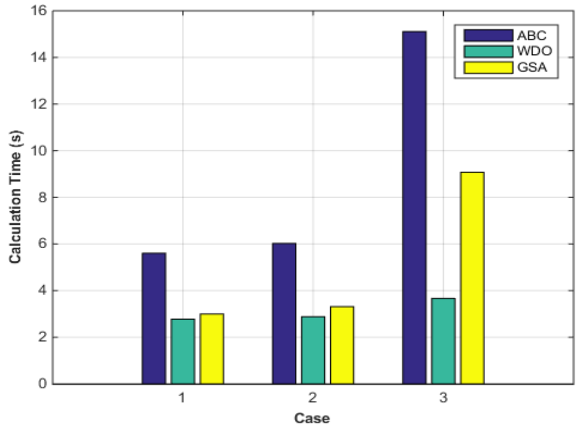

Fig. 5. Evaluation in terms of calculation time

V. CONCLUSIONS

In this paper, artificial bee colony algorithm, wind driven optimization algorithm and gravitational search algorithm have been implemented successfully in order to solve the optimal power flow problem. The simulation results show that the mentioned optimization approaches provide high quality, robust and effective solutions to achieve the optimum values of total active power losses, fuel costs, voltage deviations and calculation time. Especially, it is observed that WDO gives better results than GSA and ABC in terms of voltage deviation and calculation time. In general, ABC, WDO and GSA are found to be suitable for the optimal power flow solution in power systems. In further works, the mentioned optimization algorithms should be employed and tested for hybrid power systems.

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