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Comparison Of Techniques For Solving The Optimal Power Flow Problem In Power Systems: A case study of the Turkish Power System

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Abstract **–** Mathematical optimization techniques, simulation programs and metaheuristic optimization algorithms are used to solve optimal power flow problems. All optimization methods have their advantages and disadvantages. In this study, the results produced by classical methods and metaheuristics are compared in terms of ease, speed and accuracy with the Power World simulator program. According to the results obtained, it is observed that metaheuristic algorithms can be applied more easily to solve multi-objective optimization problems such as optimal power flow, while classical mathematical methods are more difficult to apply but can obtain faster results. When both methods are compared in terms of accuracy, it is observed that both methods produce results close to the simulator program. In this study, which shows that metaheuristic algorithms are more useful, it is seen that the CA algorithm finds the most optimum values. Additionally, the optimization time of the CA algorithm appears to be shorter than many other metaheuristic algorithms. The results found by the FA and SCE algorithms are almost the same as the results found by the Power World and classical methods.

Keywords – Power Systems, Optimal Power Flow, Metaheuristics, Optimization, Power World.

I. INTRODUCTION

The optimal power flow (OPF) problem has become very important for optimal operation of power systems and minimization of costs. As in other optimization problems, optimization in the OPF problem is aimed at providing maximum benefit with minimum cost under a set of constraints. At the same time, the optimization process is done within certain reliability limits. Since OPF is nonlinear, powerful algorithms must be used to solve it [1]. OPF optimization will continue to be a problem that needs to be addressed in the future as it is today. Because nowadays, energy consumption is increasing individually due to the increase in technological products, e.g. electric vehicles. Based on this, the OPF is constantly expanding with the inclusion of consumption forecasting and planning and the integration of renewable energy sources into grids. The methods used to solve the OPF problem are divided into two categories: classical-mathematical or metaheuristic. In this study, classical methods Gradient method and Newton's method were used. Among the metaheuristic optimization algorithms, Artificial Bee Colony (ABC), Biogeography Based Optimization (BBO), Bees Algorithm (BA), Cultural Algorithm (CA), Covariance Matrix Adaptation Evolution Strategy (CMAES), Firefly Algorithm (FA), Harmony Search (HS) , Imperialist

Competitive Algorithm(ICA), Invasive Weed Optimization(IWO), Particle Swarm Optimization(PSO), Simulated Annealing(SA), Shuffled Complex Evolution(SCE), Shuffled Frog Leaping Algorithm(SFLA), Teaching Learning Based Optimization(TLBO) optimization algorithms were used. The validity of both methods was ensured with the Power World simulation program used in power systems analysis. When studies in the literature on OPF optimization using metaheuristic algorithms are examined, Improved Equilibrium Optimizer(IEO)[2], Harris Hawk Optimization(HHO)[3], Crow Search(CS)[4], PSO[5], BAT algorithm(BA)[6], League Championship Algorithm(LCA)[7], ABC[8], Lévy Flight Spider Monkey Optimisation (LFSMO)[9], Symbiotic Organisms Search (SOS)[10], Stud Krill Herd (SKH)[11], SA[12], Moth Flame Optimization (MFO)[13], Water Evaporation Algorithm(WEA)[14], Social Spider Optimization(SSO)[15], Slime Mould Algorithm (SMA)[16], Backtracking Search Algorithm (BSA)[17], Gravitational Search Algorithm (GSA)[18], Salp Swarm Algorithm (SSA)[19], Gorilla Troops Optimization Technique (GTOT)[20], Modified Grasshopper Optimization Algorithm (MGOA)[21], GA[22] algorithms were used. In addition, it has been observed that metaheuristic algorithms are used by hybridizing them in some studies. Hybrid Sine Cosine–Grey Wolf Optimizer (HSC-GWO)[23], Hybrid Whale Optimization Algorithm-Modified Moth-Flame Optimization Algorithm (WMFO)[24], Hybrid PSO&GSA[25], Hybrid ICA&TLBO[26], Hybrid FA&PSO[27].

II. MATERIAL AND METHOD

Objective Function

The objective function for the OPF problem is fuel cost in this study. The way to increase the benefit from power systems is to reduce fuel costs. The objective function consists of two parts. The first part is the fuel cost and the second part is the balance of the demand power and the power produced by the generators. Thus, the optimization aims to reduce fuel costs within reliability limits. Objective function is calculated with equation 1.

$$f = Min[\sum_{i=1}^{NG}(a_i + b_i P_{Gi} + c_i P_{Gi}^2) + W_0 * abs\{\sum_{i=1}^{NG}(P_{Gi}) - P_D\}] \quad (1)$$

The output power of the generators must be greater than or equal to the minimum active power value or less than or equal to the maximum active power value within the specified limit values.

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \; i = 1, \dots \dots N \quad (2)$$

System Description and Simulation

The single line diagram and simulation results of the 380 kV power system with 6 generators in Turkey, where optimal power flow was achieved, can be seen in “Figure 1”. Simulation results were obtained by creating a single line diagram in Power World software.

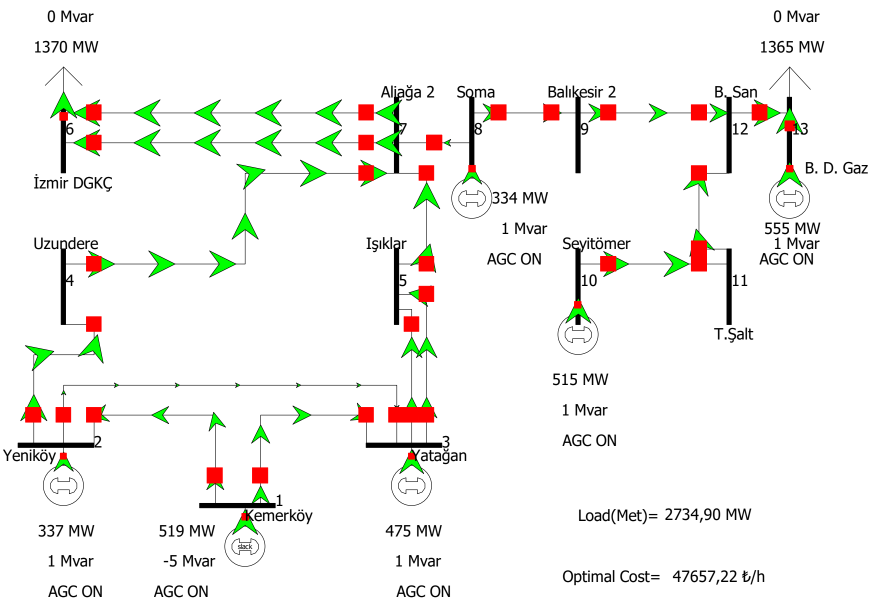

Figure 1. Single line diagram of 380 kV 6 generator system in Turkey and optimum power flow according to Power World simulator

Simulation results are presented in "Figure 1". The fuel cost function coefficients used in the simulation and the minimum and maximum powers of the generators are presented in "Table 1". The requested power is 2734.9 MW.

Table 1. Generator data and fuel cost function coefficients used in the simulation[28]

Bus number	Plant Name	P_{Gi}^{min}(MW)	P_{Gi}^{max}(MW)	a	b	c
1	Kemerköy	140	630	1697.0	3.2324	0.0137
2	Yeniköy	110	420	1159.5	3.2128	0.0210
3	Yatağan	140	630	1822.8	3.4720	0.0147
8	Soma	210	990	5134.1	6.2232	0.0168
10	Seyitömer	150	600	1564.4	3.1288	0.0139
13	Bursa D. Gaz	318	1432	6780.5	5.6820	0.0106

In the simulation made using the generator and fuel cost function parameters presented in "Table 1", the generator powers for optimum load flow are presented in "Table 2".

Table 2. Optimum Power Flow simulation results

Optimization Method	Power World Simulator
Optimal Power of Kemerköy(MW)	519 MW
Optimal Power of Yeniköy(MW)	337 MW
Optimal Power of Yatağan(MW)	475 MW
Optimal Power of Soma(MW)	334 MW
Optimal Power of Seyitömer(MW)	515 MW
Optimal Power of Bursa D. Gaz(MW)	555 MW
Cost ($/h)	47657.22 $/h
Load	2734.9 MW

Power Flow Optimization Methods

Classical Methods

Gradient Method

Gradient method is a mathematical method used to solve the optimum power flow problem. The application of this method begins with the equality of the produced power to the requested power.

$$P_L = P_{G1} + P_{G2} + \cdots + P_{Gn} \tag{3}$$

One of the generators is always assumed as the dependent variable. In this case, the expression in equation 3 is rewritten as equation 4.

$$P_{Gn} = P_L - P_{G(n-1)} - \cdots - P_{G1} \tag{4}$$

The total cost function of the system is calculated with equation 5.

$$C = F_1(P_1) + F_2(P_2) + \cdots + F_n\left(P_L - P_{G(n-1)} - \cdots - P_{G1}\right) \tag{5}$$

To minimize the cost function, the gradient method is applied with equation 6.

$$\nabla C = \begin{bmatrix} \frac{d}{dP_1}C \\ \frac{d}{dP_2}C \\ \vdots \\ \frac{d}{dP_{(n-1)}}C \end{bmatrix} = \begin{bmatrix} \frac{dF_1}{dP_1} - \frac{dF_n}{dP_1} \\ \frac{dF_2}{dP_2} - \frac{dF_n}{dP_2} \\ \vdots \\ \frac{dF_{(n-1)}}{dP_{(n-1)}} - \frac{dF_n}{dP_{(n-1)}} \end{bmatrix} \tag{6}$$

Equation 7 is used to proceed in the maximum descent direction, that is, to update from $x^{[0]}$ to $x^{[1]}$.

$$\mathrm{d}x^{[1]} = x^{[0]} - \alpha \nabla C \tag{7}$$

Here, α is an arbitrarily chosen number, and choosing it appropriately has a positive effect on convergence. The x matrix consists of the power values of the generators and is given in equation 8.

$$x = \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{(n-1)} \end{bmatrix} \tag{8}$$

Newton's Method

Newton's method, like the Gradient method, is one of the mathematical methods used to solve the optimal power flow problem. In this method, the aim is to always make the gradient zero as given by equation 9.

$$\nabla L_x = 0 \tag{9}$$

The cost function for economic power flow is given in equation 10.

$$L = \sum_{i=1}^{NG}(F_i(P_i)) + \lambda * (P_{load} - \sum_{i=1}^{NG}(P_{Gi})\} \tag{10}$$

To perform the $\nabla L_x = 0$ operation, equation 11 can be written by using the first two terms of the Taylor series.

$$L(x + \Delta x) = L(x) + \left[\frac{\partial}{\partial x}\nabla L_x\right]\Delta x = 0 \tag{11}$$

The Jacobian matrix is given in equation 12.

$$\frac{\partial}{\partial x}\nabla L_x = \begin{bmatrix} \frac{d^2L}{dx_1^2} & \frac{d^2L}{dx_1 dx_2} & \cdots \\ \frac{d^2L}{dx_2 dx_1} & \frac{d^2L}{dx_2^2} & \cdots \\ \vdots & \vdots & \ddots \\ \frac{d^2L}{d\lambda dx_1} & \frac{d^2L}{d\lambda dx_2} & \cdots \end{bmatrix} \tag{12}$$

Δx is calculated with equation 13.

$$\Delta x = -\left[\frac{\partial}{\partial x}\nabla L_x\right]^{-1}\Delta L \tag{13}$$

ΔL is named Hessian matrix and given in equation 14.

$$\nabla L = \begin{bmatrix} \frac{d^2F_1}{dP_1^2} & 0 & 0 & -1 \\ 0 & \frac{d^2F_2}{dP_2^2} & 0 & -1 \\ 0 & 0 & \frac{d^2F_3}{dP_3^2} & -1 \\ -1 & -1 & -1 & 0 \end{bmatrix} \tag{14}$$

Equation 15 is used to update from $x_{old}^{[0]}$ to $x_{new}^{[0]}$.

$$x_{new}^{[0]} = x_{old}^{[0]} - \Delta x \tag{15}$$

Metaheuristic Methods

Metaheuristic algorithms are artificial intelligence algorithms inspired by nature, animal and human behavior, and the functioning of biological structures. It can be easily used to solve many linear and nonlinear problems. Metaheuristic algorithms are easier to implement than mathematical algorithms. Therefore, in recent years, they have been practically used to overcome various optimization problems. Metaheuristic algorithms are also used to solve nonlinear and optimal power flow problems with constraints. There are dozens of metaheuristic optimization algorithms. In this study, the attitudes of 15 different metaheuristic algorithms towards the optimum power flow problem are revealed. In addition, these algorithms were compared with the Power World simulator and classical-mathematical methods.

III. RESULTS

In this study, the OPF problem was solved with 3 different methods: simulation software, classical methods and metaheuristic methods, and the results were analyzed in depth. The OPF problem was first simulated with the Power World program to obtain the most accurate results. Then, the OPF problem was solved with the Gradient method and Newton's method, which are classical-mathematical methods, and the results were compared both among themselves and on the basis of Power World. The number of iterations for both methods was determined as 50. Comparison of Power World and Classic methods is presented in "Table 3".

Table 3. Comparison the results of Power World and Classic methods

Optimization Method→	**Power World**	**Gradient Method**	**Newton's Method**
Optimal Power of Kemerköy(MW)	519	519	519
Optimal Power of Yeniköy(MW)	337	337	337
Optimal Power of Yatağan(MW)	475	475	475
Optimal Power of Soma(MW)	334	334	334
Optimal Power of Seyitömer(MW)	515	515	515
Optimal Power of Bursa D. Gaz(MW)	555	555	555
Cost ($/h)	47657	47661	47661
Iteration	----	42	2
Optimization time(sec)	----	0.0821	0.0098
Load	2734.9 MW		

When "Table 3" is examined, it is seen that Gradient Method and Newton's method can achieve the same results as Power World. However, it has been observed that Newton's method obtains results in a shorter time with fewer iterations than the Gradient Method. Therefore, it has been proven that Newton's method is more advantageous than the Gradient method in OPF solution. "Figure 2" shows the convergence curves of the Gradient method and Newton's method. It is seen that Newton's method can achieve faster convergence.

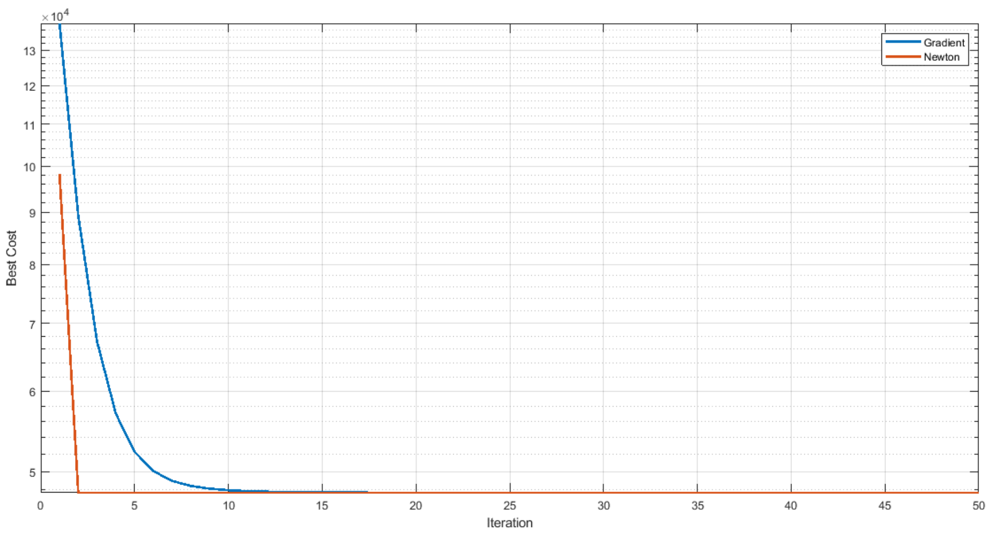

Figure 2. Convergence curves of the Gradient method and Newton's method

The OPF problem optimization was then solved with 15 different metaheuristic algorithms. The number of iterations of all algorithms was set to 50. In all metaheuristic algorithms, population numbers are set equal. The results of the metaheuristic algorithms are presented in "Table 4".

Table 4. Comparison the results of 15 different metaheuristic algorithms.

Optimization Method→	**ABC**	**ACO**	**BBO**	**BEES**	**CA**	**CMAES**	**FA**	**HS**
Kemerköy(MW)	514	630	524	564	519	630	519	529
Yeniköy(MW)	350	286	334	233	354	269	336	301
Yatağan(MW)	450	509	450	482	457	521	474	440
Soma(MW)	363	332	334	361	332	289	333	330
Seyitömer(MW)	473	474	519	467	522	469	516	514
Bursa D. Gaz(MW)	580	505	569	625	549	539	554	616
Cost ($/h)	47789	48069	47740	48008	47648	48484	47661	47773
Iteration	45	27	44	28	45	5	44	15
Optimization time(sec)	1.423	1.161	0.437	4.256	0.660	0.183	12.869	0.253
Optimization Method→	**ICA**	**IWO**	**PSO**	**SA**	**SCE**	**SFLA**	**TLBO**	
Kemerköy(MW)	603	581	526	521	518	508	517	
Yeniköy(MW)	324	344	326	350	336	331	327	
Yatağan(MW)	464	249	493	477	475	471	467	
Soma(MW)	272	422	338	334	334	348	314	
Seyitömer(MW)	408	515	503	506	515	552	531	
Bursa D. Gaz(MW)	660	621	545	544	555	521	576	
Cost ($/h)	48108	48642	47673	47669	47660	47704	47686	
Iteration	49	50	49	25	49	50	50	
Optimization time(sec)	0.780	92.235	0.520	9.430	1.914	1.819	0.641	
Load	2734.9 MW							

When "Table 4" is examined, it is seen that all algorithms successfully solve the OPF problem at values close to each other. The results found by the FA and SCE algorithms are almost the same as the results found by the Power World and classical methods. However, optimization times took longer than classical methods. The optimum values found by the CA algorithm are the most economical solution among both Power World, classical methods and other metaheuristics. Additionally, the optimization time of the CA algorithm appears to be shorter than many other metaheuristic algorithms. "Figure 3" shows the convergence curves of the metaheuristic algorithms.

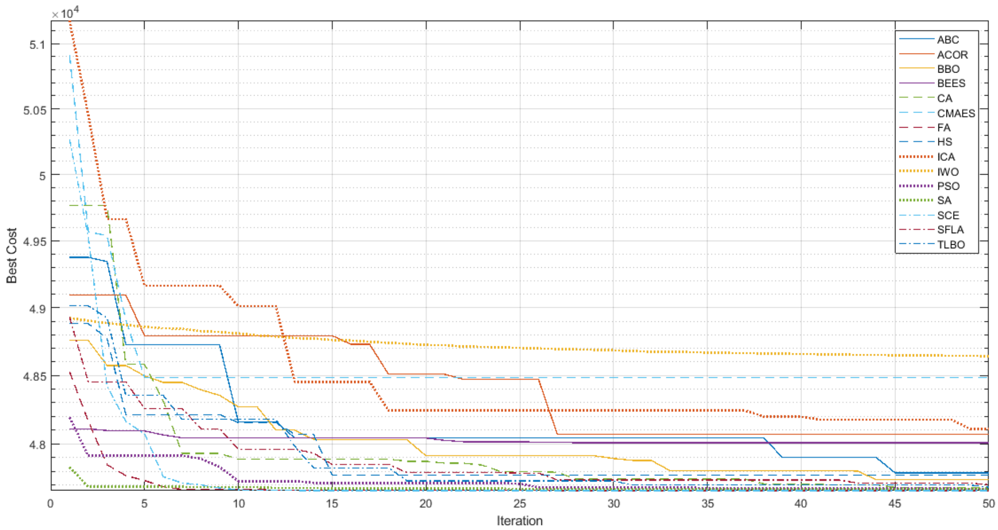

Figure 3. Convergence curves of the metaheuristic algorithms.

When "Figure 3" is examined, it is seen that the IWO, CMAES, ICA, ACO and BEES algorithms are less successful than the other algorithms.

IV. DISCUSSION

When the study is compared with previous studies carried out with the same power system, it is seen that the most optimum values in the OPF problem, which was solved using the GA, SA, TS metaheuristic algorithms in the study in reference [28], were obtained with the TS algorithm. In the relevant study, the cost value of the most optimum system with TS was found to be 47678$/h. However, in this study, the cost value of 47648 $/h obtained with CA is lower than the value obtained with TS. This result shows that CA gives better results than GA and TS, which were not used in this study. Likewise, in the OPF optimization performed using the CS algorithm with the same system in reference [4], it is seen that the most optimum cost value found by the CS algorithm is 47661$/h. This value is higher than the value found by the CA algorithm in this study and shows that the study can find more optimum values than previous studies.

V. CONCLUSION

As a result, in this study, it was seen that the CA algorithm gave better results than all methods and simulation program. Based on this, it can be seen that metaheuristic algorithms are extremely successful in the OPF problem. Another advantage of metaheuristic algorithms stands out in practice. The implementation of these algorithms, which do not require intensive mathematical operations like classical algorithms, is simpler. The advantage of classical methods is that they provide results in a much shorter time.

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