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RENEWABLE ENERGY INTEGRATED OPTIMAL POWER FLOW WITH VORTEX SEARCH OPTIMIZATION

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Abstract- Optimal power flow (OPF) is one of the most sophisticated optimization issue in power systems since planning and operation is getting harder day by day. In addition to this, fuel cost and emission are the most important concerns not for only the operators but also the consumers. Thus, in this study the OPF is applied to the power system which is integrated with wind energy conversion systems (WECS). Vortex search algorithm (VSA) is employed to solve the WECS integrated OPF problem. The results depicted that the WECS are the best option for minimizing the fuel cost and emission.

Keywords: Optimal Power Flow, Heuristic Algorithms, Power System Optimization.

I. INTRODUCTION

In the past, because of usage of electricity was limited, power systems were not in large scales. As a result of this, a number of loads were few. However, since the technology is developing fast, a number of electrical devices and usage ratio are increasing. This increase causes more loads on power systems. As a consequence, nowadays power systems are huge structures. Moreover, competition in electricity market is getting harder. All of these factors, making planning and operating the power systems important than ever before. OPF is one of the best solution to overcome these problems.

OPF is literally known as nonlinear optimization problem is formulated by Carpentier in 1962 [1]. Since then, it has been used for numerous optimization studies. Between 60s and 90s, it is solved by different numerical techniques [2-7]. However, these techniques are inadequate to find the optimal solution for the today's complex power systems due to the reasons such as insufficient convergence characteristics, failure to guarantee to find the global minimum, excess dependence on initial conditions and difficulty in adapting to possible changes in problem definition.

Thanks to the developments in computer technology, heuristic algorithms are started to be used for finding solutions of problems. Some of these algorithms: particle swarm optimization [8], genetic algorithm [9], artificial bee algorithm [10], gravitational search algorithm [11], glowworm swarm optimization [12] and moth swarm algorithm [13]. Most of the studies only generators using fossil fuels were considered even though fossil fuels are harmful to nature. In the last decade, WECS are also being considered in studies [14-17]. Underlying reason of these considerations depends on cost and environmental concerns.

Purpose of this paper is solving the WECS integrated OPF problem by using vortex search algorithm (VSA). Three different scenarios are developed to work on. The classical 30 bus test system of IEEE consist of 6 generators which are operating with fossil fuels. In first case, one of these generators converted to WECS. In second case number of WECS are increased to three and in final case the number increased to five. OPF is solved for every case.

This paper consists of five sections. In section II, WECS integrated OPF is explained. Section III provides information on proposed VSA approach. Obtained results for three cases are given in section IV and in final section these results are evaluated.

II. WECS INTEGRATED OPF

OPF is generally described as non-linear optimization problem. The intention of the OPF is optimizing the various functions within these determined constraints [8]. The mathematical representation of classical OPF is given in Equation (1) [4].

$$\begin{aligned} &\text{minimize} \quad f(y,x) \\ &\text{subject to:} \quad g(y,x)\ ,\ h(y,x) \le 0 \end{aligned} \tag{1}$$

where, f is the function which is desired to be optimized, $g(y,x)$ and $h(y,x)$ are the variables that objective function is subject to. Vector of y is called as dependent variables and consist of voltage magnitudes at lines, reactive power generation values, active power generation values at slack bus and apparent power at lines. Vector x is called as independent variables and consist of voltage magnitudes at generation buses, active power generations at generation buses other than slack bus, tap settings of transformers and shunt VAR compensators. Constraints of OPF can be divided into two as equality constraints and inequality constraints. Equality constraints are derived from power flow equations. Briefly, power generation should be equal to demand power and power losses. These are given in Equations (2) and (3) [18].

$$P_{Gj} = P_{Dj} + V_j \sum_{k=1}^{N_B} V_k \left[G_{jk} \cos(\theta_j - \theta_k) + B_{ik} \sin(\theta_j - \theta_k) \right] \quad (2)$$

$$Q_{Gj} = Q_{Dj} + V_j \sum_{k=1}^{N_B} V_k \left[G_{jk} \sin(\theta_j - \theta_k) - B_{jk} \cos(\theta_j - \theta_k) \right] \quad (3)$$

where, P_G and Q_G are active and reactive power generations, P_D and Q_D are active and reactive power demands, V is the bus voltage, G is conductance and B is susceptance. Inequality constraints are consisting of generation, transformer, shunt VAR compensator and security constraints. These constraints are physical limits of devices [8]. Equality and inequality constraints are added to the objective function as penalty coefficients to improve the suitability of the solution.

A. Integration of WECS

Thermal generation units burn fossil fuels. Because of that, they emit excessive amount of carbon dioxide. This emission is harmful for the environmental security. So, in this study wind WECS are used to decrease the emission and fuel cost. Integration of wind powered generation units can be expressed as Equation (4) [15].

$$F_W = \sum_{t=1}^{N_G} C_t(P_{Gt}) + \sum_{r=1}^{N_W} \begin{bmatrix} C_W(P_W) + \\ C_{ue}(P_{Wav} - P_W) + C_{oe}(P_W - P_{Wav}) \end{bmatrix} \quad (4)$$

where, N_G denote number of thermal generation units, N_W denote number of wind powered units. First term is cost of fossil fuel powered units as given in Equation (5) [15].

$$C_t(P_{Gt}) = P_{Gt}^2 x_t + P_{Gt} y_t + z_t \quad (5)$$

where x_t, y_t and z_t are the cost coefficients for the thermal unit t [8]. These coefficients are given in Table 1.

Table 1. Cost coefficients and power limits of thermal units [8]

Generator Number	Cost Coefficients			Min. Limit (MW)	Max. Limit (MW)
	x	y	z		
1	0.00375	2	0	50	200
2	0.0175	1.75	0	20	80
3	0.0625	1	0	15	50

Second term of Equation (4) denotes cost of the wind powered turbines and it can be written as Equation (6) [15].

$$C_W(P_W) = d_w P_W \quad (6)$$

where, d_w denotes the direct coefficient and P_W is available power of the wind turbine.

Wind is an unpredictable fact of nature. So, in some instances it might be cause difference between the planned and actual power outputs. These differences can be divided into two cases. First one is under estimation and second one is over estimation situation. The first case is third term of the Equation (4). The cost in case of under estimation of wind power can be expressed as Equation (7) [15].

$$C_{ue}(P_{Wav} - P_W) = \lambda_{ue} \int_{P_{ra}}^{P_{av}} (w - P_W) f_W(w)\, dw \quad (7)$$

where, λ_{ue} represents penalty coefficient for the wind generator in case of under estimation. $f_w(w)$ is wind powered generator's wind power probability density function (PDF) [19]. P_{ra} denote the rated power and P_{av} represents the utilizable power from the wind powered generator. Fourth term of the F_W is over estimation case. Formulation of this case is expressed in Equation (8) [15].

$$C_{oe}(P_{Wav} - P_W) = \lambda_{oe} \int_{0}^{P_{av}} (P_W - w) f_W(w)\, dw \quad (8)$$

where, λ_{oe} represents penalty coefficient for the wind generator in case of over estimation [15].

B. Emission Cost

Emission is the one of the most important concern for public since increase of industrialization accelerating the global warming. Electricity market have an undeniable share in global warming. Thermal generation units exhaust gases such as sulfur oxide (SOX) and Nitrogen oxide (NOX). These gases are harmful for the environment. Equation (9) can be used to minimize the emission in thermal units [20].

$$E = \sum_{i=1}^{N_{ÜB}} 10^{-2} (P_{Gi}^2 \gamma_i + P_{Gi} \beta_i + \alpha_i) + (w_i e^{\mu_i P_{Gi}}) \quad (9)$$

where, E is emission value of ith generator, γ, β, α, w and μ are the emission coefficients [20]. This emission value added to the objective function which is given in Equation (4) to calculate the emission cost. Emission cost function is given in Equation (10) [20].

$$F_{EW} = F_W + \lambda_E(E) \quad (10)$$

where, λ_E is penalty coefficient. λ_E is used to prevent functions from dominating one another.

III. VORTEX SEARCH ALGORITHM

Vortex search algorithm (VSA), is a heuristic algorithm developed in 2015 [21]. VSA is an artificial intelligence based heuristic algorithm. Main logic of the algorithm is finding the optimal solution in a two dimensional particle space. Developers of the algorithm are inspired by the nature events. The flow chart for the VSA-OPF is given in Figure 1.

VSA uses interwoven circles to find the solution. Initial circle is created before the iteration process. Equation (11) is used to find the center point of the initial center (μ_0) [21].

$$\mu_0 = \frac{\text{upper limit} + \text{lower limit}}{2} \quad (11)$$

where, upper and lower limits are the maximum and minimum boundaries of the problem. In addition to this, radius of the initial center must be found. Initial radius should be selected as big as possible. The weak locality is beneficial at the beginning of the program. If the initial circle's radius is chosen long enough, the algorithm can search larger space. Thus, possibility of finding the best solution is increases. Equation (12) is used to find the initial radius [21].

$$r_0 = \frac{\max(\text{upper limit}) + \min(\text{lower limit})}{2} \quad (12)$$

After the creation of the initial circle, first step is creating candidate solutions ($C(s)$). The Gaussian density function is used to create the candidate solutions. These solutions sometimes might be created outside of the limits. If these solutions are outside the boundaries, they can be shifted in to the space by using Equation (13) [21].

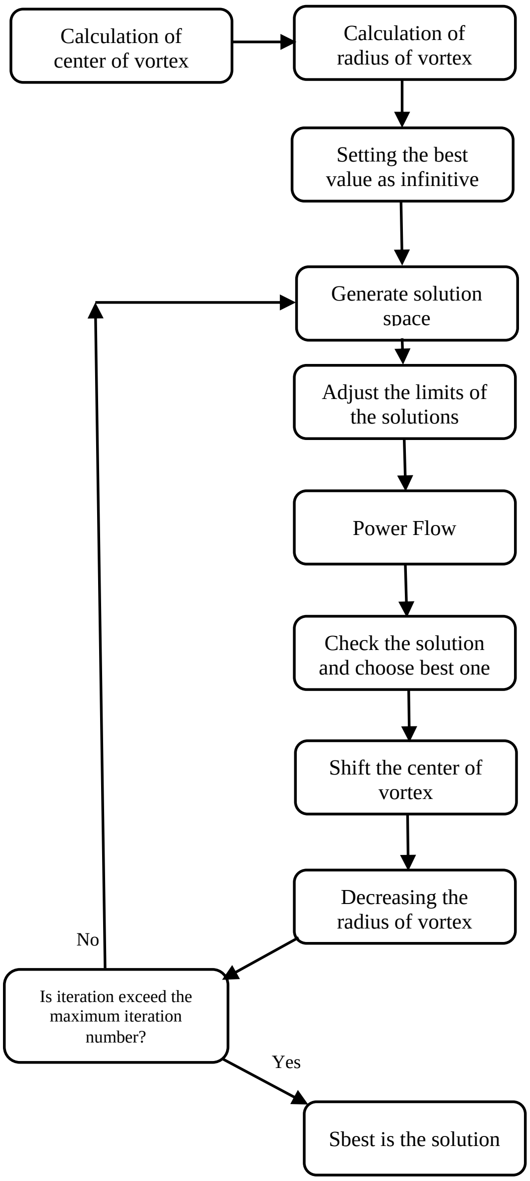

Figure 1. Flow Chart of VSA-OPF

$$C(s) = \text{rand}(\text{upper limit} - \text{lower limit}) + \text{lower limit} \quad (13)$$

where, rand is a random number between zero and one. Radius of circle is decreased by the algorithm in every iteration to converge to the best solution by using inverse of the gamma function. Function of this decrement is given in Equation (14) [21].

$$r_i = \rho_0 \left(\frac{1}{x} \right) \text{gammaincinv}(x, a_i) \quad (14)$$

where, ρ_0 represents the variance of the distribution, a_i represents the coefficient which adjust the resolution of the search and i represents the iteration number. Coefficient a_i is adjusted to 1 at starting point of the iteration to be sure that algorithm searches the all search space in iteration one. This coefficient is calculated by using Equation (15) for next iterations [21].

$$a_t = a_o - \frac{t}{\text{MaxItr}} \quad (15)$$

In addition to this, center point of the circle is shifted to the best solution to approach the optimal solution.

IV. RESULTS

Results are obtained in simulation environment by using 30 bus test system of IEEE. Test system consist of 6 thermal generation units, 41 branches, 4 transformers and shunt VAR compensators. Generators are located at bus 1, 2, 5, 8, 11 and 13. In this study, a different number of thermal generation units are converted into the WECS for each case. Real power demand is 2.834 p.u., reactive power demand is 1.262 p.u. and the base MVA value is chosen 100. VSA based OPF is solved for three different cases. First, one of six thermal generators converted to wind farm. Number of wind farms are increased to three for case 2 and increased to 5 for case 3.

A. Case 1: One Wind Powered Generator

Classical 30 bus test system of IEEE has 6 fossil fueled generators. For case 1, one of these generators converted to wind farm. This wind farm has 15 wind powered turbines and rated output power of these turbines is 2 MW. Results for the case 1 are given in Table 1.

The best cost result for the classical 6 thermal generation case is 797.270 $/h [22]. In the case 1, cost is decreased to the 752.7190 $/h by using 5 thermal generators and 1 wind farm. In other words, cost is decreased by approximately 5.5%.

These results indicate that at least one wind powered generator can decrease the costs. In addition to this, decrement of fossil powered generators provides low emission. Figure 2 shows the convergence characteristic for the case 1.

Table 1. Obtained results for the case 1

Parameters	Results
P_{G1}	161.2804 MW
P_{G2}	31.51695 MW
P_{G3}	34.2404 MW
P_{G4}	14.8497 MW
P_{G5}	23.5175 MW
P_W	25.6682 MW
V_1	1.0481 p.u.
V_2	1.0324 p.u.
V_3	0.9857 p.u.
V_4	1.0000 p.u.
V_5	1.0232 p.u.
V_W	1.0375 p.u.
Cost	752.7190 $/h
P_{loss}	7.6734 MW
Emission	0.2079 ton/h

B. Case 2: Three Wind Powered Generator

In this case, 3 generators of the IEEE 30 bus test system converted to wind farms. By this way, test system has 3 wind farms and 3 thermal generators. Each wind farm has 15 wind turbines. Each wind turbine's rated output power is 2 MW. The obtained results for case 2 are given in Table 2. Convergence characteristic of VSA based OPF for case 2 is given in Figure 3.

As seen in Table 2, fuel cost is 639.6443 $/h which is better than case 1 and the emission is 0.1724 ton/h also better than emission result of case 1. According to results of case 2, it is obvious that the more wind farms ensure lower cost and lower emission as well.

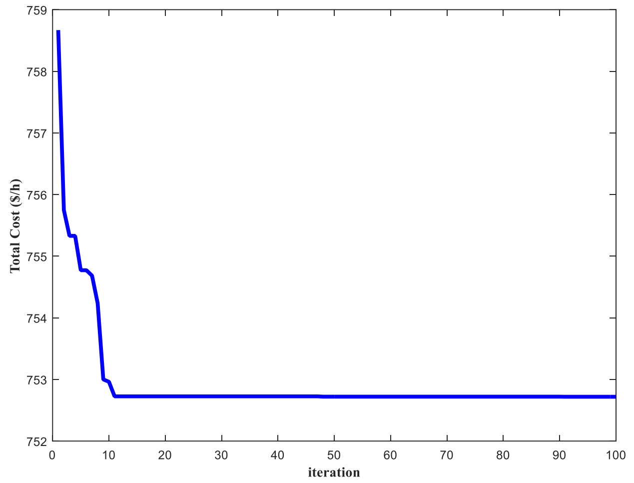

Figure 2. Convergence graph of the case 1

Table 2. Obtained results for the case 2

Parameters	Results
P_{G1}	147.667 MW
P_{G2}	45.3038 MW
P_{G3}	28.1768 MW
P_{W1}	23.4438 MW
P_{W2}	24.0432 MW
P_{W3}	22.0532 MW
V_1	1.0478 p.u.
V_2	0.9936 p.u.
V_3	1.0063 p.u.
V_{W1}	0.9973 p.u.
V_{W2}	1.0294 p.u.
V_{W3}	0.9906 p.u.
Cost	639.6443 $/h
P_{loss}	7.2887 MW
Emission	0.1724 ton/h

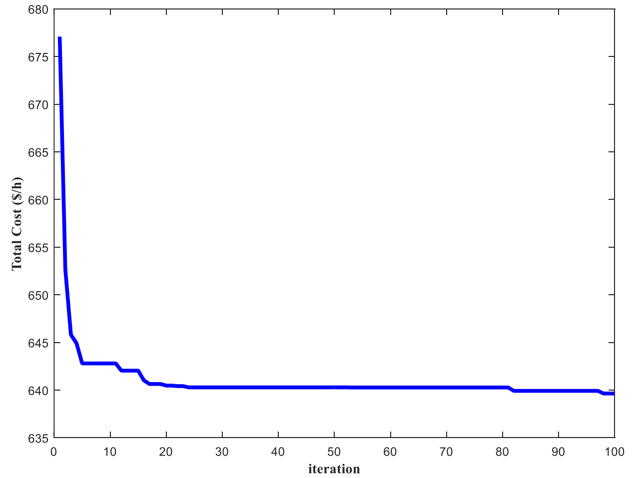

Figure 3. Convergence graph of the case 2

C. Case 3: Five Wind Powered Generator

For case 3, all of the thermal generators except the slack bus generator converted into the wind farms. Each wind farm has 15 wind powered turbines and each turbine's rated output power is 2 MW. The obtained results of case 3 are given in Table 3. Figure 4 illustrates the convergence graph of VSA for total cost in case 3.

Table 3. Obtained results for the case 3

Parameters	Results
P_{G1}	154.8224 MW
P_{W1}	26.7678 MW
P_{W2}	28.0511 MW
P_{W3}	27.0752 MW
P_{W4}	27.5179 MW
P_{W5}	26.4063 MW
V_1	1.0222 p.u.
V_{W1}	0.9814 p.u.
V_{W2}	0.9709 p.u.
V_{W3}	0.9892 p.u.
V_{W4}	1.0315 p.u.
V_{W5}	0.9622 p.u.
Cost	535.3509 $/h
P_{loss}	7.2410 MW
Emission	0.1718 ton/h

The best cost result for the case 3 is 535.3509 $/h which is lower than case 2 and case 1 as well. In addition, emission and power loss values are better than case 2 and case 1. These results shows that the increment of the wind farms are provided better results. If only wind farms are used, the costs and emission can be reduced the most.

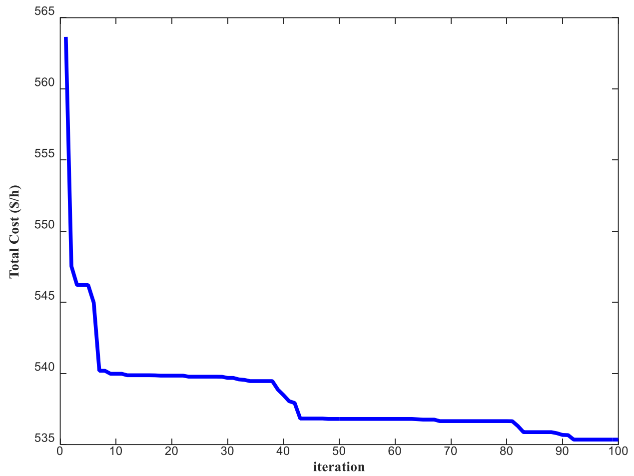

Figure 4. Convergence graph of the case 3

V. CONCLUSION

In this study, OPF problem is solved for three cases by using VSA. Cases are structured by converting different numbers of thermal generators to the WECS. In the first case, one of six thermal generators converted to WECS and results are obtained according to this condition. Results show that, total fuel cost is minimized to the 752,7190 $/h. This value is lower than the six thermal generators total cost. In addition to this, emission value is found as 0.2079 $/h. Wind farms are increased to three for case 2. In case 2, total fuel cost is decreased to 639.6443 $/h and emission is minimized to 01724 ton/h. In case 3, wind farm number is increased to five. The obtained results show that the optimal total cost is 535.3509 $/h and emission is 0.1718 ton/h. The obtained results show that the number of WECS effects the cost and emission. It is found that the higher number of WECS, the lower the cost and emission. Usage density of WECS should be increased to decrease the fuel costs and emission values.

However, as shown in Figure 3 and Figure 4, even if the number of wind farms are increased, cost is not greatly reduced because of the saturation. This saturation is caused by the nominal power of the wind powered generator. In addition to this, it can be seen in Figure 4, the algorithm has difficulty in finding the best cost for case 3. But, for case 1 and 2 best cost results found in earlier iterations. Whole results show that to get better emission and cost results, not only number of wind farms but also nominal power of wind powered turbines should be increased.

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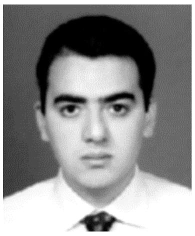

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