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Optimal Power Flow with Wind Turbine and Thyristor-Controlled Series Compensator Based on Particle Swarm Optimization

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Abstract
Increasing the penetration of Renewable Energy Sources (RES) into power systems created challenges and difficulties in the management of power flow since RES have variable power production based on their sources, such as Wind Turbines (WT), which depend on the wind speed. This article used Optimal Power Flow (OPF) to reduce these difficulties and to explain how the OPF can manage the power flow over the system, taking different cases of WT power production based on the different wind speeds. It also used Fixable AC Transmission (FACT) devices such as Thyristor-Controlled Series Compensators (TCSC) to add features to the controllability of the power system. The OPF is a non-linear optimization problem. To solve this problem, the artificial intelligence optimization technique is used. Particle Swarm Optimization (PSO) has been used in the OPF problem in this article. The Objective Functions O.F. discussed here are losses (MW), Voltage Deviation VD (p.u.), and thermal generation fuel Cost ($/h). This article used the wind turbine bus magnitude voltage and the reactance of TCSC as a control variable in OPF. To test this approach, the IEEE 30 bus system is used.

Keywords
Optimal Power Flow, Wind Turbine, Thyristor-Controlled Series Compensator, TCSC, Particle Swarm Optimization.

I. Introduction

Wind Turbines (WT) are one of the most widely used Renewable Energy Sources (RES) in recent years., so incorporating WT with power systems will reduce emissions and fuel costs. The energy production of WT is dependent on the wind speed; the nature of the wind speed is variable and intermittent. Consequently, since the nature of wind speed, the integration of WT with power systems has become complicated and faces many challenges [1]. The Optimal Power Flow (OPF) represents a significant tool to optimize the performance of the power system, like the production of generators and their voltages to achieve minimum cost generation, active power losses, or other objective functions [2]. The Thyristor Controlled Series Compensator (TCSC) is a Fixable AC Transmission (FACT) device that offers the flexibility to manage the power flow in lines and adjust the reactance of lines; therefore, adding the TCSC to the system is a decent addition to controlling power systems [3]. A lot of researchers investigate the combination of OPF, WT, and TCSC with power systems. Combining stochastic WT power with a power system by using the Weibull Probability Distribution Function (PDF) for forecasting the output power of WT with a differential evolution algorithm is adopted to handle various constraints [4]. Model AC-OPF using various types of generation units (thermal, wind, solar, and tidal) with different objective functions (generation cost, active power losses, voltage deviation, stability, and contingency) and solving optimization problems by the symbiotic organisms search algorithm [5]. The authors in studies [6–9] apply various techniques to solve OPF issues with the modified IEEE 30 bus test system, the Aquila Optimizer (AO) technique to reduce the total cost of operation, and the hybrid algorithm phasor particle swarm optimization and gravitational search (PPSOGSA) applied to reduce the generation cost with active power generation and voltage magnitude as control variables. The Modified Turbulent Water Flow-based Optimization (MTFWO) and the White Shark Optimizer (WSO) algorithms use power output from renewable sources as a dependent variable and voltage at the bus as a control variable. In [10], the authors propose a hybrid decomposition-based multi-objective evolutionary algorithm (MOEA) to solve the OPF problem with RES uncertainties. This proposed algorithm is used to minimize various objective functions (total cost, total emission, active power loss, and voltage magnitude deviation) and is tested with standard IEEE 30, 57, and 118-bus test systems. To achieve reactive power management, minimize power losses, and enhance the voltage profile the authors in [11] introduce a gravitational search algorithm (GSA) for incorporating TCSC with power systems. The Salp Swarm Algorithm (SSA) is proposed in [12] for solving OPF in power systems by incorporating TCSC. This approach was validated and tested on IEEE-30 bus systems to determine optimal control variables (generator bus power, voltages, and tap changer transformer ratios). Using the Grey Wolf Algorithm (GWA) to optimize tuning for control variables with a combination of the WT and TCSC with power systems to reduce fuel cost, real power losses, carbon emissions, and voltage deviation, this approach was validated with the IEEE 57 bus test system under normal and contingency conditions [13]. The study's authors [14] solve OPF in power systems with RES and FACTS with four new optimization algorithms Slime Mould Algorithm: Artificial Ecosystem-based Optimization, Marine Predators Algorithm, and Jellyfish Search. The authors of the study [15] and [14] introduce the History-based Adaptive Differential Evolution (SHADE) and Enhanced Hunter-Prey Optimization (EHPO) methods for solving the OPF with stochastic wind power and FACTS, considering thermal generation, direct wind power cost, penalty cost, and reserve cost. In [16], the authors use the Chaos Game Optimization (CGO) algorithm to solve the OPF problem in power systems for objective functions (generation costs, emissions, active power loss, voltage deviation, and enhancing voltage profiles), the FACTS and RES integrated with the IEEE 30 bus system, the RES taken as dependent variables, and probabilistic models.

This article aims to establish an appropriate power system approach that integrates power production from WT by investigating different features of OPF with WT and TCSC. The reactance of the TCSC is taken as a control variable; the first case in this article integrates the TCSC with the power system, and the system is managed by the PSO algorithm. The following case discusses integrating the WT with the power system, and the last case integrates the WT and the TCSC with the power system. The last two cases discuss a crucial point, when the speed of wind is high (like a storm), the WT produces the rated power and the system has its base load, in what way can the algorithm manage the generation of the other generators to solve this situation? On the contrary, the second crucial point is when the speed of wind is lower than in the first case and the WT output power is reduced, so the PSO how can manage the system. This article emphasizes the ingenuity of the algorithm to manage the system and optimize it for the minimum objective function. The rest of the paper is organized as follows: in section II. problem formulation of OPF is explained. The PSO algorithm and its steps are organized in section III. . Section IV. shows the modelling of WT and TCSC that is used in this paper. The last two sections are the results and the conclusion respectively.

II. Problem Formulation

Essentially, the OPF is an optimization problem to find optimal operation parameters for economic dispatch, reducing power losses, or enhancing the voltage profile [17]. Equations (1) to (3) describe the problem:

$$minimum\ f(x,u) \tag{1}$$

Subject to

$$g(x,u) = 0 \tag{2}$$

$$h(x,u) \leq 0 \tag{3}$$

where f is the objective function, g and h are equality and inequality constraints, respectively. x is a state variable vector consisting of active power generation at slack bus P_{G1}, generator reactive power outputs Q_G, and load-bus voltage V_L. u is a control variable vector such as active power generation of generators except for the slack bus, voltage magnitude of generators including the slack bus, tap setting of transformers, and injected reactive power by capacitor banks.

A. Objective Functions

Three objective functions have been discussed in this article with its Equations [18], as follows:

1) Total Active Power Losses

$$f_1 = P_{loss} = \sum_{k=1}^{NE} G_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij}) \tag{4}$$

Here P_{loss} is the active power loss of the network, V_i and V_j are the bus voltage magnitude; θ_{ij} is the difference in the voltage angle of buses, G_{ij} is transmission line conductance between bus i and j, and NE refers to the system branches.

2) Voltage Deviation

$$f_2 = VD = \sum_{k=1}^{NL} |V_k - 1| \tag{5}$$

Where VD represents the sum of voltage deviation, NL is the number of load buses, and V_k is the voltage magnitude of the load bus.

3) The Fuel Cost

$$f_3 = cost = \sum_{i=1}^{NGT} a_i + b_i P_{Gi} + c_i P_{Gi}^2 \tag{6}$$

Where a_i, b_i, and c_i are the cost coefficients of the thermal generator, P_{Gi} real power generation, and NGT is the number of thermal generators.

B. Constraints

1) Equality Constraints

The typical load flow represents the equality constraints [18]:

$$P_{Gi} - P_{Li} = V_i \sum_{j=1}^{NB} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \tag{7}$$

$$Q_{Gi} - Q_{Li} = V_i \sum_{j=1}^{NB} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \tag{8}$$

Where P_{Li}, Q_{Li} are active and reactive load power of bus i, G_{ij}, B_{ij} are conductance and susceptance of line ij, NB the number of buses.

2) Inequality Constraints

- Based on control variables limits

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max},\ i = 1, 2, \ldots, NG \tag{9}$$

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max},\ i = 1, 2, \ldots, NG \tag{10}$$

$$T_i^{\min} \leq T_i \leq T_i^{\max},\ i = 1, 2, \ldots, NT \tag{11}$$

$$Q_{Ci}^{\min} \leq Q_{Ci} \leq Q_{Ci}^{\max},\ i = 1, 2, \ldots, NC \tag{12}$$

- Based on state variables limits

$$V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max},\ i = 1, 2, \ldots, NL \tag{13}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max},\ i = 1, 2, \ldots, NG \tag{14}$$

$$P_{Gs}^{\min} \leq P_{Gs} \leq P_{Gs}^{\max} \tag{15}$$

Where T_i, Q_{Ci}, P_{Gs} are transformer tap setting, injected reactive power by capacitor banks, and generator power of slack power respectively. NG, NT, and NC are the number of generators, the number of tap-changing transformers, and number of compensators, respectively. min and max refer to the lower and upper limits. s refer to the slack bus.

III. PARTICLE SWARM OPTIMIZATION PSO

The PSO is stimulated by bird flocking or fish schooling when searching for food; each particle represents a candidate solution, and these particles, with a random velocity, fly over the search space, each particle modifies its position based on its own experiences as well as those of its nearby particles [19]. The best position is called the individual best position, while the global best position is the best value over all particles. Tow characteristics each particle has, a velocity and a position based on objective function each particle remembers the best position if this discovered path is well for the food source, so other particles will get this information to get a better position. Equations (16) and (17) explained the velocity updating and the position updating [20]:

$$V_{id}^{t+1} = V_{id}^{t} \times W + C_1 \times R_1 \times \left(P_{bestid}^{t} - X_{id}^{t}\right) + C_2 \times R_2 \times \left(g_{bestid}^{t} - X_{id}^{t}\right) \tag{16}$$

$$x_{id}^{t+1} = x_{id}^{t} + V_{id}^{t+1} \tag{17}$$

Where $V_{id}^{t+1}, V_{id}^{t}, x_{id}^{t+1}$, and x_{id}^{t} are the updated and current velocity; and the updated and current position of the particle, respectively. W is inertia weight; C_1, C_2 are positive constants R_1, R_2 are random numbers between [0,1]. The PSO algorithm can be described as following steps:

- Step 1: Initialize the position of the swarm (x_{id}^{0}).
- Step 2: Initial Velocity (V_{id}^{0}).
- Step 3: Find the initial best local position (P_{bestid}^{0}).
- Step 4: Find the global best position (g_{bestid}^{0}).
- Step 5: Updating the iteration $(t = t + 1)$.
- Step 6: Updating the velocity (V_{id}^{t}).
- Step 7: Updating the position (x_{id}^{t}).
- Step 8: Individual best position updating (P_{bestid}^{t}).
- Step 9: Updating the global best position (g_{bestid}^{t}).
- Step 10: Stopping criteria when reaching the maximum number of iterations.

Fig. 1 explains the flow chart of the algorithm.

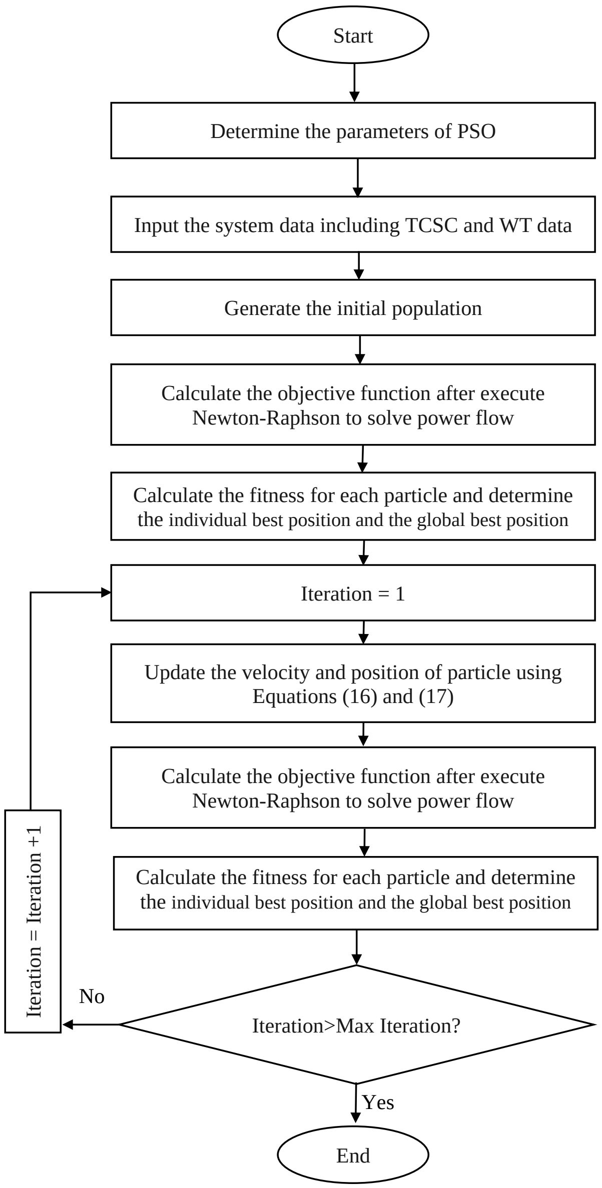


Fig. 1. The flow chart of PSO.

IV. The WT and TCSC Modeling

A. The WT Modeling

Simulating the wind speed of any location gives a crucial feature in the expected output power of a wind farm, and this is useful for many applications such as the operation and control of power systems or economic dispatch even unit commitment. The wind speed in nature is variable, so it can be estimated by its probability, the Weibull PDF is used in this article:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{18}$$

Where $f(v)$ is the probability of wind speed, v is the wind speed, k is the shape parameter and c is the scale parameter. Due to its adaptability and ability to characterize the distribution of wind speeds, the Weibull PDF is commonly used in wind speed applications. The common feature of such PDFs that leads to parameter variation and the possibility of error is data error. This error can impact the parameter estimation of the Weibull PDF and thus affect the distribution of probability, which leads to deflection in the application. The power curve of WT in Fig. 2, explains the relationship between the output electrical power and wind speed, by the power curve provided by the manufacturer, the output power of a WT for a specific speed is calculated with 19.

$$P_w(v) = \begin{cases} 0, & for\ \ v < v_{in}\ and\ v > v_{out} \\ P_{wr}\left(\frac{v-v_{in}}{v_r-v_{in}}\right), & for\ \ v_{in} \le v \le v_r \\ P_{wr}, & for\ \ v_r < v \le v_{out} \end{cases} \tag{19}$$

Where P_w is generated power, P_{wr} is the rated power of the WT, v_{in} is the cut-in speed, v_r is the rated wind speed, and v_{out} is the cut-out speed.

This model of WT is simple and suitable for OPF and power flow analysis applications. This model focuses on the output power concerning the wind speed; the bus that consists of the WT takes the form of a PV bus (voltage control bus); the voltage of WT takes as a control variable; and the power of the WT can be calculated by (19). The parameter of wind speeds of WT is identified using the power curve of WT; when the wind speed is less than the cut-in speed, the output power will be zero; when the wind speed is between the cut-in and rated speeds, the output power can be calculated using the second term of (19); and if the wind speed is higher than the rated power, the output power will be the rated power of WT.

B. Modeling of TCSC

TCSC consists of a thyristor-controlled reactor TCR and is paralleled with a fixed capacitor bank, as shown in Fig. 3a. When the firing angle of the thyristor changes the total reactance of TCSC, it can work in two modes. The first one is capacitor reactance, as shown in Fig. 3b; the second one is inductance reactance, as shown in Fig. 3c. In this article taking the reactance of TCSC as a control variable [1, 13].

$$X_{TCSC}^{\min} \le X_{TCSC} \le X_{TCSC}^{\max} \tag{20}$$

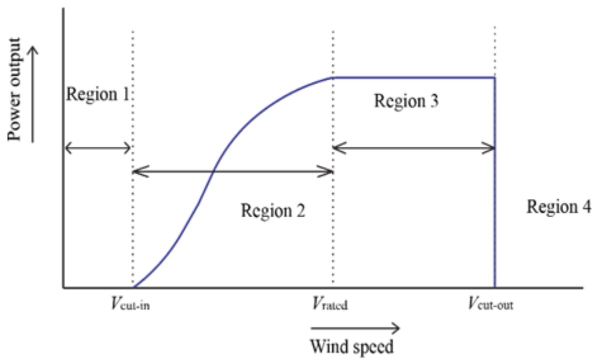


Fig. 2. The power curve of WT.

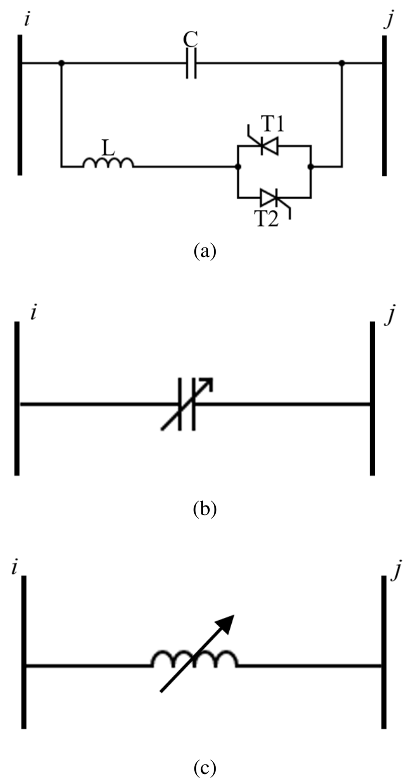


Fig. 3. TCSC diagram and modes: (a) The diagram of TCSC, (b) The inductance mode of TCSC, (c) The capacitance mode of TCSC.

V. Simulation Results

Three Objective Functions (OF); active power losses (MW), voltage deviation (p.u.), and generation fuel cost ($/h) have been used to apply the OPF with the IEEE 30 bus system that is shown in Fig 4. This system has 24 control variables (5 generators active power, 6 generator magnitude voltage, 4 transformer tapping and 9 shunt injection capacitance).

TABLE I.
The Lower and Upper Limits of Generators

Control var.	Lower limits MW	Upper limits MW
P_2	20	80
P_5	15	50
P_8	10	35
P_{11}	10	30
P_{13}	12	40

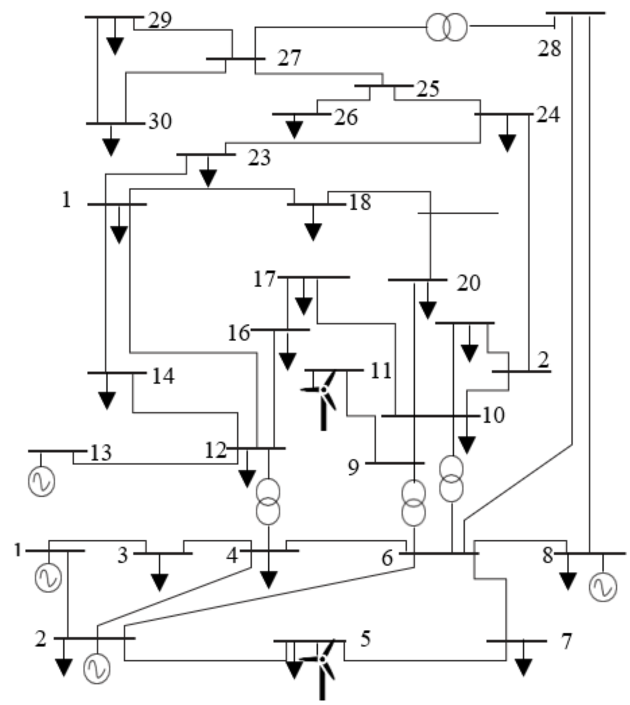


Fig. 4. IEEE 30 bus system with WT at bus 5 and bus 11.

The lower limits and upper limits of generators are shown in Table I, the limits of generator voltage are (0.95, 1.1) p.u. for all generators, the limits of transformer settings are (0.90, 1.1) p.u. for all transformers, and the limits of injected reactive power by capacitor banks are (0, 5) MW for all capacitor banks. The proposed algorithm used the Wind Turbine bus magnitude voltage and TCSC reactance as control variables. The software that used to execute this approach is MATLAB 2019a.

The PSO parameters used in this article are as follows: the maximum number of iterations is 100 iterations, the number of particles is 100 particles, and the inertia weight W range is (0.4, 0.9), $C_1, C_2 = 2$. Table II shows the results of OPF without WT and TCSC.

TABLE II.
THE OPTIMAL SETTING FOR THE CONTROL VARIABLE

Control var.	Base case	OF losses	OF VD	OF Cost
P_2	80	80	80	49.211
P_5	50	50	50	21.35
P_8	20	35	10	21.66
P_{11}	20	30	29.9	10
P_{13}	20	40	40	12
V_1	1.05	1.100	1.015	1.100
V_2	1.04	1.100	1.016	1.038
V_5	1.01	1.082	1.067	1.064
V_8	1.01	1.089	1.007	1.100
V_{11}	1.05	1.100	1.009	1.100
V_{13}	1.05	1.100	1.000	1.100
T_{11}	1.078	0.986	1.019	1.100
T_{12}	1.069	1.100	0.900	1.100
T_{15}	1.032	1.100	0.961	1.099
T_{36}	1.068	1.015	0.966	1.100
QC_{10}	0	5	4.33	5
QC_{12}	0	5	2.64	0
QC_{15}	0	5	5	0
QC_{17}	0	5	3.27	5
QC_{20}	0	3.971	4.7	0.337
QC_{21}	0	5	5	5
QC_{23}	0	5	0	5
QC_{24}	0	5	5	5
QC_{29}	0	5	5	5
Total losses	5.842	2.973	5.274	9.077
VD	1.1567	1.451	0.1237	0.724
Gen. cost	901.94	967.41	944.51	800.44

Three cases have been used in this article, as follows:

A. Case 1: OPF With TCSC Based on PSO Technique

The TCSC is installed at the line (9-11) by trial and error. The adjustment range of the TCSC reactance is from -0.7 to 0.3 from the line reactance. The reactance of the line (9-11) is 0.2 p.u., so the range of TCSC reactance X_{TCSC} is (-0.14 p.u., 0.06 p.u.). The results of this case are shown in Table III. The results show the base case control variable of the IEEE 30 bus system and optimal control variables of the minimum objective function (total active power losses, voltage deviation, and generation cost) based on the PSO algorithm.

The results show the total active power losses, voltage deviation, and generation cost are reduced compared with the base case results. Therefore, it can be concluded that the addition of TCSC and applied PSO improves the power system's performance. Fig. 5 explains the convergence of an algorithm for those three objective functions after 100 iterations.

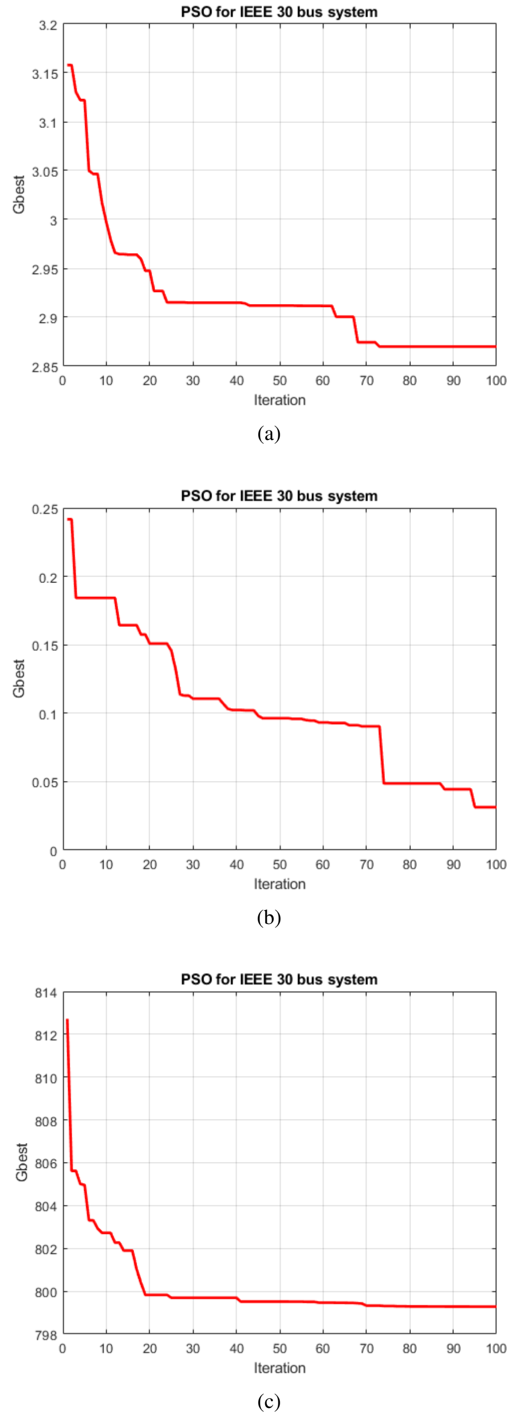


Fig. 5. For case 1: (a) Total active power losses objective function, (b) Voltage deviation objective function, (c) Generation cost objective function.

TABLE III.
THE OPTIMAL SETTING OF CONTROL VARIABLES FOR CASE 1.

Control var.	Base case	OF losses	OF VD	OF Cost
P_2	80	80	20	48.69
P_5	50	50	50	21.32
P_8	20	35	10.04	21.19
$P_1$1	20	30	18.47	11.74
$P_1$3	20	40	40	12
V_1	1.05	1.100	1.024	1.100
V_2	1.04	1.100	1.003	1.035
V_5	1.01	1.089	1.014	1.061
V_8	1.01	1.100	1.008	1.100
V_{11}	1.05	1.099	1.100	1.100
V_{13}	1.05	1.100	0.995	1.100
T_{11}	1.078	0.960	1.073	1.069
T_{12}	1.069	1.100	0.900	0.900
T_{15}	1.032	1.021	0.963	1.016
T_{36}	1.068	1.015	0.972	0.983
QC_{10}	0	5	3.317	5
QC_{12}	0	5	5	5
QC_{15}	0	5	4.663	5
QC_{17}	0	5	0	5
QC_{20}	0	5	5	5
QC_{21}	0	4.989	3.585	5
QC_{23}	0	5	5	5
QC_{24}	0	5	5	5
QC_{29}	0	4.985	3.120	5
XTCSC	NA	0.04	0.06	0.06
Total losses	5.842	2.967	7.375	8.683
VD	1.1567	1.783	0.111	1.646
Gen. cost	901.94	967.39	897.19	799.29

B. Case 2: OPF With Wind Turbine WT Only Based on PSO Technique

Two wind farms were installed in the system instead of the generators at buses 5 and 11. The data shown in Table IV of WT and the Weibull PDF of wind speed is from the reference [8]. Each WT has a rated power of 3 MW, so the bus 5 wind farm rated power is 75 MW and the bus 11 wind farm rated power is 60 MW. Weibull PDFs for buses 5 and 11 are shown in Fig. 6.

TABLE IV.
WT AND PDF PARAMETERS OF THE WIND FARM

Wind farm	No. of turbines	WT speed	PDF parameters
Bus 5	25	$v_{in} = 3m/s$ $v_r = 16m/s$ $v_{out} = 25m/s$	$c = 9$ $k = 2$
Bus 11	20		$c = 10$ $k = 2$

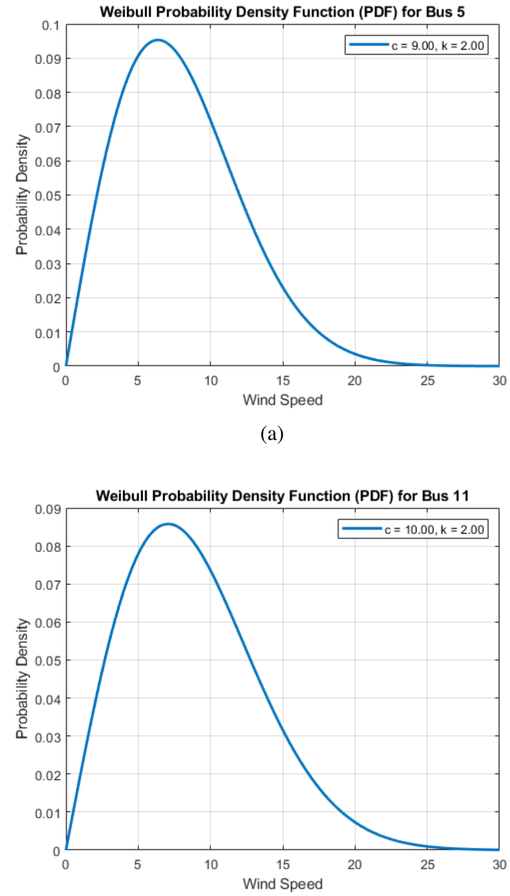


Fig. 6. (a) Weibull PDF for bus 5, (b) Weibull PDF for bus 11.

1) Case 2.1

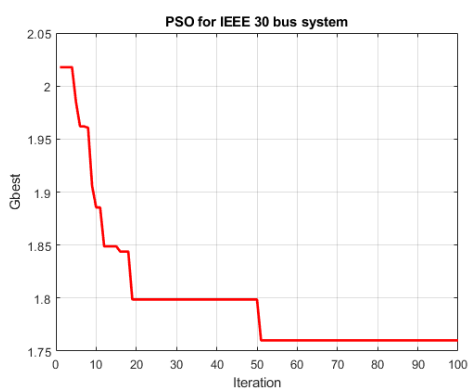
In this case, the wind farm works with full generation rated power, which means the wind speed is high at rated speed, so that the generation of bus 5 is 75 MW and for bus 11 is 60 MW. Table V shows the results of the optimal setting for the control variables and the value of each O.F of real power losses (MW), voltage deviation (p.u.), and generation cost ($/h).

From the values of the optimized objective function, can observe the enhanced results; the convergence for each objective function based on the PSO technique is clear, as shown in Fig. 7. In this case, the power of WT has been used at its rated value according to the rated wind speed. The rated power at bus 5 is 75 MW, and the rated power at bus 11 is 60 MW. This case simulates if a high wind speed occurs, like in a storm situation. This case aims to explain how the PSO algorithm can manage the system under the condition that the generation of the system is redundant compared with the total load of the system.

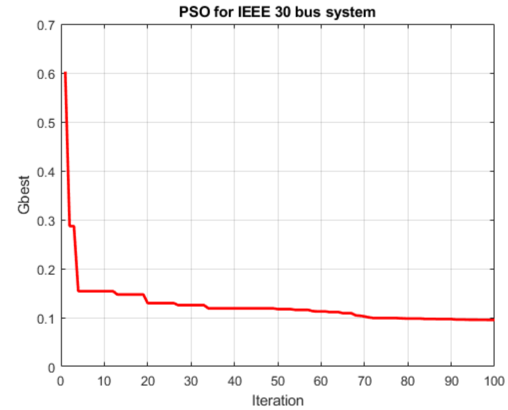
TABLE V.
THE OPTIMAL SETTING OF CONTROL VARIABLES FOR CASE 2.1.

Control var.	Base case	OF losses	OF VD	OF Cost
P_2	80	20	20.78	28.46
P8	20	35	10	10
P_13	20	40	12.54	12
V_1	1.05	1.100	1.027	1.100
V_2	1.04	1.097	1.058	1.095
V_5	1.01	1.093	0.950	1.079
V_8	1.01	1.100	01.003	1.087
V_{11}	1.05	1.100	1.099	1.100
V_{13}	1.05	1.100	0.969	1.100
T_{11}	1.078	0.966	1.100	0.984
T_{12}	1.069	1.100	0.900	1.100
T_{15}	1.032	1.025	0.945	1.098
T_{36}	1.068	1.001	0.972	0.999
QC_{10}	0	1.372	0	0
QC_{12}	0	0.166	4.656	5
QC_{15}	0	5	5	5
QC_{17}	0	5	0	2.165
QC_{20}	0	5	5	5
QC_{21}	0	5	5	0
QC_{23}	0	5	4.99	0
QC_{24}	0	5	5	5
QC_{29}	0	5	5	0
Total losses	5.842	1.845	4.424	3.427
VD	1.1567	1.757	0.11	1.15
Gen. cost	901.94	447.95	382.78	378.24

The results show how the PSO reschedules the generation of the system generators according to this situation. From the Weibull PDF for bus 5 and bus 11, as shown in Fig 6, the probability of this situation is low, so the next subcase will show the wind speed has a probability higher than this subcase to show the ability of the algorithm.



(a)



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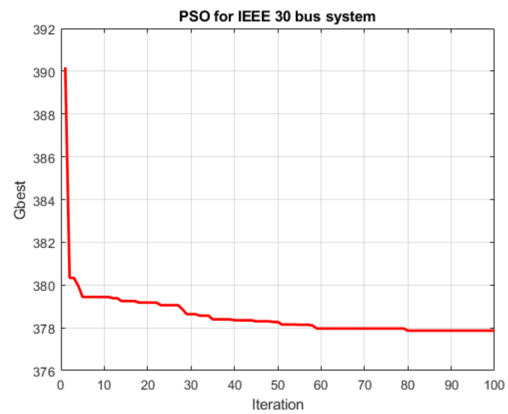


(c)

Fig. 7. For case 2.1 (a) total active power losses objective function (b) voltage deviation objective function (c) generation cost objective function.

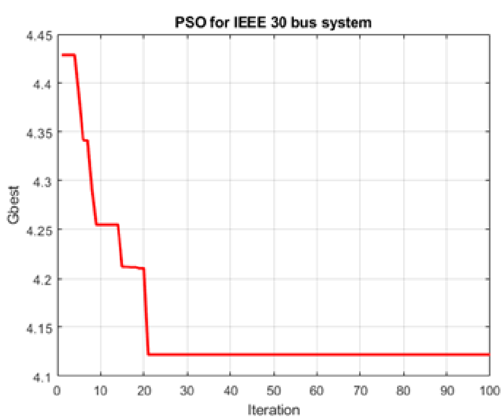
2) *Case 2.2*

The same data from the previous subcase of WT has been used in this case, but the difference here is that the generation power of the WT is not at rated power; it is taken according to the probability of wind speed. The mean wind speed of bus 5 is 7.976 m/s and 8.862 m/s for bus 11, according to 19, the power produced by bus 5 is 28.71 MW and 27.1 MW by bus 11. The results of this subcase are presented in Table VI, which explains the optimal control variables based on the PSO algorithm of each objective function of losses (MW), voltage deviation (p.u.), and fuel cost ($/h). Also, this table shows the base case of OPF. Fig. 8 shows the convergence for each of these three objective functions based on the PSO algorithm.

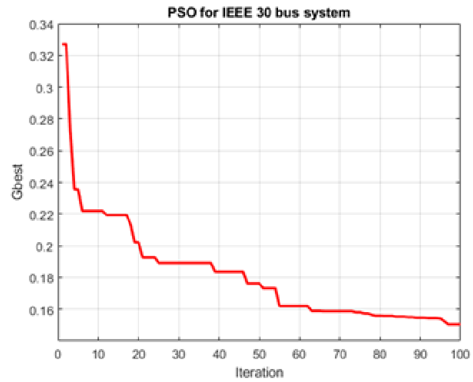
TABLE VI.
THE OPTIMAL SETTING OF CONTROL VARIABLES FOR CASE 2.2.

Control var.	Base case	OF losses	OF VD	OF Cost
P_2	80	80	80	45.45
P_8	20	35	35	13.38
P_{13}	20	40	12.39	12
V_1	1.05	1.100	1.019	1.100
V_2	1.04	1.096	1.011	1.035
V_5	1.01	1.073	1.025	1.066
V_8	1.01	1.083	0.993	1.080
V_{11}	1.05	1.100	0.998	1.100
V_{13}	1.05	1.100	1.076	1.099
T_{11}	1.078	0.947	0.994	1.100
T_{12}	1.069	1.100	0.918	0.900
T_{15}	1.032	1.046	1.100	1.031
T_{36}	1.068	0.985	0.935	0.991
QC_{10}	0	5	3.28	5
QC_{12}	0	5	0	5
QC_{15}	0	5	5	4.9
QC_{17}	0	5	0.242	5
QC_{20}	0	5	4.953	5
QC_{21}	0	5	5	0
QC_{23}	0	5	5	5
QC_{24}	0	5	3.832	5
QC_{29}	0	3.858	0	5
losses	5.842	4.213	6.638	7.580
VD	1.1567	1.683	0.128	1.514
Gen. cost	901.94	7.117	673.49	630.25

The results of optimization are less than case 2.1 because the generation is reduced and for the same base load of the system, but the results are still less than the base case of the system. These two subcases show the ingenuity of the algorithm to manage the system under different conditions.



(a)



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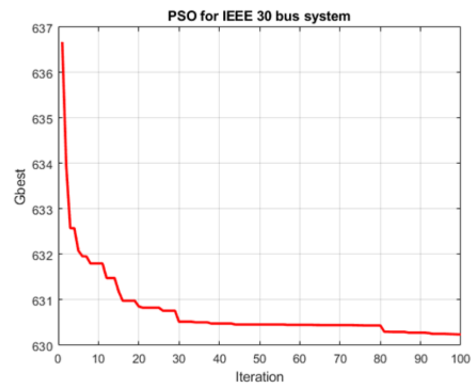


(c)

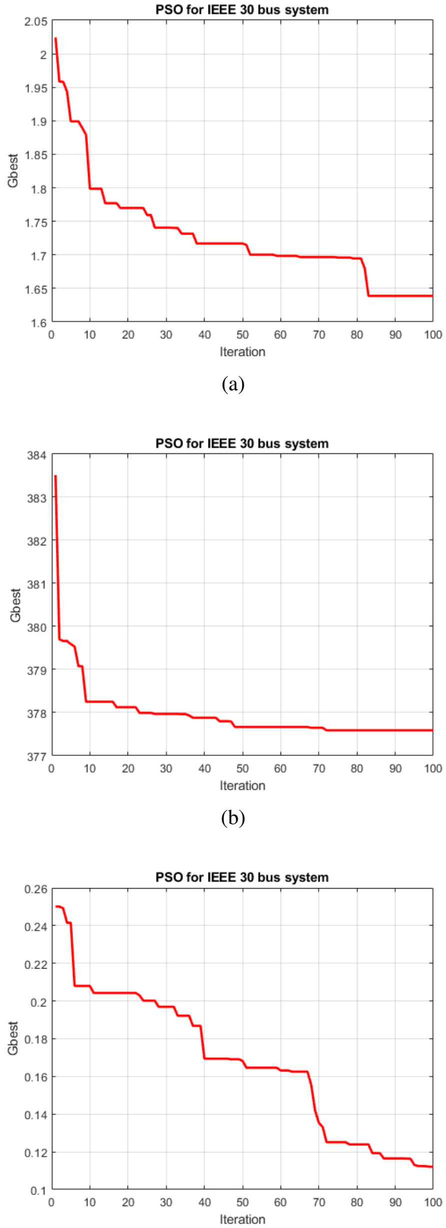
Fig. 8. For case 2.2 (a) total active power losses objective function (b) voltage deviation objective function (c) generation cost objective function.

C. Case 3: OPF with WT and TCSC Based on PSO Technique

In this case, the WT with its two subcases in (2.1 and 2.2) and TCSC reactance have been used together as a control variable in OPF for the same three O.F objective functions; losses (MW), voltage deviation (p.u.), and fuel cost ($/h). Integrating TCSC with WT provides flexibility in improving the OPF of the system as shown in the following two subcases.

1) Case 3.1

In this case, the same TCSC reactance range in the same location in case 1 and the same condition of WT rated generation power in case 2.1 have been used in this subcase. As observed from the following results in Table VII, the TCSC gives more flexibility to innovative management of the system by PSO algorithm when compared with the results of subcase 2.1. Fig. 9 shows the convergence for each objective function based on the PSO algorithm.



(a)

(b)

(c)

Fig. 9. For case 3.1 (a) total active power losses objective function (b) voltage deviation objective function (c) generation cost objective function.

The incorporation of TCSC with the WT and applying the PSO as observed from Table VII and compared with the results in 2.1, the optimization of the O.F in this case is considered much better.

TABLE VII.
THE OPTIMAL SETTING OF CONTROL VARIABLES FOR CASE 3.1.

Control var.	Base case	OF losses	OF VD	OF Cost
P_2	80	25.02	20	30.727
P_8	20	35	20.33	10
$P_{1}3$	20	40	40	12
V_1	1.05	1.100	1.005	1.100
V_2	1.04	1.100	0.993	1.089
V_5	1.01	1.093	1.085	1.073
V_8	1.01	1.100	0.95	1.070
V_{11}	1.05	1.100	1.100	1.100
V_{13}	1.05	1.100	1.049	1.100
T_{11}	1.078	1.100	1.087	0.933
T_{12}	1.069	0.900	0.900	1.100
T_{15}	1.032	0.988	1.039	1.031
T_{36}	1.068	0.988	0.949	1.005
QC_{10}	0	5	4.973	5
QC_{12}	0	0	5	0
QC_{15}	0	3.909	0.178	5
QC_{17}	0	5	0.294	5
QC_{20}	0	5	5	3.338
QC_{21}	0	3.552	5	4.876
QC_{23}	0	5	5	5
QC_{24}	0	5	5	5
QC_{29}	0	5	2.427	5
XTCSC	NA	0.14	0.04	0.06
losses	5.842	1.739	3.347	3.287
VD	1.1567	2.15	0.110	1.45
cost	901.94	448.69	413.61	377.92

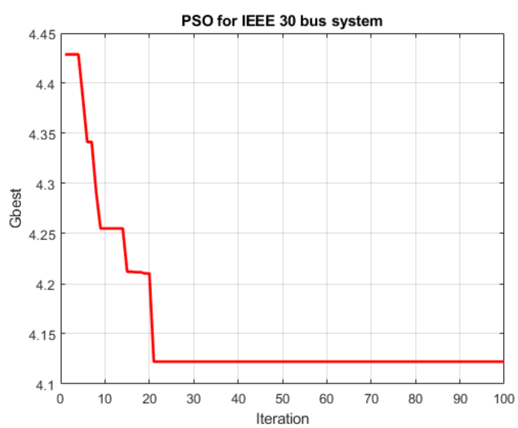
2) Case 3.2

This case is the same as the previous case but in this case, the generation of wind turbines is subject to wind speed as in subcase 2.2. By comparing the results of this case with the subcase of 2.2, the result will be improved since adding a TCSC gives more flexibility to control the system, and this is what can be observed in Table VIII. Fig. 10 shows the convergence for each objective function based on the PSO algorithm.

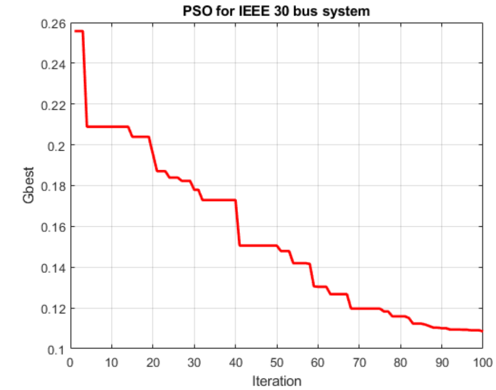
Table IX compares between case 3 in that the WT with the TCSC is better than in case 2 (without TCSC) because the TCSC improved the system performance by controlling the inductance of the line.

TABLE VIII.
THE OPTIMAL SETTING OF CONTROL VARIABLES FOR CASE 3.2.

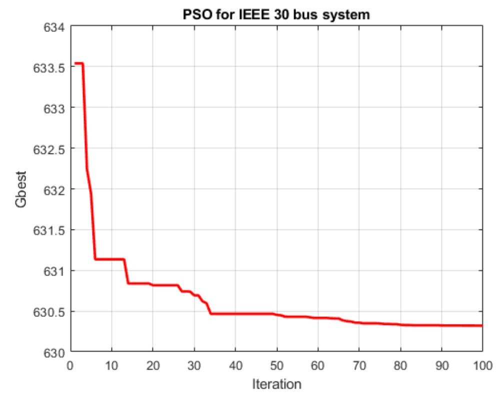
Control var.	Base case	OF losses	OF VD	OF Cost
P_2	80	80	70.6	45.52
P_8	20	35	26.53	13.77
P_{13}	20	40	40	12
V_1	1.05	1.100	1.034	1.100
V_2	1.04	1.100	0.993	1.037
V_5	1.01	1.075	1.079	1.063
V_8	1.01	1.089	0.950	1.100
V_{11}	1.05	1.100	1.094	1.100
V_{13}	1.05	1.100	1.002	1.100
$T_1$1	1.078	1.094	1.086	0.965
T_{12}	1.069	0.914	0.900	1.100
T_{15}	1.032	1.023	0.979	1.100
T_{36}	1.068	0.984	0.961	1.007
QC_{10}	0	5	5	0
QC_{12}	0	5	4.686	5
QC_{15}	0	3.255	5	5
QC_{17}	0	4.459	1.721	5
QC_{20}	0	5	5	5
QC_{21}	0	5	4.979	5
QC_{23}	0	5	5	3.43
QC_{24}	0	5	5	5
QC_{29}	0	5	4.704	5
XTCSC	NA	0.06	0.059	0.06
losses	5.842	4.206	6.259	7.573
VD	1.1567	1.781	0.114	1.196
Gen. cost	901.94	712.88	673.29	630.33



(a)



(b)



(c)

Fig. 10. For case 3.1 (a) total active power losses objective function (b) voltage deviation objective function (c) generation cost objective function.

TABLE IX.
COMPARED BETWEEN CASE 2 AND CASE 3.

	Case 2.1			Case 3.1		
	OF losses	OF VD	OF Cost	OF losses	OF VD	OF Cost
Total power losses (MW)	1.845	4.424	3.427	1.739	3.347	3.287
VD	1.757	0.11	1.15	2.15	0.110	1.45
Gen. cost ($/h)	447.95	382.78	378.24	448.69	413.61	377.92
	Case 2.2			Case 3.2		
Total power losses (MW)	4.213	6.638	7.580	4.206	6.259	7.573
VD	1.683	0.128	1.514	1.781	0.114	1.196
Gen. cost ($/h)	7.117	673.49	630.25	712.88	673.29	630.33

VI. CONCLUSION

In this article, the OPF has been presented with the WT and TCSC device based on the PSO algorithm to minimize the objective function of losses (MW), voltage deviation (p.u.), and fuel cost ($/h). The proposed approach was tested on the IEEE 30 bus system, MATLAB 2019a with the m-file script used to execute the algorithm. The results showed the algorithm's ability to improve and manage the network, its generation, and the power flow. The results also showed that adding a TCSC gives additional flexibility to control the network. Despite the challenges posed by WT with the power system, the OPF using the PSO algorithm leads to better management of power flow over the system, also the TCSC gives additional features to manage and control the power flow, as shown in the results of this article, the results of case 3 compared with results of case 2 that show the effect of adding the TCSC with WT, the TCSC gives an available to control for the line impedance that allows to manage the power flow in the line. The limitations of this approach are the time consumed by the algorithm and the data on wind speed.

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CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

ABBREVIATIONS

OPF	Optimal Power Flow
TCSC	Thyristor Controlled Series Compensator
WT	Wind Turbine
PSO	Particle Swarm Optimization
FACT	Flexible AC Transmission
OF	Objective Function

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