# Optimal Power Flow in Power System Considering Wind Power Integrated into Grid

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ABSTRACT

This paper implements a new metaheuristic, called Equilibrium optimizer (EO), to find out the optimal results for a modified Optimal Power Flow (OPF) problem considering Wind turbine (WT) located at a load node. This paper runs EO for different versions of OPF problem including a basic OPF problem without considering the contribution of any renewable energy sources, a modified OPF problem considering the presence of WT. The IEEE-30 node system and its modified versions are utilized to evaluate the effect of EO after comparison with other methods. By applying sensitivity method, node 3 and node 30 (the most unsuitable node and the most suitable node) are placed a wind turbine for using the lowest electric generation cost of TGUs. For the case without WT, EO can save a cost from 0.11% to 0.65% from other methods. For the two cases of WT placement, EO can save a cost with 0.64% and 0.63% of other methods. As a result, EO is decided a powerful novel metaheuristic for OPF problem with the trend of using renewable energies in power systems.

## 1. INTRODUCTION

Optimal Power Flow (OPF) is one of the most important problems in power system operation. The primary target associated with this problem is to reach the steady state in working process of power system in which all electrical elements in grid is operated within its limitation and the main objectives are obtained at minimum value. The process to solve the OPF problem considers each of single objective functions, namely total electricity production fuel cost belonging all thermal generating units (TGUs), total power loss, emission volume, voltage deviation and voltage improvement. In addition, the physical limitations and constraints, specifically active and reactive power of all TGUs, transformer taps, switchable capacitor banks, voltage at nodes and the transmission line capacity limitations must be all satisfied. Normally, the control variables such as power output of TGUs except for the thermal generating unit at slack node, voltage generated by all TGUs, reactive power supplied by capacitor bank and transformer taps setting must be predetermined at the beginning of the process to solve the OPF problem. After that, dependent variables such as power output belonging the TGU at slack node, voltage at load nodes, reactive power of TGUs, etc are calculated by using a tool called

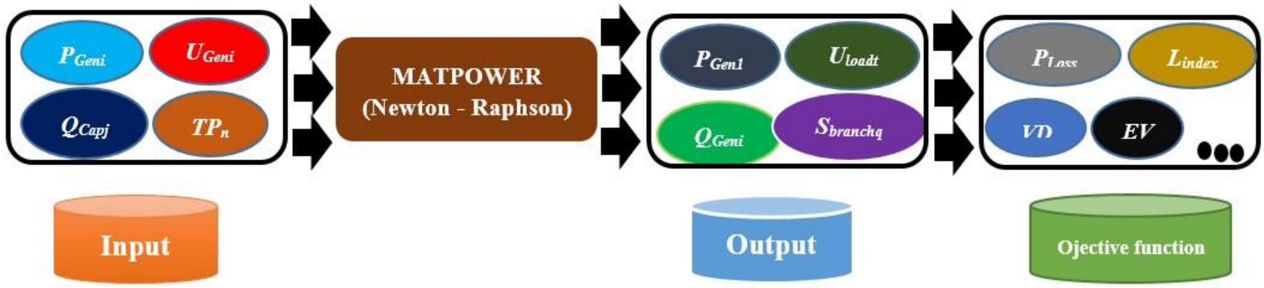

**Fig. 1. The entire process of solving the basic OPF problem.**

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Matpower. Matpower is developed based on Newton-Raphson method and this tool is also utilized widely to support the whole process of solving OPF problem. The explanation of Matpower can be viewed in Figure 1.

Figure 1 shows that the inputs of Matpower consist power output of TGUs except for the TGU at slack bus ($P_{Gen}$), voltage generated by TGUs ($U_{Gen}$), reactive power supplied by capacitor banks ($Q_{Cap}$) and transformer tap positions (*TP*). These inputs are also considered as the control variables for optimal algorithm. After being selected optimally by optimal algorithm these control variables are utilized by Matpower to calculate the other dependent variables at its output such as power output belonging the TGU at slack node ($P_{Gen1}$), voltage at load nodes ($U_{Load}$), reactive power of TGUs ($Q_{Gen}$) and apparent power sent though transmission line ($S_{Branch}$). Next, the value belonging each single objective function such as total power loss ($P_{Loss}$), voltage deviation (*VD*), voltage enhancement index (*L index*), emission volume (*EV*), etc will be determined based on dependent variables given by inputs of Matpower, control variables and grid parameters.

The high significant role of OPF have attracted lot of attention from researchers therefore there were plenty of studies proposed to solve this problem [1-17]. OPF problem is applied for transmission power networks and the type of power sources are not considered in particular but normally the main power source in this case is thermal generating units (TGUs) only. The main duty of the problem is to find active power generation of power plants, voltage at power plants, generation of shunt capacitors and tap position of transformers. Others parameters are reached after running Matpower program [18-19]. In modified OPF problem with the integration of wind farms, there is a difference of power source. Wind farms are added and placed at nodes where loads are working. Normally, TGUs supply enough power energy to loads, however, as wind farms placed in transmission networks, they can supply a part of power to loads or full power to load or higher than the amount of power required by loads [20]. In case the power supplied by wind farms is less than load demand at a particular node, the remaining power required by load will be provided by TGUs. For another case that power supplied by wind farms is higher than load requirement, the spare power will be injected back to the grid and transferred to the other loads where wind farm is not located. As considering the modified OPF problem, we must determine two more control variables for each wind turbine placed in transmission network such as power output of wind turbine ($P_{WT}$) and its power factor ($\theta_{WT}$). In case that the number of wind turbine needed to integrate with transmission network is *n*, so the number of additional control variables must be *2n*. Both control variables in conventional OPF problem and *2n* additional control variables must be found in the modified OPF problem and they become a big challenge for applied approaches. Recently, the rates of renewable energies mainly wind power and solar energy integrated into grid have grown so fast.

Because of the presences of renewable energies the basic OPF problem is modified into various versions, specifically OPF considering wind power that wind turbine can generate both active and reactive power [21-26], OPF considering both wind and solar energy [27-36], OPF considering wind power that wind turbine just only generates active power [37-40]. In conclusion, the main differences between the conventional OPF and the modified OPF problem are:

1. First, in the conventional OPF problem, the generating source is thermal generator only whist in the modified OPF, the generating source is the co-oporation of TGU, wind power, solar energy (PV) or distribuited generator (DG).
2. The other differences come from the quantities of control variables. Specifically, in the conventional OPF the control variables are $P_{Gen}$, $U_{Gen}$, $Q_{Cap}$, *TP* whist the control variables of modified OPF problem are $P_{Gen}$, $U_{Gen}$, $Q_{Cap}$, *TP*, $P_{WT}$ and $\theta_{WT}$.
3. Finally, the process of solving the modified OPF problem with wind turbine integrated with grid get the number of control variables increased by two more for each turbine placed at a particular node, specifically, active power output of wind turbine ($P_{WT}$) and its power factor $\theta_{WT}$. If the quantities of wind turbine installed is *n* the quantities of control variables that needed to determine increased by $2n$. That means, the process of solving the modified OPF problem will be more complicated

Equilibrium optimizer (EO) developed in early 2020 was formed by inspiring from liquid mass balance state [41]. This metaheuristic has been applied for a high number of benchmark functions and it has reached better optimums than other popular and recent metaheuristics for these benchmark functions. The outstanding performance of EO has attracted the authors and it has been selected to find the most suitable active power and reactive power of wind turbine (WT) in a power system with 30 nodes. Thanks to the EO application, the contribution of the paper is as follows:

1) Apply a new metaheuristic for a modified OPF problem with the placement of a WT.
2) EO can find more optimal parameters in transmission power system to reach less cost than other methods for conventional OPF problem.
3) EO also find more suitable $P_{WT}$ and $Q_{WT}$ of the added WT together with reasonable parameters in the modified system with 30 nodes.
4) EO can reach smaller power generation cost than other compared methods for all study cases.

## 2. OBJECTIVE FUNCTION AND CONSTRAINTS IN PROCESS OF SOLVING OPTIMAL POWER FLOW

### *2.1 Objective function*

### *2.1.1 Minimize total electricity production cost of TGUs*

In this study the first goal ($G_1$) – minimize total electricity production cost by TGUs can be achieved through minimizing fuel cost function for all generator placed at various nodes.

$$G_1 = \min(\sum_{i=1}^{N_{Gen}} F_{Geni}(P_{Geni})) \tag{1}$$

And the fuel cost function is approximately represented by the quadratic function described below

$$F_{Geni}(P_{Geni}) = \psi_1 + \psi_2 P_{Geni} + \psi_3 (P_{Geni})^2 \tag{2}$$

### *2.1.2 Minimize total power loss in the whole system*

Transmission network is designed with ability to carry the enormous amount of power which is sent through lot of transmission lines. When power circulates though each transmission line from sending end to receiving end because of line impedance, loss always exists there. The second goal ($G_2$) is mainly minimizing entire power loss in the whole transmission line:

$$G_2 = \min(P_{Loss}) \tag{3}$$

with

$$P_{Loss} = \sum_{i=1}^{N_{Gen}} P_{Geni} - \sum_{i=1}^{N_{no}} P_{ri} \tag{4}$$

or

$$P_{Loss} = \sum_{x=1}^{N_{no}} \sum_{\substack{y=1,\\ x\neq y}}^{N_{no}} \begin{matrix} A_{xy}[U_x^2 + U_y^2 \\ -2U_x U_y \cos(\varepsilon_x - \varepsilon_y)] \end{matrix} \tag{5}$$

### *2.2 Constraints in transmission network*

### *2.2.1 TGU working constraints or Generator working constraints*

Every TGU in the whole system must respect all constraints listed below such as the limitation for active, reactive power and generating voltage as well. That means, these are thresholds in the operating process which cannot be overshot.

$P_{Gen}^{min} \le P_{Geni} \le P_{Gen}^{max}$ with $i = 1,.., N_{Gen}$ and $N_{Gen}$ is the quantity of generator (6)

$Q_{Gen}^{min} \le Q_{Geni} \le Q_{Gen}^{max}$ with $i = 1,.., N_{Gen}$ and $N_{Gen}$ is the quantity of generator (7)

$U_{Gen}^{min} \le U_{Geni} \le U_{Gen}^{max}$ with $i = 1,.., N_{Gen}$ and $N_{Gen}$ is the quantity of generator (8)

### *2.2.2 Active power equal constraints*

The corresponding for both total active power generated by TGUs in the whole system and the amount of active power consumed by load must be followed the formula below

$$\begin{aligned} P_{Genx} - P_{rx} = U_x \sum_{y=1}^{N_{no}} U_y \big[ & A_{xy} \cos(\delta_x - \delta_y) \\ & + S_{xy} \sin(\delta_x - \delta_y) \big] \end{aligned} \tag{9}$$

### *2.2.3 Reactive power equal constraints*

The association among reactive power supplied by TGUs, the reactive power injected into specific node by bank capacitor and the volume of reactive power required by load must be satisfied the Equation (10) below:

$$\begin{aligned} & Q_{Genx} + Q_{Capx} - Q_{rx} \\ & \quad = U_x \sum_{y=1}^{N_{no}} U_y \big[ A_{xy} \sin(\delta_x - \delta_y) \\ & \quad - S_{xy} \cos(\delta_x - \delta_y) \big] \end{aligned} \tag{10}$$

with:

$$Q_{Cap}^{min} \le Q_{Capi} \le Q_{Cap}^{max} \; with \; i = 1, \dots, N_{Cap} \tag{11}$$

### *2.2.4 Active and reactive power equal constraints in case of wind turbine integrated*

In this situation, because of the presence of wind turbine both active and reactive power equal constraints are needed to revise as follows [23]:

$$\begin{aligned} & P_{Genx} + P_{WTx} - P_{rx} \\ & \quad = U_x \sum_{y=1}^{N_{no}} U_y \big[ A_{xy} \cos(\delta_x - \delta_y) \\ & \quad + S_{xy} \sin(\delta_x - \delta_y) \big] \end{aligned} \tag{12}$$

And the same behavior is also applied for reactive power equal constraints [23]

$$\begin{aligned} & Q_{Genx} + Q_{WTx} + Q_{Capx} - Q_{rx} \\ & \quad = U_x \sum_{y=1}^{N_{no}} U_y \big[ A_{xy} \sin(\delta_x - \delta_y) \\ & \quad - S_{xy} \cos(\delta_x - \delta_y) \big] \end{aligned} \tag{13}$$

### *2.2.5 Transformer tap located constraints*

Transformer tap must be located inside of the range value that satisfy the constraint depicted below:

$$TP^{min} \leq TP_i \leq TP^{max} \; with \; i = 1, \ldots, N_T \tag{14}$$

### *2.2.6 Safety constraints*

To make sure the entire system working normally and efficiently, voltage at various node loads as well as the apparent power allowed to circulate in every single branch must be imposed these constraints as follow:

$$\begin{gathered} U_{load}^{min} \leq U_{loadt} \leq U_{load}^{max} \\ \text{with } t = 1, \ldots, N_{load} \end{gathered} \tag{15}$$

and

$$\begin{gathered} S_{branchq} \leq S_{branch}^{max} \\ \text{with } q = 1, \ldots, N_{branch} \end{gathered} \tag{16}$$

## 3. THE EQUILIBRIUM OPTIMIZER ALGORITHM

### ***3.1 Inspiration***

EO is developed based on the determination of dynamic and equilibrium state for mass balance model [41] that its mathematical formula is described in the equation (17) below:

$$CV\frac{dM}{dt} = QM_{eq} - QM + M_G \tag{17}$$

When the mass balance model reaches the equilibrium state, the term $CV\frac{dM}{dt}$ equals zero. That means the optimal result is determined. The main job in the entire operation of EO is to find out the concentration in order to help the mass balance model reach optimal result

The concentration update of EO is dependent on four best individuals and the average individual. In addition, to avoid the local optima, the update process of concentration of EO uses a term called Generating expectation ($M_G$). The concentration update process of EO is formulated as follows:

$$M_{new} = M_x + (M - M_x)E + \frac{M_G}{\varepsilon CV}(1 - E) \tag{18}$$

The main steps of EO algorithm are presented in the section 3.2.

### ***3.2 EO procedure***

### *3.2.1 The initialization*

In the first step, each individual of population is generated corresponding to its own concentration boundaries. Specifically, these boundaries are the lower and the upper concentration boundaries. The mathematical formulation of the initialization phase is expressed in the equation (19) below:

$$\begin{gathered} M_i = M_{min} + \alpha(M_{max} - M_{min}) \\ with \; i = 1, 2, \ldots, Pop \end{gathered} \tag{19}$$

Each solution $M_i$ is a term of the general matrix (*M*) and the fitness value of each solution is a term of the fitness matrix (*F*). *M* and *F* are expressed as follows:

$$M = [M_i] \; with \; i = 1, 2, \ldots, Pop \tag{20}$$

$$F = [F_i] \; with \; i = 1, 2, \ldots, Pop \tag{21}$$

### *3.2.2 The update of new concentration*

At the end of every iteration in entire optimal process of EO, all individuals will be updated its own concentration. This procedure is formulated in the following equation:

$$M_i^{new} = M_x + (M_i - M_x).E + \frac{M_G}{\varepsilon CV}(1 - E) \tag{22}$$

Equation (22) above points out that, the concentration update procedure for each individual is highly dependent on three main components; the equilibrium candidate ($M_x$); the exponential term (*E*) and the mass generation rate ($M_G$).

These three main components will be expressed in detail as follows:

- *Equilibrium pool ($M_{eq}$)*

Equilibrium candidate ($M_x$) is randomly selected from a set of solution candidates $M_{eq}$ consisting of the four best solutions in the current population expressed in equation (23) below:

$$M_{eq} = \{M_{eq1}, M_{eq2}, M_{eq3}, M_{eq4}, M_{eqm}\} \tag{23}$$

where $M_{eq1}, M_{eq2}$ , $M_{eq3}$ , $M_{eq4}$ is the best, second best, third best and fourth best solution in the population; $M_{eqm}$ is the average candidate (average solution) of the four best individuals and obtained by equation (24) below:

$$M_{eqm} = \frac{(M_{eq1} + M_{eq2} + M_{eq3} + M_{eq4})}{4} \tag{24}$$

Each individual in every iteration updates its concentration based on the $M_x$ candidate selected randomly from equilibrium pool $M_{eq}$ as described in the equation (25) below:

$$M_x = \in (M_{eq}) \tag{25}$$

For example, in the first iteration, the *i*$^{th}$ individual updates all of its concentration based on $M_{eq1}$ then, in the second iteration, it may updates its concentration based on the $M_{eqm}$. When the optimal process reaches the maximum iteration (*Max_iter*), every individual in population will utilize all of equilibrium candidate for its update of new concentration

- *Exponential term (E)*

The exponential term ($E$) is considered to be one of the most crucial factors in the update process of new concentration of each individual. In addition, a factor called turnover rate and denoted by $\xi$ with the range value from 0 to 1 randomly is also utilized to define the proper exponential term.

$$E = \omega_1 ED[e^{-\xi t} - 1] \tag{26}$$

In the update process of new concentration $\xi$ is supposed to be equal to $\varepsilon$.

- *Mass generation rate ($M_G$)*

$$M_G = M_{G0}E \tag{27}$$

where

$$M_{G0} = PM_G(M_x - \xi M) \tag{28}$$

and

$$PM_G = \begin{cases} 0.5k_1, & k_2 \geq G_e \\ 0\,, & k_2 < G_e \end{cases} \tag{29}$$

In addition, in the equation (29), the generating expectation rate ($G_e$) controls the participating probability of concentration update process. In case of $G_e$ = 1, there will be no generation rate term participating in the optimization process. This state emphasizes high exploration capability, and often leads to non-accurate solutions. On the other hand, if $G_e$ = 0, the generation rate term will always be participating in the process, which increases the trapped probability in local optima. According to the practical test, $G_e$ = 0.5 proved its high performance in entire the optimal process.

### 3.2.3 Checking violation and correcting the new solution

This step is highly important to make sure that each of new concentration belonging every individual is restricted inside the range of lower and upper boundaries. In case of the new concentration violates the lower boundary, it will be set to the lower boundary value. Vice versa, the new concentration will be set equal the upper value if it violates the upper boundary. The mathematical model about this step is described as follows:

$$M_i^{new} = \begin{cases} M_{min} \; if \; M_i^{new} < M_{min} \\ M_{max} \; if \; M_i^{new} > M_{max} \end{cases} \tag{30}$$

### 3.2.4 Evaluating new solution

In this step, the new fitness value ($F_i^{new}$) of $i^{th}$ individual is calculated based on its new concentration ($M_i^{new}$). Each $F_i^{new}$ is a term of the new fitness matrix ($F^{new}$) which is expressed in the equation (31) below:

$$F^{new} = [F_i^{new}] \; with \; i = 1, 2, \dots, Pop \tag{31}$$

### 3.2.5 Memory saving

The main purpose behind this procedure is to save the better individual by comparing the new fitness value with the old fitness value belonging the individual considered.

$$M_i = \begin{cases} M_i^{new} \; if \; F_i^{new} < F_i \\ M_i \;\; else \end{cases} \tag{32}$$

$$F_i = \begin{cases} F_i^{new} \; if \; F_i^{new} < F_i \\ F_i \; if \; F_i^{new} > F_i \end{cases} \tag{33}$$

The entire optimal process of EO is described in Fig. 2.

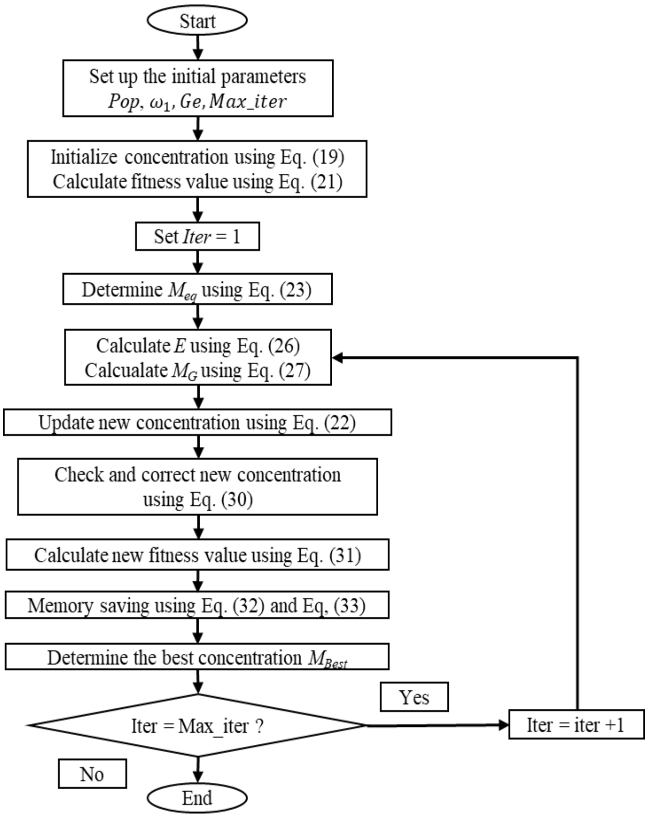

**Fig. 2. The entire searching process of EO.**

## 4. THE IMPLEMENTATION OF EQUILIBRIUM OPTIMIZER TO SOLVE THE OPF PROBLEM

### 4.1 The initialization

In the whole process of solving the OPF problem mentioned in this study, each individual of the EO algorithm is represented for a specific solution consisting of a set of variables. These control variables are listed as power output of thermal generators, voltage generated by TGUs, transformer's tap setting, reactive power supplied by capacitor banks, power output generated by wind turbine and power factor of wind turbines. The equation (34) below will describe in the details a specific solution of the problem considered.

$$M_p = \begin{Bmatrix} P_{Gen2,p},\dots,P_{N_{Gen},p};\ U_{Gen1,p},\dots,U_{N_{Gen},p}; \\ TP_{1,p},\dots,TP_{N_T,p};\ Q_{cap1,p},\dots,Q_{capN_c,p}; \\ P_{WT1,p},\dots,P_{WTN_{WT},p};\ \theta_{1,p},\dots,\theta_{N_{WT},p} \end{Bmatrix}^T \quad (34)$$

$$p = 1,2,\dots,Pop$$

In addition, each variable of an individual (solution) will be generated initially as follow:

$$P_{Geni,p} = P_{Gen}^{min} + \alpha.\left(P_{Gen}^{max} - P_{Gen}^{min}\right) \quad (35)$$

$$with\ i = 2,\dots,N_{Gen};\ p = 1,2,\dots,Pop$$

$$U_{Geni,p} = U_{Gen}^{min} + \beta.\left(U_{Gen}^{max} - U_{Gen}^{min}\right) \quad (36)$$

$$with\ i = 1,2,\dots,N_{Gen};\ p = 1,2,\dots,Pop$$

$$Q_{Capj,p} = Q_{Cap}^{min} + \gamma.\left(Q_{Cap}^{max} - Q_{Cap}^{min}\right) \quad (37)$$

$$with\ j = 1,2,\dots,N_{Cap};\ p = 1,2,\dots,Pop$$

$$TP_{n,p} = TP^{min} + \tau.(TP^{max} - TP^{min}) \quad (38)$$

$$with\ n = 1,2,\dots,N_T;\ p = 1,2,\dots,Pop$$

$$P_{WTm,p} = P_{WT}^{max} + \chi.(P_{WT}^{max} - P_{WT}^{max}) \quad (39)$$

$$with\ m = 1,2,\dots,N_{WT};\ p = 1,2,\dots,Pop$$

$$\theta_{WTm,p} = \theta_{WT}^{min} + \sigma.\left(\theta_{WT}^{max} - \theta_{WT}^{min}\right) \quad (40)$$

$$with\ m = 1,2,\dots,N_{WT};\ p = 1,2,\dots,Pop$$

Once the control variables are fully generated as follows equation (35) to (40) they will be utilized to set input data for the OPF tool (Matpower) to obtain the other dependent variables as listed at equation (41) below:

$$N_p = \begin{Bmatrix} P_{gen1};\ Q_{Gen1},\dots,Q_{GenN_{Gen}}; \\ U_{load1},\dots,U_{loadN_t}; \\ S_{branch1},\dots,S_{branchN_q}; \\ Q_{WT1},\dots,Q_{WTN_{WT}} \end{Bmatrix} \quad (41)$$

where $Np$ is a set of dependent variables of the $p^{th}$ individual (solution)

More important, both control variables and dependent variables must keep the fitness function described below reach the minimum value:

$$\begin{aligned} Fitness_p = Goal_p &+ \mu(P_{Gen1,p}^{res})^2 + \mu(Q_{Geni,p}^{res})^2 \\ &+ \mu(U_{loadn,p}^{res})^2 \\ &+ \mu(S_{branchq,p}^{res})^2 \\ &+ \mu(Q_{WTm,p}^{res})^2 \end{aligned} \quad (42)$$

where $Goal_p$ is the objective function of the solution obtained by using equation (35) and equation (40) as mentioned in section 2; $\mu$ is the penalty weight.

The violation of boundaries of dependent variables in equation (42) is restricted in formulas as follow

$$P_{Gen1,p}^{res} = \begin{cases} P_{Gen1,p} - P_{Gen1}^{max}\ if\ P_{Gen1,p} > P_{Gen1}^{max} \\ P_{Gen1}^{min} - P_{Gen1}^{min}\ if\ P_{Gen1,p} < P_{Gen1}^{min} \\ P_{Gen1,p}\quad Otherwise \end{cases} \quad (43)$$

$$Q_{Geni,p}^{res} = \begin{cases} Q_{Geni,p} - Q_{Gen}^{max}\ if\ Q_{Geni,p} > Q_{Gen}^{max} \\ Q_{Gen}^{min} - Q_{Geni,p}^{min}\ if\ Q_{Geni,p} < Q_{Gen}^{min} \\ Q_{Geni,p}\quad Otherwise \end{cases} \quad (44)$$

$$U_{loadt,p}^{res} = \begin{cases} U_{loadt,p} - U_{load}^{max}\ if\ U_{loadt,p} > U_{load}^{max} \\ U_{load}^{min} - U_{loadt,p} if\ U_{loadt,p} < U_{load}^{min} \\ U_{loadt,p}\quad Otherwise \end{cases} \quad (45)$$

$$S_{branchq,p}^{res} = \begin{cases} S_{branchq,p} - S_{branch}^{max}\ if\ S_{branchq,p} > S_{branch}^{max} \\ S_{branch}^{min} - S_{branchq,p}\ if\ S_{branchq,p} < S_{branch}^{min} \\ S_{branchq,p}\quad Otherwise \end{cases} \quad (46)$$

$$Q_{WTm,p}^{res} = \begin{cases} Q_{WTm,p} - Q_{WTm}^{max}\ if\ Q_{WTm,p} > Q_{WTm}^{max} \\ Q_{WTm}^{min} - Q_{WTm,p}\ if\ Q_{WTm,p} < Q_{WTm}^{min} \\ Q_{WTm,p}\quad Otherwise \end{cases} \quad (47)$$

### *4.2 Solution update procedure*

The entire solution update procedure of EO algorithm is highly dependent on three main elements: the four best candidates from equilibrium pool, the exponential term and the generating expectation. The whole process of EO new concentration update is described in details at section 3 above.

### *4.3 Terminating condition*

This is one of the most ubiquitous techniques utilized to stop the searching process. In general, this technique will utilize a specific number of iteration that means when the searching process reaches the maximum iteration. the searching operation will be terminated there. There is no common number of maximum iteration for all situations when this type of algorithm is applied. The number of iterations is completely dependent on the experiences of developer and the problem under considered over the most circumstances.

### *4.4 The entire searching operation of EO applied for the problem consider*

EO implementation for OPF problem with WT placement is shown in the following steps and also summarized in Fig. 3.

Step 1: Set up the initial parameters such as population size (*Pop*), the constant manipulates exploitation phase ( $\omega_1$ ), the generating expectation ($G_e$), the maximum number of iterations (*Max_iter*).

Step 2: Generate the concentration of each individual in population as described at equation (35) to (40) after that, using Matpower to determine the other variables as equation (41). Set 1 to current iteration.

Step 3: Calculate the fitness value of each individual in population based on the control variables and the dependent variables achieved in step 2 after running Matpower.

Step 4: Determine the equilibrium pool (*Meq*)

Step 5: Calculate the exponential term (*E*) and the mass generation rate ($M_G$)

Step 6: Update new concentration then checking the violation of new concentration, after that, using the Matpower to re-determine the dependent variables as described at equation (41)

Step 7: Calculate the new fitness value of each individual based on the new concentration and the dependent variables determined at step 6

Step 8: Memory saving that means comparing and retaining the better individual via its own fitness value using equation (32) and (33)

Step 9: Find out the best individual of population ($M_{Best}$)

Step 10: Check the terminating condition as depicted at section 4.3. If the number of current iteration equal maximum iteration, stop the searching operation. Otherwise, increase the number of current iteration by 1 and then, return Step 4.

The flowchart of using Equilibrium optimizer (EO) to solve the optimal power flow problem is presented as follows:

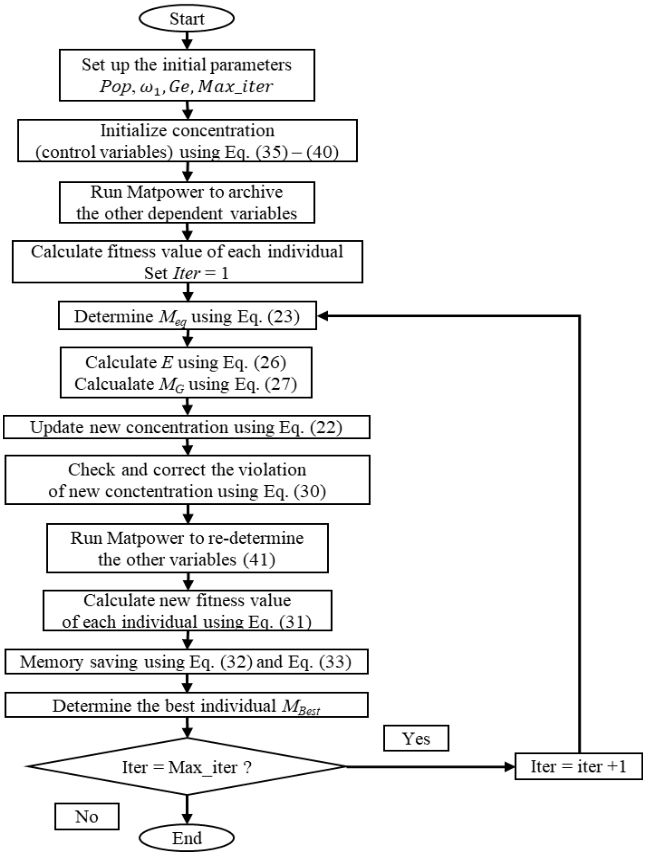

**Fig. 3. The implementation of EO for solving the OPF problem.**

## 5. RESULTS

In this section, the efficiency of EO is assessed when solving different case studies of OPF problem. Specifically, the evaluation of EO's performance is based on two separate case studies they are minimizing the TEPC with and without considering wind turbine integrated as mentioned in details at section 5.1 and section 5.2 respectively. The entire work regarding implementation of EO to solve the OPF problem is programed in Matlab 2018a version and run on a personal computer with the processor 2.6 Ghz and 8 GB of RAM.

### *5.1 Selection of Pop and Max_iter*

The main obstacle in applying EO method for reaching good results that we have to implement various separated tests in order to determine two highly important control parameters. They are the optimal population size (*Pop*) and the optimal maximum of iterations (*Max_iter*). When only these control parameters are determined properly, the first priority for reaching the best results with optimal computing time is reached. In particular, *Pop* affects substantially to the quality of solution and the computing time in each iteration. *Max_iter* affects directly the quality of solution and computing time of each run. Therefore, if

*Pop* is set to a large number then the best quality solution can be determined but the time computing of each iteration and each run is longer. In case *Max_iter* is set to a great number, the results obtained after each run can be better but the whole operating process will be last longer. In conclusion, the selection of *Pop* and *Max_iter* must consider for the target that how to achieve the best quality solution with optimal computing time. In case *Pop* and *Max_iter* are set to great numbers randomly, then the best result will be obtained at the end of process after long time operation. However, the performance of a particular algorithm in this case is hard to judge properly. By experiment, we set *Pop* to 10, 20, 30, 40, 50, respectively and *Max_iter* to 100, 200, 300, respectively then we realized EO can achieve the best results for *Pop* and *Max_iter* are 30 and 100, respectively.

### *5.2 Minimizing the TEPC without renewable energy*

In this case of study, the original configuration of IEEE 30-node system is utilized to evaluate the performance of EO. In this configuration, there are 6 generators (TGUs) placed at nodes 1, 2, 5, 8, 11 and 13; 4 transformers; 41 branches; 24 loads and 9 shunt capacitor banks. The one-line graph of the original configuration of IEEE 30 node is modeled at Figure 4. The results obtained by EO in this section are implemented by 50 separate runs with the settings: population 30 and 100 iterations for each single run.

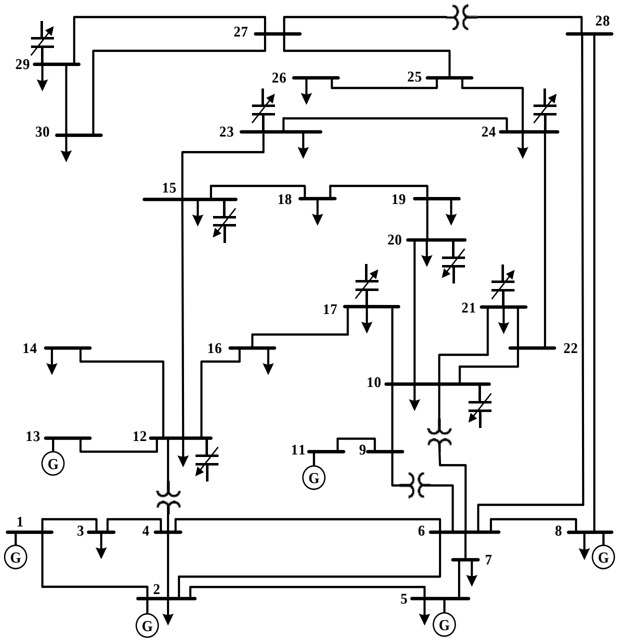

**Fig. 4. The configuration of IEEE-30 node system.**

Over 50 runs, EO can find the minimum TEPC of 799.6519 ($/h) as reported in Table 1 together with that from other methods [40]. The data from Table 2 showed that the best fitness obtained from EO and others have the same value as TEPC and all constraints were successfully handled with the penalty terms of zero. TEPC value of EO is better than the one obtained by the others. Specifically, the TEPC value given by EO is 799.6519 ($/h) whist the similar value of the other method such as EGA, GPM, ICA, ABC, PSOGSA, and JAYA are 802.06 ($/h), 804.853 ($/h), 800.805 ($/h), 800.66 ($/h), 800.49859 ($/h) and 800.4794 ($/h) respectively. From the TEPC value ($/h), it can find the saving cost of EO in comparison with EGA, GPM, IGA, ABC, PSOGSA, and JAYA by 2.4091 ($/h); 5.2011($/h), 1.1531 ($/h), 1.0081 ($/h), 0.84669 ($/h), 0.8275 ($/h), respectively. The saving cost is converted to 0.3 %, 0.65 %, 0.14 %, 0.13 %, 0.11% and 0.11 % of EGA, GPM, ICA, ABC, PSOGSA, and JAYA, respectively.

**Table 1: The comparison of TEPC value obtained by EO with the other methods**

| **Methods** | **Best fitness** | **TEPC value ($/h)** | **Computing time (s)** |
|---|---|---|---|
| EGA [40] | 802.06 | 802.06 | - |
| GPM [40] | 804.853 | 804.853 | - |
| IGA [40] | 800.805 | 800.805 | - |
| ABC [40] | 800.66 | 800.66 | - |
| PSOGSA [40] | 800.49859 | 800.49859 | - |
| JAYA [40] | 800.4794 | 800.4794 | 72.4 |
| EO | 799.6519 | 799.6519 | 4.828 |

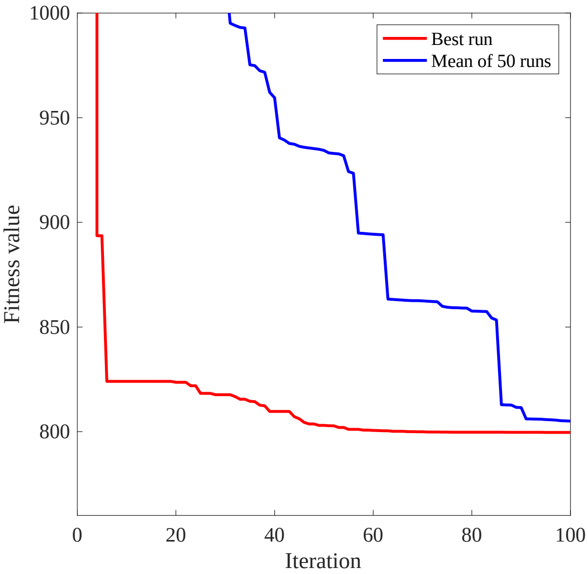

**Fig. 5. The best run and the mean run of EO without wind turbine connected into system.**

Figure 5 above describes the convergence of EO in process to solve the OPF problem. The blue line represented for the average convergence after 50 runs independently whist the red line is represented for the best convergence after completing 50 runs.

### *5.3 Minimizing the TEPC with the presence of renewable energy*

In this case of study, the EO is applied to solve the OPF problem considering the presence of renewable energy, specifically, it is one wind turbine. The placement of the wind turbine into the IEEE 30-node system configuration is based on the sensitive method. Base on the results obtained from sensitive method, the re-configuration of original IEEE-30 configuration with the presences of wind turbine placed at node 3 and node 30, respectively is illustrated at Figure 6 below. In this section, EO is operated to solve the OPF problem considering the wind turbine placed at node 3 and node 30 separately. The population size and maximum number of iterations for both situations are set at 30 and 100, respectively. The convergences of both situations are described at Figure 7 and Figure 8, respectively. Where, the blue line is represented for the average convergence obtained after 50 runs independently whist the red line is the best convergence achieved after completing 50 runs.

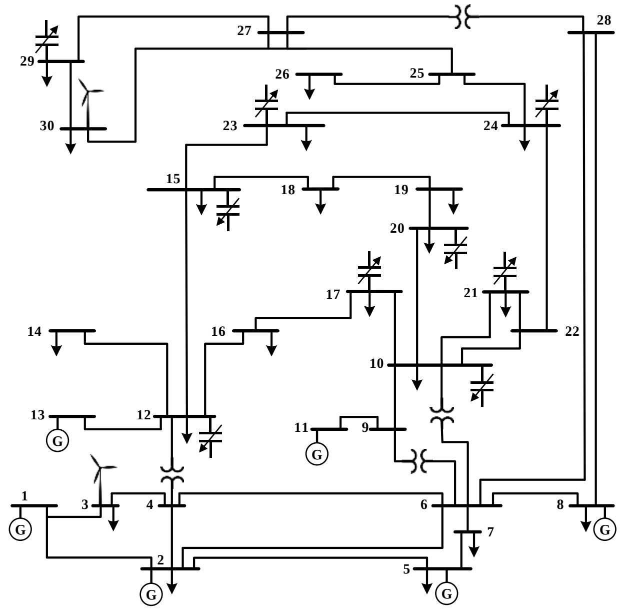

**Fig. 6. The configuration of IEEE-30 node with wind turbine connected in node 3 and node 30.**

After that, the EO is utilized to find the optimal results of TEPC for both situation that wind turbine placed at node 30 and node 3, separately. In addition, a DFIG wind turbine that can generate 10 MW in maximum with power factor varying from 0.8 to 1 is utilized in the process of solving the OPF problem. For both situations, EO is operated by 50 runs independently with 100 iterations and population size is set at 30 for each run. The results obtained is presented in Table 2.

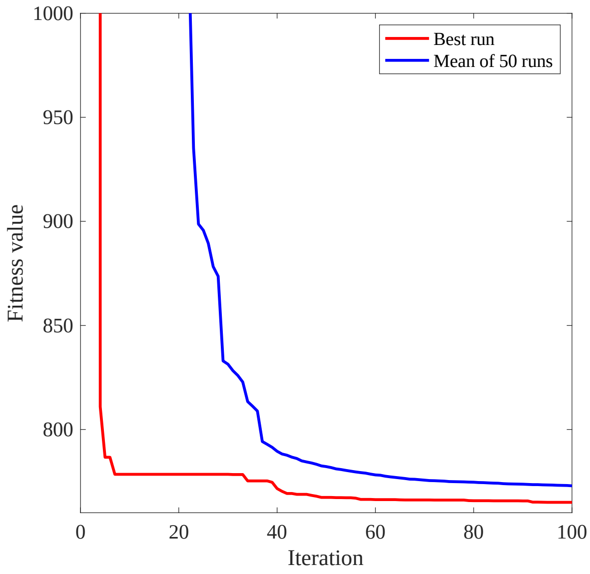

**Fig. 7. The convergence for the situation with wind turbine connected at node 3.**

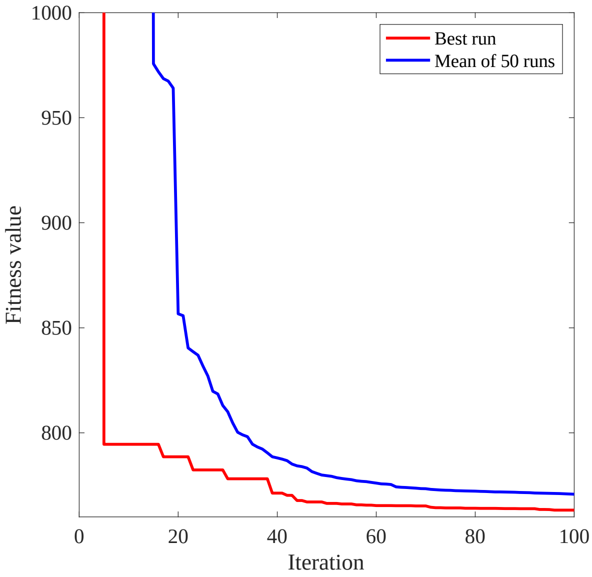

**Fig. 8. The convergence for the situation with wind turbine connected at node 30.**

Table 2 showed that the presence of wind turbine made a substantial reduction of TEPC for both situation when wind turbine is placed at node 3 and node 30. Specifically, for the situation that wind turbine is not considered the best value of TEPC obtained is 799.6519 ($) whist the TEPC value in the situation considering wind turbine placed at node 3 and node 30 are 765.0251 ($) and 763.2083 ($) with the reduced percentages are 4.33% and 4.56%, respectively.

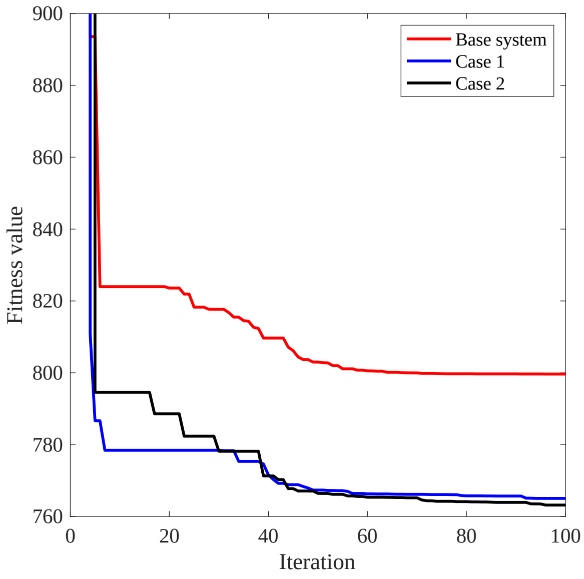

**Fig. 9. The convergence of different case studies with and without wind turbine connected.**

**Table 2: The TEPC values obtained by EO for the situations wind turbine connected**

| **Values** | **Wind turbine at node 3** | **Wind turbine at node 30** |
|---|---|---|
| Min | 765.0251 | 763.2083 |
| Aver | 772.9504 | 770.7948 |
| Max | 807.4648 | 862.5949 |
| STD | 10.506 | 14.9155 |

**Table 3: The TEPC values given by EO and the other method**

| **Method** | **TEPC value ($/h)** | **Computing time (s)** |
|---|---|---|
| JAYA<br>(with a DG 10MW placed at node 30) [40] | 768.0398 | 72.4 |
| JAYA<br>(with a DG 10MW placed at node 3) [40] | 769,963 | 72.4 |
| EO<br>(with a wind turbine 10MW placed at node 3) | 765.0251 | 14.838 |
| EO<br>(with a wind turbine 10MW placed at node 30) | 763.2083 | 14.838 |

The effect of wind turbine connected in the IEEE-30 node is presented in Figure 9 above for both situation that wind turbine placed at node 30 (case 1) and node 3 (case 2). The differences between the fitness values (TEPC) for the situation without wind turbine (Base system) and the situation that wind turbine connected into grid is huge.

Besides, in other to prove the high performance of EO, the results showed in Table 3 is compared with the other method [40].

The data from Table 3 one more time prove the high performance of EO when the TEPC value obtained from both situations with wind turbine connected in node 3 and node 30 are highly better than the TEPC value given by the other methods. For more details, the TEPC value in both situations are 765.0251 ($/h) and 763.2083 ($/h) whist the similar one given by JAYA [40] are 769,963 ($/h) and 768.0398 ($/h), respectively. The percentage reduction of TEPC achieved by EO when compared with JAYA method are 0.64% and 0.63%, respectively. Furthermore, the active power of wind turbine and the power factor obtained by EO satisfied all constraints regarding the maximum power output of wind turbine and the power factor limits in the adjustable range. Specifically, the maximum power output of wind turbine and its power factor for both situation when wind turbine connected in node 3 and node 30 are 10 MW and 0.95968846, and 9.99893483 MW and 0.85159655, respectively. The control variables in cases of wind turbine connected are presented at the Table 4.

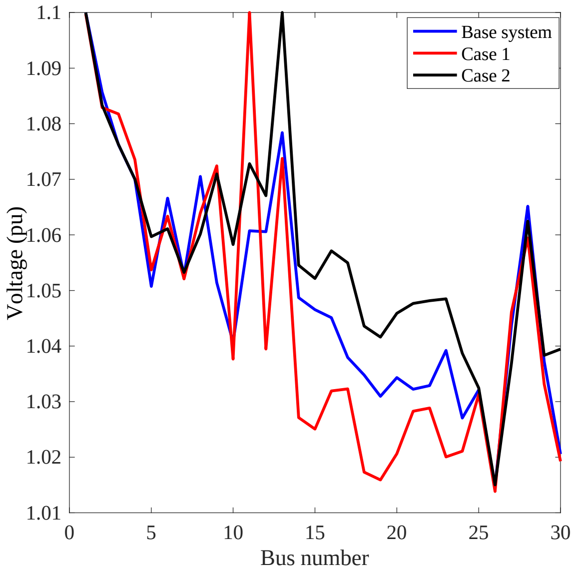

**Fig. 10. The voltage graphs in different case studies with and without the wind turbine connected.**

**Table 4: The control variables of all case studies obtained by EO**

| Control variables | CASE STUDIES | | | | | |
|---|---|---|---|---|---|---|
| | **Without wind turbine EO** | **Wind turbine at node 3 EO** | **Wind turbine at node 30 EO** | **Without DG [40]** | **DG at node 3 [40]** | **DG at node 30 [40]** |
| $P_{Gen2}$ (MW) | 48.3748049 | 46.6813938 | 47.8716134 | 48.1929 | 47.9308 | 47.6388 |
| $P_{Gen3}$ (MW) | 20.399962 | 19.9054383 | 22.2978356 | 21.4679 | 21.1194 | 20.8386 |
| $P_{Gen4}$(MW) | 22.5558938 | 18.8276419 | 16.066402 | 21.1103 | 20.8342 | 20.6944 |
| $P_{Gen5}$(MW) | 12.3574341 | 12.8417652 | 11.8174518 | 11.7820 | 11.8917 | 11.8375 |
| $P_{Gen6}$ (MW) | 12.2250679 | 12.6039997 | 12.6258217 | 12.1169 | 12.0307 | 12.0173 |
| $V_{Gen1}$(V) | 1.09999877 | 1.1 | 1.0997487 | 1.08620 | 1.07033 | 1.07264 |
| $V_{Gen2}$ (V) | 1.08565546 | 1.08332825 | 1.08290355 | 1.06653 | 1.05308 | 1.05512 |
| $V_{Gen3}$ (V) | 1.05073546 | 1.05969447 | 1.05369377 | 1.03350 | 1.02076 | 1.01985 |
| $V_{Gen4}$ (V) | 1.07050353 | 1.06015673 | 1.06394762 | 1.03722 | 1.02941 | 1.03177 |
| $V_{Gen5}$ (V) | 1.06072886 | 1.07281676 | 1.1 | 1.09983 | 1.07827 | 1.07907 |
| $V_{Gen6}$ (V) | 1.07838353 | 1.1 | 1.07375634 | 1.05041 | 1.04283 | 1.04054 |
| $Q_{Cap1-}$ (MVAr) | 4.12990185 | 0.25031307 | 0.12141221 | 5 | 2.3639 | 2.1837 |
| $Q_{Cap2}$ (MVAr) | 2.76459572 | 4.56623555 | 3.49471668 | 0.62598 | 2.8944 | 2.483 |
| $Q_{Cap3}$ (MVAr) | 4.52854051 | 0.40546239 | 1.4298683 | 3.55399 | 1.7063 | 1.4851 |
| $Q_{Cap4}$ (MVAr) | 1.51117691 | 3.27742888 | 2.42019913 | 4.17065 | 1.51184 | 1.6798 |
| $Q_{Cap5}$ (MVAr) | 3.15269482 | 1.62299368 | 0.12500249 | 5 | 2.3638 | 2.0074 |
| $Q_{Cap6}$ (MVAr) | 4.65482541 | 2.14681881 | 3.91092065 | 4.98427 | 1.7446 | 1.5623 |
| $Q_{Cap7}$ (MVAr) | 3.81639981 | 4.6377473 | 0.29437826 | 3.70495 | 1.2183 | 0.9789 |
| $Q_{Cap8}$ (MVAr) | 2.25446641 | 4.36884479 | 4.58464864 | 5 | 1.2115 | 1.4621 |
| $Q_{Cap9}$ (MVAr) | 4.14732277 | 2.11961896 | 2.06324619 | 2.95702 | 1.1184 | 1.3188 |
| $TP_1$ (%) | 1.00227674 | 0.96919193 | 0.95583162 | 1.1000 | 1.06116 | 1.05793 |
| $TP_2$ (%) | 1.0502781 | 0.97396512 | 1.09946599 | 0.90000 | 0.9782 | 0.9659 |
| $TP_3$ (%) | 1.00761 | 1.03532949 | 1.07155239 | 0.97321 | 1.0217 | 1.0021 |
| $TP_4$ (%) | 1.01071203 | 1.0381601 | 0.99047248 | 0.97869 | 1.0012 | 1.0145 |
| PWT (MW) | | 10 | 9.99893483 | | 9.1169 | 9.1478 |
| $\theta_{WT}$ | | 0.95968846 | 0.85159655 | | 0.85 | |

On the other hand, voltage magnitude is one of the most important factors of power system operation and they need to keep in the allowed boundary. Figure 10 presents the voltage profiles for different case studies considered in this paper, base system, case 1 with wind turbine at node 30 and case 2 with wind turbine at node 3. Three cases are depicted by the blue line, red line and black line, respectively. Where Base system represents for the situation without wind turbine connected; the case 1 represents for the situation with wind turbine connect at node 30 and the last one presents of the situation with wind turbine connected at node 3. The observation on voltage magnitude of all nodes does not indicate the best case for the best voltage profile because the three curves have the same points that all nodes have voltage higher than 1.0 Pu and less than 1.1 Pu, and there was not comparison criterion to conclude the more stable voltage profile excluding the constraint from 0.9 to 1.1 Pu. This situation can be understood simply because the three study cases only concentrated on TEPC as the core objective while voltage was constrained in a predetermined range.

## 6. CONCLUSION

In this paper, a new meta-heuristic method called Equilibrium Optimizer (EO) is successfully implemented to handle the OPF problem with and without considering the presence of renewable energy that is actually wind energy. In addition, the performance of EO is evaluated though minimizing the TEPC for in different case studies. Specifically, they are minimizing the TEPC for the situation that's not considering the contribution of wind energy; minimizing the TEPC in case of considering wind turbine placed at node 3 and minimizing the TEPC in case of wind turbine placed at node 30. All of case studies as mentioned are implemented on IEEE-30 node configuration and its modified versions. The most important is the results achieved by EO are not only better than the similar ones reported from the other methods such as EGA, GPM, ICA, ABC, PSOGSA, JAYA but also satisfy all the constraints regrading OPF problem.

## ABBREVIATION

| | |
|---|---|
| TEPC | Total electricity production cost |
| TGUs | Thermal generating units (thermal generator) |
| PV | Photovoltaic |
| RES | Renewable energy sources |
| WT | Wind turbine |
| EGA | Enhanced Genetic Algorithm |
| GPM | Gaussian process model |
| IGA | Improved Genetic Algorithm |
| ABC | Artificial Bee Colony algorithm |
| PSOGSA | Hybrid Particle Swarm Optimization and Gravitational Search Algorithm |
| JAYA | JAYA algorithm |
| Min | Minimum cost ($/h) |
| Max | Maximum cost ($/h) |
| Aver | Average cost ($/h) |
| STD | Standard deviation cost value ($/h) |
| Pu | Per- unit |

## NOMENCLATURE

| | |
|---|---|
| $N_{Gen}$ | The quantity of TGUs (generator) |
| $F_{Geni}$ | The fuel cost function of the $i^{th}$ TGU ($/h) and $i = 1,\ldots, N_{Gen}$- |
| $P_{Geni}$ | The active power generated by the $i^{th}$ TGU and $i = 1,\ldots, N_{Gen}$ (MW) |
| $\psi_1, \psi_2$ and $\psi_3$ | The coefficient in fuel cost function belonging the $i^{th}$ TGU and $i = 1,\ldots, N_{Gen}$ |
| $N_{no}$ | The quantity of node (bus) |
| $x; y$ | The $x^{th}$, $y^{th}$ node respectively |
| $U_x; U_y$ | Voltages at node $x$ and node $y$ respectively (V) |
| $\varepsilon_x; \varepsilon_y$ | Phase angles of voltage at node $x$ and node $y$ respectively |
| $P_{ri}$ | The power required by demand at the $i^{th}$ *node* (MW) |
| $A_{xy}$ | The admittance of transmission line connecting node $x$ and node $y$ together ($\Omega^{-1}$) |
| $P_{Gen}^{min}; P_{Gen}^{max}$ | Minimum and maximum active power output of TGU (generator), respectively (MW) |
| $Q_{Gen}^{min}; Q_{Gen}^{max}$ | Minimum and maximum reactive power output of TGU (generator), respectively (MVAr) |
| $U_{Gen}^{min}; U_{Gen}^{max}$ | Minimum and maximum voltage output of TGU (generator) (V) respectively (V) |
| $S_{xy}$ | Susceptance between node $x$ and node $y$ ($\Omega^{-1}$) |
| $\delta_x\ ; \delta_y$ | Voltage phasors at node $x$ and node y respectively ($^0$) |
| $Q_{Cap}$ | Reactive power supplied by capacitor banks (MVAr) |
| $Q_{Cap}^{min}\ ; Q_{Cap}^{max}$ | Minimum and maximum reactive power output supplied by bank capacitor (MVAr); |
| $TP_i$ | The tap position fixed for transformer placed at the $i^{th}$ node (%) |
| $TP_i^{min}; TP_i^{max}$ | The maximum and the minimum tap position in the range value of transformer placed at the $i^{th}$ node (%) |
| $N_T$ | The quantity of transformer |
| $P_{WTx}$ | Active power output of wind turbine placed at node x (MW) |
| $Q_{WTx}$ | Reactive power output of wind turbine placed at node x (MVAr) |
| $U_{load}^{min};\ U_{load}^{max}$ | The maximum and the minimum voltage magnitude at the $i^{th}$ node (V) |
| $U_{loadi}$ | The voltage magnitude at the $i^{th}$ node (V) |
| $S_{branchi}$ | The apparent power that circulates through the $i^{th}$ branch (MVA) |
| $S_{branch}^{max}$ | The maximum apparent power allowed to circulate through the $i^{th}$ branch (MVA) |
| CV | Control volume |

| | |
|---|---|
| $CV\dfrac{dM}{dt}$ | The variation of concentration following time in control volume |
| $Meq$ | The concentration at the equilibrium state |
| $Q$ | The volumetric of mass inside the control volume |
| $M$ | The concentration of mass inside the control volume |
| $M_G$ | Generating expectation rate. |
| $M_{new}$ | The new concentration after update process |
| $M_x$ | The candidate selected randomly from the equilibrium pool ($M_{eq}$) |
| $E$ | The exponential term considered to be the replacement rate |
| $\varepsilon$ | Turnover rate calculated by $\frac{Q}{V}$ |
| $M_i$ | The initial concentration of the $i^{th}$ individual generated randomly |
| $M_{min}$; $M_{max}$ | The lower boundary and upper boundary of concentration |
| $\alpha$ | The value generated randomly in [0, 1] |
| $Pop$ | The population size |
| $F_i$ | The fitness value of $i^{th}$ individual given by the fitness function. |
| $\omega_1$ | The constant value manipulates the exploration phase; |
| $ED$ | The effect on direction over both exploration and exploitation ability. ED is determined by $sign(\vec{r} - 0.5)$ |
| $r$ | The random factor in [0, 1] |
| $\xi$ | The turnover rate and the range of value is defined in [0, 1] randomly |
| $PM_G$ | Parameter that manipulates the mass generation rate |
| $k_1$; $k_2$ | The random numbers in the range of [0, 1] |
| $G_e$ | The generating expectation rate |
| $M_i^{new}$ | The new concentration of the $i^{th}$ individual. |
| $F_i^{new}$ | The new fitness value of the $i^{th}$ individual. |
| $\alpha, \beta, \gamma, \tau, \chi$ and $\sigma$ | The values randomly generated in [0,1 |
| $\theta_m$ | The power factor of wind turbine of the $m^{th}$ wind turbine |
| $\theta_{WT}^{max}$; $\theta_{WT}^{min}$ | The maximum power factor and minimum power factor of the $m^{th}$ wind turbine respectively |
| $P_{WT}^{max}$; $P_{WT}^{min}$ | The maximum and minimum power output of the $m^{th}$ wind turbine (MW) |

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