Transient Stability Improvement based on Optimal Power Flow using Particle Swarm Optimization

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Abstract. Optimal Power Flow (OPF) is one of most important aspect in power system operation and control. It is a non linear optimization problem based on minimization an objective function such as the active power losses, fuel cost, voltage deviation, voltage stability, reliability evaluation,…etc. Transient stability analysis is an important concept to determine whether the system is stable or not when a heavy disturbance such as the fault or loss of generation or a sudden large increased in the load,…etc occur in the system. In this article the transient stability according to the fault occurrence are used as a constraint in the optimal power flow, where minimization a three objective function of the active power losses, the fuel cost of thermal generation units and the voltage deviation at the load buses separately for each one can improve the transient stability and keep all the generators in the synchronization system. Particle Swarm Optimization PSO of an artificial intelligence optimization techniques has been used for this purpose. Minimization the objective function can be satisfied by choosing an optimal control variables from their constraints keeping the state variables in their limits. The control variables in this article are the generator voltage magnitude, the transformer tap changer and the generator active power except the slack generator while the state variables are the stability system based on increasing the clearing time of the circuit breaker, the slack generator active power, the generator reactive power and the magnitude of the load voltage. Increasing the clearing time of the circuit breaker leads to increase the maximum value of the generator rotor angle and go towards the instability system. The maximum clearing time that keep the system stable is called the Critical Clearing Time TCC. This article used the Optimal Power Flow with Transient Stability as a constraint to increase the Critical Clearing Time TCC with stable system. The proposed algorithm has been tested on the two systems of IEEE 9 bus and IEEE 30 bus and compare the result with other reference. The implementation of this work are programming by the author using matlab software.

1. Introduction

Transient Stability in power system may be occurs according to many reasons such as the occurrence of the fault, sudden outage of the generator, sudden outage of the line or sudden large increasing in the load. It is important issue and more reliable to operate under stable power system and remain with supplying the electrical energy under these conditions of transient stability. One of the most important index in the transient stability analysis is the generator rotor angle, where increasing the generator rotor angle may be cause the instability in the power system. Any delay time to cleared the fault by the circuit breaker leads to increase the swing of the generator rotor angle and go to the instability system [1].

One of the most important techniques that used to solve the instability of the power system and improve the transient stability analysis is the Optimal Power Flow (OPF). Optimal Power Flow is a static non linear optimization tool used to re setting the control variables to meet a minimum objective function while at the same time satisfying a different equality and inequality constraints. In this article transient stability are used as inequality constraints in the state variables of the OPF analysis to solve the instability of the system. Different objective functions can be used in the optimal power flow such
as the active power losses of the transmission line, the fuel cost of the thermal generation unit, the voltage deviation at the load buses, line and bus voltage stability,…etc. The control variables may be the generator voltage magnitude, the transformer tap changer, the capacitance shunt injection Mvar and the generators active power except the slack generator,…etc, while the state variables are stability system, the active power of the slack generator, the reactive power of the generator, the magnitude of load voltage and the maximum capability power of the line,…etc.[2]

Two mainly type of optimization techniques are used to solve the Optimal Power Flow. The first one is the classical optimization technique like the Gradient base, Linear programming, Non linear program, Quadratic programming, Newton-Raphson,…etc. All these methods are based on assumption of linearity, continuity and differentiability of objective function which is not actually allowed in a practical system. In order to overcome this limitations of the classical optimization techniques, the second type of optimization techniques which is known the modern heuristic optimization techniques has been used. This type of optimization technique simulate the natural phenomena or the social behavior of humans or animals. A wide range of these modern optimization techniques have been used to solve the OPF problems such as Artificial Neural Network ANN, Simulated Ennealing SE, Tabu Search TS, Genetic Algorithm GA, Evolutionary Programming EP, Ant Colony Optimization, Particle Swarm Optimization PSO, Differential Evolution DE,…etc.[3].

2. Lecture Review

Transient stability can improve by decreasing the generator rotor angle using PSO. This technique is applied on IEEE 9 bus [1]. Optimal Power Flow has been implemented on IEEE 30 bus by minimization the objective function of active power losses and fuel cost using PSO [2]. The transient stability constraint is used in Optimal Power Flow based on Artificial Bee Colony for IEEE 9 bus with fuel cost as objective function [4]. An improved PSO has been used to solve the transient stability constrained Optimal Power Flow. The technique is tested on IEEE 9 bus and IEEE 30 bus with fuel cost as objective function [5]. Also the problem of transient stability constrained in Optimal Power Flow are solved using Artificial Neural Network on IEEE 39 bus and IEEE 300 bus systems [6]. Reference 7 using the genetic algorithm to perform the transient stability as a constrained in optimal power flow of alternating current-direct current (AC-DC) in High Voltage Direct Current (HVDC) systems. The Optimal Power Flow are used with small signal stability as additional constraints using particle swarm optimization. The technique is programing in MATLAB and implemented to a nine-bus test power system of large-scale wind power integration [8]

3. Optimal Power Flow OPF

The idea of Optimal Power Flow OPF is to find an optimal control variables from their limits to satisfied a specific optimal objective function keeping the constraint of the state variables in their limits.

3.1. Objective Function

This article used three objective functions separately for each one for the transient stability analysis. These function are:

3.1.1. The fuel cost of the thermal generation units

The fuel cost of thermal generation units $C_G$($/h)$ can be presented in equation (1)

$$C_G = \sum_{i=1}^{N_G} C_{Gi}$$  

(1)

$$C_{Gi} = a_i P_{Gi}^2 + b_i P_{Gi} + c_i$$  

(2)

where $C_G$ is the fuel cost of all thermal generating units; $C_{Gi}$ is the fuel cost of the $i^{th}$ thermal generator unit; $a_i, b_i, c_i$ are the fuel cost coefficients of $i^{th}$ thermal generator unit; $P_{Gi}$ is the active power of $i^{th}$ thermal generator unit; $N_G$ is the number of thermal generator units including the thermal slack generator [2, 3].

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3.1.2. The active power losses \( (P_{\text{loss}}\text{(MW)}) \)
The active power losses of the transmission line can be formulated as:

\[
P_{\text{loss}} = \sum_{k=1}^{N} G_{(i,j)} \left( V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_{ij}) \right)
\]  

(3)

where \( N \) is the number of transmission line; \( G_{(i,j)} \) is the line mutual conductance between bus \( i \) and \( j \); \( V_i, V_j \) are the per unit magnitude voltages of buses \( i \) and \( j \) respectively; \( \delta_{ij} \) are the phase difference angle of the voltage \( V_i \) and \( V_j \) respectively [2, 3].

3.1.3. The Voltage Deviation \( VD \) \( (\text{pu}) \)
The voltage deviation at the load buses can be formulated as:

\[
VD = \sum_{i=1}^{NL} (V_i - 1)^2
\]  

(4)

where \( VD \) is the total voltage deviation at the load buses; \( V_i \) is the per unit magnitude voltage at load bus \( i \) and \( NL \) is the number of load buses [3].

3.2. Control variables
The propose algorithm used three types of the control variables, the magnitude voltage of the generator \( (|V_G|) \), the tap changer of the transformer \( (T) \) and the active power of the generator except the slack \( (P_G) \). The vector of control variables \( (CV) \) is represented in equation (5)

\[
CV_n = |V_{G1}|, ..., |V_{GNG}|, T_1, ..., T_{NT}, P_{G2}, ..., P_{GNG}
\]  

(5)

where \( NG, NT \) are the total number of generators and transformer respectively; \( n \) is the number of control variables [3, 4]

3.3. State variables
The vector of the state variables \( (SV) \) in this article include four type of variables, the Transient Stability \( TS \) of the system, the active power of the slack generator \( (P_{GS}) \), the reactive power of the generators \( (Q_G) \) and the magnitude of the load voltage \( (|V_L|) \); \( m \) is the number of state variables [3, 4].

\[
SV_m = TS, P_{GS}, Q_{G1}, ..., Q_{GNG}, |V_{L1}|, ..., |V_{LN}|\]

(6)

3.4. System constraints
The minimization of the above objective functions are subjected to a number of equality and inequality constraints

3.4.1. Equality constraints
The load flow analysis in the equation (7) and (8) represent the equality constraints

\[
\sum_{i=1}^{NB} P_i - (P_{Gi} - P_{Li}) = V_i \sum_{j=1}^{NB} V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] = 0
\]  

(7)

\[
\sum_{i=1}^{NB} Q_i - (Q_{Gi} - Q_{Li}) = V_i \sum_{j=1}^{NL} V_j [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})] = 0
\]  

(8)

where \( NB \) is the number of buses except the slack bus; \( NL \) is the number of load buses; \( P_i, Q_i \) are the active and reactive power injection into \( i^{th} \) bus respectively; \( P_{Gi}, Q_{Gi} \) are the generator active and reactive power at bus bar \( i \) respectively; \( P_{Li}, Q_{Li} \) are the load active and reactive power at bus bar \( i \).
respectively. $G_{ij}$ and $B_{ij}$ are the line transfer conductance and susceptance between bus $i$ and bus $j$ respectively [3, 5].

3.4.2. Inequality constraints

The inequality constraints of the system have two parts

- The inequality constraints of the control variables
  
  $$V_{G_i,\text{min}} \leq V_{G_i} \leq V_{G_i,\text{max}} \quad i = 1,2, \ldots, NG$$
  $$T_{i,\text{min}} \leq T_i \leq T_{i,\text{max}} \quad i = 1,2, \ldots, NT$$
  $$P_{G_i,\text{min}} \leq P_{G_i} \leq P_{G_i,\text{max}} \quad i = 1,2, \ldots, NG - 1 \text{ except the slack}$$

  where $V_{G_i,\text{min}}$, $V_{G_i,\text{max}}$ are the minimum and maximum magnitude voltage limit of generator $i$ respectively; $T_{i,\text{min}}$, $T_{i,\text{max}}$ are the minimum and maximum tap changer limit of transformer $i$ respectively; $P_{G_i,\text{min}}$, $P_{G_i,\text{max}}$ are the minimum and maximum active power limit of generator $i$ except the slack respectively.

- The inequality constraints on state variable

  \[ Stability \ system \ according \ to \ increasing \ the \ circuit \ breaker \ clearing \ time \]

  $$V_{L_i,\text{min}} \leq V_{L_i} \leq V_{G_i,\text{max}} \quad i = 1,2, \ldots, NL$$
  $$Q_{G_i,\text{min}} \leq Q_{G_i} \leq Q_{G_i,\text{max}} \quad i = 1,2, \ldots, NG$$
  $$P_{G_S,\text{min}} \leq P_{G_S} \leq P_{G_S,\text{max}}$$

  $V_{L_i,\text{min}}$, $V_{G_i,\text{max}}$ are the minimum and maximum magnitude voltage of the load bus $i$;
  $Q_{G_i,\text{min}}$, $Q_{G_i,\text{max}}$ are the minimum and maximum reactive power of generator $i$;
  $P_{G_S,\text{min}}$, $P_{G_S,\text{max}}$ are the minimum and maximum active power of the slack generator [3, 6].

4. Transient Stability Analysis

The propose algorithm in this article deals with the transient stability according to the occurrence of fault. The swing equation of multi generators are satisfied as:

$$\frac{H_{Gi}}{\pi f} \frac{d^2 \delta_{Gi}}{dt^2} = P_{mGi} - P_{eGi}$$

$$P_{eGi} = \sum_{j=1}^{m} |E_{Gi}||E_{Gj}||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j)$$

where $P_{mGi}$ is the mechanical output active power of the generator $i$; $P_{eGi}$ is the electrical active power of the generator $i$ according to the load flow analysis in equation (10); $\delta_{Gi}$ is the rotor angle of the generator $i$; $H_{Gi}$ is the inertia constant of the generator $i$; $f$ is the system frequency; $\frac{d^2 \delta_{Gi}}{dt^2}$ is the acceleration factor of the generator $i$; $E_{Gi}$, $E_{Gj}$ are the internal voltage of the generator $i$ and $j$ respectively. The transient stability model includes two state variables

$$\frac{d\delta_{Gi}}{dt} = \Delta \omega_{Gi}$$

$$\frac{d^2 \delta_{Gi}}{dt^2} = \frac{d\Delta \omega_{Gi}}{dt} = \frac{\pi f}{H_{Gi}} (P_{mGi} - P_{eGi})$$

where $\Delta \omega_{Gi}$ is the rotor velocity of the generator $i$. In order to solve these two state equations, the propose algorithm used the Modified Eulers Method, where [7, 9, 10]
\[ \delta_{G(t+1)} = \delta_{G(t)} + \left( \frac{d\delta}{dt} \right|_{\Delta W_{G(t)}} + \frac{d\delta}{dt} \right|_{\Delta W_{G(t+1)}} \right) \Delta t \] (13)

\[ \Delta W_{G(t+1)} = \Delta W_{G(t)} + \left( \frac{d\Delta W}{dt} \right|_{\delta_{G(t)}} + \frac{d\Delta W}{dt} \right|_{\delta_{G(t+1)}} \right) \Delta t \] (14)

5. Particle swarm optimization

Particle swarm optimization PSO is one of the modern optimization techniques that inspired from the social behaviours of bird flocking for searching the food. It developed by Kennedy and Eberhart in 1995. PSO technique try to search the optimal solution using a population of particles, where each particle represents a candidate solution of the problem. These particles constitute a swarm. The particles moving through the search region with a random velocity looking for the optimal solution and each particle change its position according to its own experience (best position of the particle (pbest)) and the experience of neighboring particles (best position in the swarm(gbest)). The velocity of each particle are represented in the equation (15), where:

\[ v_{ip}^t = wv_{ip}^{t-1} + a_1 \times rand_1 \times (pbest_{ip}^{t-1} - x_{ip}^{t-1}) + a_2 \times rand_2 \times (gbest_i^{t-1} - x_{ip}^{t-1}) \] (15)

where \( i \) (1, 2, ..., n), \( p \) (1, 2, ..., M); \( n \) is the number of control variables; \( M \) is the number of particles in each control variables; \( t \) is the currently iteration number; \( v_{ip}^{t-1} \) is the previously particle velocity; \( pbest \) is the best position of each particle; \( gbest \) is the best position of all pbest in the swarm; \( a_1 \) & \( a_2 \) are the acceleration constants; \( rand \) is the randomly constant between 0 and 1; \( x_{ip}^{t-1} \) is the previously particle position. \( w \) is the function of the weight and calculating according to equation (16);

\[ w = w_{max} - \left( \frac{w_{max} - w_{min}}{T} \right) \times t \] (16)

where \( w_{max} \) is the maximum value of the weight = 0.9; \( w_{min} \) is the minimum value of the weight = 0.4; \( T \) is the maximum iteration. The particles update its position and velocity into their pbest and gbest positions at each time. The new particle position \( x_{ip}^t \) are update according to the following equation

\[ x_{ip}^t = x_{ip}^{t-1} + v_{ip}^t \] (17)

The particles position \( pbest \) & \( gbest \) are update for each iteration as follow:

- **Updating of pbest position**
  
  If \( f(x_{ip}^t) < f(pbest_{ip}^{t-1}) \rightarrow pbest_{ip}^t = x_{ip}^t \) & \( f(x_{ip}^t) = f(x_{ip}^t) \)
  
  If \( f(x_{ip}^t) > f(pbest_{ip}^{t-1}) \rightarrow pbest_{ip}^t = pbest_{ip}^{t-1} \) & \( f(x_{ip}^t) = f(pbest_{ip}^{t-1}) \)

- **Updating of gbest position**
  
  If \( f(gbest_i^t) < f(gbest_i^{t-1}) \rightarrow gbest_i^t = gbest_i^{t-1} \) & \( f(gbest_i^t) = f(gbest_i^t) \)
  
  If \( f(gbest_i^t) > f(gbest_i^{t-1}) \rightarrow gbest_i^t = gbest_i^{t-1} \) & \( f(gbest_i^t) = f(gbest_i^{t-1}) \)

where the symbol \( (f) \) is refers to an objective function like the active power losses or fuel cost or voltage deviation. If the iteration number is reached the maximum number of iteration \( T \), the program will be stopped and the final result are obtained \( [2, 3, 10, 11] \).
6. Result and Discussion

Two systems of IEEE 9 bus and IEEE 30 bus are tested for transient stability according to the fault assurance based on minimization the objective functions of active power losses (MW), fuel cost ($/hr) and voltage deviation (pu) separately for each one using Particle Swarm Optimization.

The propose algorithm assume that the internal voltage magnitude of the generators are constant before, during and after the fault occurrence. Also the damper winding are not used. The propose algorithm used the response of the generators rotor angle with respect to the slack generator rotor angle, as example the rotor angle response of the second generator are \( \delta_{G2} = \delta_{G2} - \delta_{G1} \), where \( \delta_{G2} \) is the rotor angle response of the second generator; \( \delta_{G1} \) is the rotor angle response of the slack generator and so on for other generators.

6.1 IEEE 9 bus

This system has three generators \( G_1, G_2 \) and \( G_3 \). The first one is the slack generator and the others are PV generators as shown in the Fig. 1. Table 1 shows the data of power generation limits with the cost coefficient of each unit [1, 12].

![IEEE 9 bus system](image)

**Figure 1.** IEEE 9 bus system

| Unit Number | \( P_{G1} (\text{min}) \) (MW) | \( P_{G1} (\text{max}) \) (MW) | \( Q_{G1} (\text{min}) \) (MW) | \( Q_{G1} (\text{max}) \) (MW) | \( a \) $/h | \( b \) $/Mwh | \( c \) $/Mw^2h |
|-------------|-----------------|-----------------|-----------------|-----------------|------|------|------|
| 1           | 10              | 300             | -20             | 200             | 150  | 2    | 0.1100 |
| 2           | 30              | 300             | -20             | 300             | 600  | 1.2  | 0.0850 |
| 3           | 25              | 250             | -20             | 300             | 355  | 1    | 0.1225 |

The fault occurs in the line (5-7) near the bus 5. Increasing the circuit breaker clearing time tc lead to increase the generator rotor angle and go to the instability system. The maximum clearing time that keep the system stable is called Critical Clearing Time TCC and equal to 0.32 sec as shown in the figure (2). After that at time 0.33 sec, the system will be unstable as shown in the figure (3).

With increasing the clearing time at 0.5 sec , the rotor angle increase and the system is more unstable and faraway from the stability point as shown in the figure (4).

In order to solve the problem of instability system, the propose algorithm used the transient stability under fault condition as a constraints in the state variables of the optimal power flow and using the Particle Swarm Optimization to find the optimal control variables and minimize the objective functions.
In this system two types of the control variables have been used, the magnitude of the generator voltage and the active power of the generator except the slack. Therefore the total number of control variables will be five and the vector of control variables is:

$$CV_5 = [V_{G1}, V_{G2}, V_{G3}, P_{G2}, P_{G3}]$$

(15)

PSO choose an optimal values of these control variables to minimize the three objective functions of the active power losses (MW), the fuel cost of the thermal generator ($/hr) and the voltage deviation (pu) separately for each one.

Figures (5, 6 and 7) show the response of the active power losses, fuel cost and the voltage deviation respectively with its number of iterations. After 25 iteration PSO minimize the active power losses from (4.6410 MW) to (2.3212 MW) and the fuel cost from (5451.8 $/h) to (5315.8 $/h) and the voltage deviation from (0.0028 pu) to (0.000637 pu) as shown in table (2).

Figures (8, 9 and 10) show the response of generators rotor angle at clearing time tc 0.33, 0.5 and 1.5 at minimum active power losses (2.3212 MW). Minimization the active power based on PSO succeed to keep the system stable with increasing the circuit breaker clearing time tc.

The figures (11, 12 and 13) show the response of generators rotor angle at clearing time 0.33, 0.5 and 0.6 sec at minimum fuel cost (5315.8 $/h). Minimization the fuel cost based on POS succeed to keep the system stable with increasing the clearing time until 0.5 sec and fail at 0.6 sec.

Figures (14, 15 and 16) show the response of generator rotor angle at clearing time 0.33, 0.5 and 1.5 at minimum voltage deviation (0.000637 pu). Minimization the voltage deviation based on POS succeed to keep the system stable with increasing the clearing time.

Table (2) shows the minimum, maximum, initial and optimal control variables of IEEE 9 bus with its objective function of active power losses, fuel cost and voltage deviation.

Table (3) shows a comparison between the Critical Clearing Time TTC of the propose algorithm and reference [5] for the Transient Stability under fault condition of the IEEE 9 bus at the minimum objective function of the fuel cost. According to this table the TTC in [5] is equal to 0.225 sec at minimum fuel cost of 5304.4 $/h with the transient stability while the propose algorithm has TTC equal to 0.5 sec at minimum fuel cost of 5315.8 $/h. The Critical Clearing Time TTC of the propose algorithm is larger than TTC in [5] at the minimum fuel cost. Increasing the Critical Clearing Time TTC is very important for stable the system in the transient analysis.

In the case of minimum active power losses at 2.3212 MW and minimum voltage deviation at 0.000639 pu of the IEEE 9 bus system, the propose algorithm tested a wide number of clearing time such as 0.33, 0.5 and 1.5 sec (in text of article) and another number of clearing time more than 1.5 sec such as 10, 20, 30 sec,…., etc. All of these clearing time have a stable system. That’s mean there is no Critical Clearing Time TTC at all the tested numbers of clearing time with minimum objective function of active power losses and voltage deviation and this is an excellent result.

| Table 2. Optimal Power Flow result of IEEE 9 bus based on PSO technique. |
|-------------------------------------------------|-----------|-----------|-----------------|-----------|
| Control variables                              | Limit     | Initial   | Control variables when Objective function is |
|                                                | Minimum   | Maximum   | Fuel cost ($/h) | Losses (MW) | Voltage deviation (pu) |
| Generator active power (MW)                    | $P_{G2}$  | 30        | 300            | 163        | 134.2             | 82.34 | 42.162 |
| Generator magnitude voltage (pu)               | $P_{G3}$  | 30        | 250            | 85         | 94.19             | 76.58 | 50    |
| $V_{G1}$                                       | 1.000     | 1.100     | 1.040           | 1.000      | 1.1000            | 1.1000 | 1.0418 |
| $V_{G2}$                                       | 1.000     | 1.100     | 1.025           | 1.000      | 1.0925            | 1.0340 |
| $V_{G3}$                                       | 1.000     | 1.100     | 1.025           | 1.0987     | 1.0316            | 1.0174 |
| Fuel cost ($/h)                                | 10143     | 25515     | 5451.8          | 5315.8     | 6127.1            | 5940.7 |
| Losses (MW)                                    | 5.7827    | 46.2851   | 4.6410          | 3.2681     | 2.3212            | 3.1523 |
| Voltage deviation (pu)                         | 0.0033    | 0.0139    | 0.0028          | 0.0549     | 0.0505            | 0.000637 |
| Critical Clearing Time TCC (sec)               | 0.32      | 0.5       | -              | -          | -                 |

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Table 3. Comparison between [5] and the propose algorithm of IEEE 9 bus system.

| Objective Function | Critical Clearing Time TCC (sec) | Objective Function | Critical Clearing Time TCC (sec) |
|--------------------|----------------------------------|--------------------|----------------------------------|
| Ref. 5 with        | Proposed algorithm               |                     |                                  |
| Fuel cost ($/h)    | 5304.4                           | 5315.8             | 0.225                            | 0.5                              |
| Active losses (MW) | -                                | -                  | 2.3212                           | There is no Critical Clearing Time TCC and the system is stable at all the tested values of the clearing time t\(_c\) 0.33, 0.5, 1.5, 10, 20, etc |
| Voltage deviation (pu) | -                              | -                  | 0.000637                         | There is no Critical Clearing Time TCC and the system is stable at all the tested values of the clearing time t\(_c\) 0.33, 0.5, 1.5, 10, 20, etc |

Figure 2. Generator rotor angle of IEEE 9 bus at initial operation with clearing time t\(_c\) 0.32 sec

Figure 3. Generator rotor angle of IEEE 9 bus at initial operation with clearing time t\(_c\) 0.33 sec
Figure 4. Generator rotor angle of IEEE 9 bus at initial operation with clearing time tc 0.5 sec

Figure 5. Active power losses of IEEE 9 bus based on POS optimization technique

Figure 6. Fuel cost of IEEE 9 bus based on POS optimization technique
Figure 7. Voltage Deviation of IEEE 9 bus based on POS optimization technique

Figure 8. Generator rotor angle of IEEE 9 bus at min. active power losses with clearing time 0.33 sec

Figure 9. Generator rotor angle of IEEE 9 bus at min. active losses with clearing time 0.5 sec
Figure 10. Generator rotor angle of IEEE 9 bus at min. active losses with clearing time 1.5 sec

Figure 11. Generator rotor angle of IEEE 9 bus at min. fuel cost with clearing time 0.33 sec

Figure 12. Generator rotor angle of IEEE 9 bus at min. fuel cost with clearing time 0.5 sec
Figure 13. Generator rotor angle of IEEE 9 bus at min. fuel cost with clearing time 0.6 sec

Figure 14. Generator rotor angle of IEEE 9 bus at min. voltage deviation with clearing time 0.33 sec

Figure 15. Generator rotor angle of IEEE 9 bus at min. voltage deviation with clearing time 0.5 sec
6.2 IEEE 30 bus

The IEEE 30 bus system has six generators $G_1, G_2, G_5, G_6, G_{11}$ and $G_{13}$. The slack generator is the first one and the others are PV generators as shown in the figure (17). Also this system has four transformer, 41 lines and 21 load. Table (4) shows the generation limits and cost coefficients of each units [13].

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**Figure 16.** Generator rotor angle of IEEE 9 bus at min. voltage deviation with clearing time 1.5 sec

**Figure 17.** One Line Diagram of IEEE-30
This system has three type of control variables, the generator magnitude voltage; the transformer tap changer and the generator active power except the slack. Therefore the total number of control variables are 15. The vector of the control variables $\mathbf{CV}_{15}$ are

$$CV_{15} = ||V_{G1}|, |V_{G2}|, |V_{G5}|, |V_{G6}|, |V_{G11}|, |V_{G13}|, T_{6-9}, T_{6-10}, T_{4-12}, T_{27-28}, P_{G2}, P_{G5}, P_{G6}, P_{G11}, P_{G13}|$$

where the $|V_{G}|$ is the generator magnitude voltage; $T$ is the transformer tap changer and $P_{G}$ is the generator active power except the slack. The fault occurs in the line (2-5) near the bus 5. The maximum clearing time tc that keep the system stable is called the Critical Clearing Time TCC which is equal to 0.17 sec as shown in the figure (18). With increasing the clearing time tc at 0.18 sec, the system will be unstable as shown in the figure (19). The system remains unstable with increasing the clearing time tc.

Figure (20) shows the response of the generators rotor angle at clearing time tc equal to 0.5 sec. PSO optimization technique has been used to minimize the Optimal Power Flow objective functions of active power losses, fuel cost and Voltage Deviation and solve the problem of the instability system by insertion the transient stability analysis as a constraint in the state variable of the Optimal Power Flow.

Figures (21, 22 and 23) show the response of active power losses, fuel cost and the voltage deviation respectively with respect the number of iterations based on PSO optimization technique. PSO minimize the objective functions of active power losses from (5.83MW) to (3.3391 MW) and fuel cost from (901.96 $/h) to (801.22 $/h) and voltage deviation from (0.0869 pu) to (0.0099 pu) after 25 iteration.

Figures (24, 25 and 26) show the response of generators rotor angle at clearing time tc 0.18, 0.5 and 1.5 with minimum active power losses of 3.3391 MW. Minimization the active power based on POS succeeded to keep the system stable with increasing the clearing time.

Figures (27, 28 and 29) show the response of generators rotor angle at clearing time tc 0.18, 0.21 and 0.5 with minimum fuel cost of 801.2271$/h. Minimization the fuel cost based on POS fail to keep the system stable with increasing the clearing time.

Figures (30, 31 and 32) show the response of generators rotor angle at clearing time tc 0.18, 0.5 and 1.5 with minimum voltage deviation of 0.0099 pu. Minimization the voltage deviation based on POS succeeded to keep the system stable with increasing the clearing time.

Table (5) shows the minimum, maximum, initial and optimal control variables of IEEE 30 bus with its objective function of active power losses, fuel cost and voltage deviation based on PSO technique.

| Unit Number | $P_{G1}(\text{min})$ (MW) | $P_{G1}(\text{max})$ (MW) | $Q_{G1}(\text{min})$ (MW) | $Q_{G1}(\text{max})$ (MW) | $a$ ($$/\text{h})$ | $b$ ($$/\text{MWh})$ | $c$ ($$/\text{MW}^2\text{h})$ |
|-------------|-------------------------|--------------------------|-------------------|-------------------|------------|-------------|-------------|
| 1           | 50                      | 200                      | -20               | 200               | 0.00       | 2.0         | 0.0037      |
| 2           | 20                      | 80                       | -20               | 100               | 0.00       | 1.75        | 0.0175      |
| 5           | 15                      | 50                       | -15              | 80                | 0.00       | 1.00        | 0.0625      |
| 8           | 10                      | 35                       | -15              | 60                | 0.00       | 3.25        | 0.0083      |
| 11          | 10                      | 30                       | -10              | 50                | 0.00       | 3.00        | 0.0250      |
| 13          | 12                      | 40                       | -15              | 60                | 0.00       | 3.00        | 0.0250      |

Table 4. Power generation limits with cost coefficients for IEEE 30 bus.
Figure 18. Generator rotor angle of IEEE 30 bus at initial operation with clearing time 0.17 sec.

Figure 19. Generator rotor angle of IEEE 30 bus at initial operation with clearing time 0.18 sec.

Figure 20. Generator rotor angle of IEEE 30 bus at initial operation with clearing time 0.5 sec.
Figure 21. Active power losses of IEEE 30 bus based on PSO optimization technique.

Figure 22. Fuel cost of IEEE 30 bus based on PSO optimization technique.

Figure 23. Voltage Deviation of IEEE 30 bus based on PSO optimization technique.
Figure 24. Generator rotor angle of IEEE 30 bus at min. active losses with clearing time 0.18 sec.

Figure 25. Generator rotor angle of IEEE 30 bus at min. active losses with clearing time 0.5 sec.

Figure 26. Generator rotor angle of IEEE 30 bus at min. active losses with clearing time 1.5 sec.
Figure 27. Generator rotor angle of IEEE 30 bus at min. fuel cost with clearing time 0.18 sec.

Figure 28. Generator rotor angle of IEEE 30 bus at min. fuel cost with clearing time 0.21 sec.

Figure 29. Generator rotor angle of IEEE 30 bus at min. fuel cost with clearing time 0.5 sec.
Figure 30. Generator rotor angle of IEEE 30 bus at min. voltage deviation with clearing time 0.18 sec.

Figure 31. Generator rotor angle of IEEE 30 bus at min. voltage deviation with clearing time 0.5 sec.

Figure 32. Generator rotor angle of IEEE 30 bus at min. voltage deviation with clearing time 1.5 sec.
Table 5. Optimal Power Flow result of IEEE 30 bus based on PSO technique.

| Control Variables | Limits | Initial value | Control variables when Objective function is |
|-------------------|--------|---------------|---------------------------------------------|
|                   | Minimum | Maximum       | Fuel cost ($/h) | Losses (MW) | Voltage deviation (pu) |
| Generator active power except slack (MW) |
| \( P_{G3} \) | 20 | 80 | 80 | 49.1428 | 80 | 42.1627 |
| \( P_{G5} \) | 15 | 50 | 50 | 21.6777 | 50 | 50 |
| \( P_{G8} \) | 10 | 35 | 20 | 17.5167 | 35 | 35 |
| \( P_{G11} \) | 10 | 30 | 20 | 12.0088 | 30 | 30 |
| \( P_{G13} \) | 12 | 40 | 20 | 12.0000 | 40 | 40 |
| Generator magnitude voltage (pu) |
| \( V_{G1} \) | 0.95 | 1.10 | 1.05 | 1.0916 | 1.0659 | 1.0418 |
| \( V_{G3} \) | 0.95 | 1.10 | 1.04 | 1.0709 | 1.0602 | 1.0340 |
| \( V_{G5} \) | 0.95 | 1.10 | 1.01 | 1.0273 | 1.0316 | 1.0174 |
| \( V_{G8} \) | 0.95 | 1.10 | 1.01 | 1.0417 | 1.0445 | 1.0096 |
| \( V_{G11} \) | 0.95 | 1.10 | 1.05 | 1.1000 | 1.1000 | 1.0345 |
| \( V_{G13} \) | 0.95 | 1.10 | 1.05 | 1.1000 | 1.0686 | 1.0399 |
| Transformer tap changer (pu) |
| \( T_{6-9} \) | 0.9 | 1.10 | 1.078 | 1.0041 | 1.0193 | 1.0051 |
| \( T_{6-10} \) | 0.9 | 1.10 | 1.069 | 1.0471 | 1.0627 | 0.9898 |
| \( T_{4-12} \) | 0.9 | 1.10 | 1.032 | 0.9277 | 0.9000 | 0.9296 |
| \( T_{27-28} \) | 0.9 | 1.10 | 1.068 | 0.9539 | 0.9753 | 0.9390 |

Table 6. Comparison between [5] and the propose algorithm of IEEE 30 bus system.

| Transient Stability | Ref. 5 with Objective Function | Propose algorithm Objective Function | Critical Clearing Time TCC (sec) |
|---------------------|--------------------------------|--------------------------------------|--------------------------------|
| Fuel cost ($/h)     | 814.45                         | 801.227                              | 0.20 |
| Losses (MW)         | 852.13                         | 968.74                               | 901.96 |
| Voltage deviation (pu) | 0.1073                        | 0.0125                               | 0.0869 |
| Critical Clearing Time TCC (sec) | 0.17                          | 0.20                                 | - |
| Active losses (MW)  | -                              | -                                    | 3.3391 |
| Voltage deviation (pu) | -                            | -                                    | 0.0099 |

7. Conclusion
Minimization the objective function of the Optimal Power Flow has been used to solve the problem of the transient stability analysis according to the fault occurrence in the system where the stability condition are used as a constraint in the state variables of the Optimal Power Flow. This article used three objective functions, the active power losses, the fuel cost of the thermal unit and the voltage
deviation at the load buses. Particle swarm optimization has been used to minimize the objective function based on choosing an optimal control variables keeping the state variables in their limits. The propose algorithm used three types of the control variables, the generator magnitude voltage, the trasformer tap changer and the generators active power except the slack, while the state variables are the active power of the slack generator, the reactive power of the generators, the manitude voltage at the load buses and the transient stability condition according to increasing the clearing time of the circuit breaker. In both systems of IEEE 9 bus and IEEE 30 bus, the minimization of active power losses and voltage deviation succeeded in solving the instability of the system with increasing the clearing time while the minimization the fuel cost fail for this purpose. The propose algorithm gives a good result when copmare with other reference has the same data.

8. References
[1] AL-bahrani L T 2018 “Transient Stability Optimization based on increasing the Critical Clearing Time using Particle Swarm Optimization” International Journal of Engineering & Technology, 7, (4.19), pp. 874-879.
[2] AL-bahrani L T, Dumbrava V 2016 “Optimal Power Flow Based On Particle Swarm Optimization” U.P.B. Sci. Bull., Series C, Vol. 78, Iss. 3, pp. 253-264.
[3] AL-Bahrami L T 2015 “Optimal Power Flow (OPF) with different Objective Function based on modern heuristic optimization techniques,” PhD Thesis, University POLITEHNICA of Bucharest, Romania.
[4] Kursat A and Ulas K 2013 “Solution of transient stability-constrained optimal power flow using artificial bee colony algorithm” Turkish Journal of Electrical Engineering & Computer Sciences, 21, pp. 360 – 372.
[5] Oubbati Y, Arif S, Abido A 2016 “Improved PSO Applied to the Optimal Power Flow with Transient Stability Constraints” J.Electrical System, 12-4, pp. 672-686.
[6] Huy N, Linh T and Dieu 2017 “ A novel approach to solve transient stability constrained optimal power flow problems” Turkish Journal of Electrical Engineering & Computer Sciences, 25, pp. 4696-4705.
[7] Ulas K and Kursat A 2013”Transient stability constrained optimal power flow solution of ac-dc systems using genetic algorithm” 3rd International Conference on Electric Power and Energy Conversion Systems, Yildiz Technical University, Istanbul, Turkey.
[8] Chi S and Zhe C 2010 “ An Optimal Power Flow (OPF) Method with Improved Power System Stability” Proceedings of the 45th International Universities Power Engineering Conference, UPEC, pp. 1-6 IEEE Pres
[9] Sadat H 1999 “ Power System Analysis” McGraw Hill Education.
[10] Duncan J G, Mulukutla S S and Thomas J O 2008 “Power System Analysis and Design” Fourth Edition, Thomson,
[11] Ignacio A C 2015 “Transient Stability Constrained Optimal Power Flow: Improved Models and Practical Applications” PhD Thesis, University of CarlosIII De, Madrid.
[12] Abdul baeer M 2014 “ Transient Stability Improvement of Multi-machine Power System using Fuzzy Controlled TCSC ” JOSR Journal of Electrical and Electronics Engineering, Vol. 9, Issue 1, Ver 1, pp. 28-40.
[13] Lee K, Park Y and Ortiz J 1985, “A united approach to optimal real and reactive power dispatch”, IEEE trans. on Power apparatus and systems, vol. PAS-104, No 5, pp 1147-1153.