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Research paper

Transient Stability Optimization based on increasing the Critical Clearing Time using Particle Swarm Optimization

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Abstract

Transient stability Analysis under fault condition is one of the most important concept for a secure and reliable power system operation. Any delay time to cleared the fault and remove the line may be caused the system unstable. Increasing the clearing timetc leads to increase the rotor angle of the generator and go towards the instability system. The clearing time before the system become unstable is called the critical clearing time tcc. This article design a new architecture algorithm to improve the transient stability of the system under fault condition by increase the critical clearing time without adding any external dives. An artificial intelligence technique of Particle Swarm Optimization PSO has been used for this purpose. PSO technique minimize the maximum rotor angle of the generator according to optimize the control variable of the system such as the magnitude voltage of the generator. A load flow analysis based on Newton Raphson method has been used for the pre fault calculation. The two state equations for both during and post fault cases are solved using the modified Euler method to calculate the rotor angle of the generators. Different cases of clearing time are tested in this article to specified the system stability and access to the critical clearing time. The propose algorithm has been applied on the IEEE 9 bus system. This algorithm improve the system transient stability by increasing the critical clearing time by 28%. The propose algorithm are programming by author using matlab software.

Keywords: *Transient Stability Analysis, Fault condition, rotor swing angle, critical clearing time, Particle Swarm Optimization*.

1. Introduction

The Transient Stability is the capability of power system to remain in synchronism and continuous of supplying the electrical energy when a heavy or large disturbance is occur in the system like loss of the generation units, sudden large increase in the load, fault,…..etc.[1].The response of the transient stability influence on the rotor angle and power angle relation. In general the rotor angle of the generator is taken as an index of the transient stability analysis[2]. The faults are one of the most important and risk topics that affect on the transient stability analysis according to the cleared time (delay time) of the circuit breaker to cleared the fault and remove the line [3].Any cleared time may be caused the system instability where increasing the cleared time lead to increase the rotor swing angle of some generators and loss the synchronism with the other generators. It depend on the ability of the system to swing rotor process and restore the equilibrium between the electrical power and mechanical power re-backing the system to its steady state [4].The maximum time that the system remain stable during the occurrence of the fault is called critical clearing time. After the critical clearing time the system become unstable [5].

This article proposed a new technique for transient stability optimization based on minimization the maximum rotor swing angle of the generator using an artificial intelligence of particle swarm optimization. Minimization the maximum rotor swing angle leads to increase the critical clearing time and improve the transient stability without using any external devise. It depends on re-adjusting the setting of some parameters on the power system like the generator magnitude voltage, tap changer of the transformer, shunt injection capacitance and generator active power.

2. Lecture Revie

Different techniques has been used to improve the transient stability. Some of these techniques are used an external devise such as FACTS devise. Other techniques has been used a simulator programming like the Electrical Transient Analyzer Program (ETAP),..etc. A fuzzy controlled Thyristor Controlled Series Compensation (TCSC) devise is used to improve the transient stability in [2].An Electrical Transient Analyzer Program (ETAP) has been used in [3] to show the effect of Power System Stabilizer (PSS) and shunt capacitor on the reduction of the oscillation for the generator electrical power and satisfying the steady state power transfer. In[4] SVC FACTS devise of a MATLAB SIMULINK is used to modeled and improve the transient stability of the system, also in this reference a Static Var Compensator and a series compensator have been used in the network to improve the transient stability and to increase the transmission capacity of the system. A combination of Power System Stabilizer PSS and Static Var Compensator SVC has been used to improve the transient stability under fault condition[5]. [6] concludes that's SVC is the best FACTs devise among the TCSC and Static Synchronous Series Compensator SSSC for improving the rotor angle transient stability in Matlab Simulink software. The Distributed Power Flow Controller (DPFC) in combination with fuzzy controller is used to improve the transient stability of Single Machine Infinite Bus system [7].

3. Mathematical Model of Transient Stability under Fault Condition

The mathematical model of Transient Stability of multi machine are presented according to the following steps [8,9]

1) Calculate the load flow analysis of the n bus systemusingNewton Raphson method.

2) Calculate the internal transient voltage of each generator according to load flow in step 1, where

$$\bar{E}_i = V_i + \bar{x}_{di} I_i = |\bar{E}_i| \llcorner \delta_i \tag{1}$$

$$I_i = \frac{S_i^*}{V_i^*} = \frac{(P_i + jQ_i)^*}{V_i^*} = \frac{P_i - jQ_i}{V_i^*} \tag{2}$$

where $i = 1,2,\ldots,m$; $m$is the number of the generators including slack generator;I_i is the current at the bus i;S_i is the apparent power at the bus i;$\bar{E}_i$ is the transient internal voltage of the generator i;δ_i is the rotor angle of the generator i,$\bar{x}_{di}$ is the transient internal direct reactance of the generator i;V_i is the terminal voltage at bus i.

3) The mechanical power of each machineis equal to the output electrical active power of each generator, where

$$P_{mi} = P_{Gi} \quad i = 1,2,\ldots\ldots,m \tag{3}$$

$$P_{Gi} = \sum_{j=1}^{m} |E_i||E_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \tag{4}$$

where P_{mi} is the mechanical active power of the generator i;$P_{Gi}$is the electrical active output of generator i after load flow calculation;Y_{ij} is the bus admittance element ij of the original bus admittance Y_{bus}; θ_{ij} is the angle of bus admittance element ij of original bus admittance Y_{bus}, where

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{1i} & Y_{1n} \\ Y_{i1} & Y_{ii} & Y_{in} \\ Y_{n1} & Y_{ni} & Y_{nn} \end{bmatrix} \tag{5}$$

4) Conversion the load that connected to bus i to the equivalent constant admittance using the following relation:

$$Y_{iL} = \frac{S_i^*}{|V_i|^2} = \frac{P_i - jQ_i}{|V_i|^2} \tag{6}$$

5) The constant load admittances Y_{iL} and the generator direct transientadmittance $\frac{1}{\bar{x}_{di}}$ are adding only to the diagonal element$Y_{ii}(Y_{11}, Y_{22}, \ldots, Y_{ii}, \ldots, Y_{nn})$ of the original bus admittance Y_{bus}. The new admittance presented asY_{n*n}.

6)In order to simplify the complexity of the Transient Stability Analysis of multi machine power system under fault condition and to include the internal voltages behind the direct transient reactance of generators, the new admittance Y_{n*n} of order n*n are reduction to the admittance Y_{red} oforder m*m according to Kron reduction method as inequation (7) [9].

$$Y_{red} = Y_{m*m} - Y_{m*n} Y_{n*n}^{-1} Y_{n*m} \tag{7}$$

where

$$Y_{m*m} = \begin{bmatrix} \frac{1}{\bar{x}_{d1}} & 0 & 0 \\ 0 & \frac{1}{\bar{x}_{di}} & 0 \\ 0 & 0 & \frac{1}{\bar{x}_{dm}} \end{bmatrix} \tag{8}$$

$$Y_{n*m} = Y_{m*n}^T = \begin{cases} -\frac{1}{\bar{x}_{di}} & \text{at the diagonal element} \\ 0 & \text{off diagonal element} \end{cases} \tag{9}$$

where $\bar{x}_{di}$ is the generator direct transient reactance of the generator i.According to three cases of the fault (pre, during and post), three reduction admittance are presented as follow:

a) The pre fault admittance matrix: The new admittance matrix Y_{n*n} are reduced to the prefault admittance matrix Y_{m*m}according to the Kron Reduction Method (elimination all the load nodes except the internal generator node).

b) The during fault admittance matrix: If a fault occurs in the line i-k near the bus k, the kth row and the kthcolum are removing from the new admittance Y_{n*n}. The new admittance matrix are reduced to during fault admittance matrix Y_{m*m} according to the Kron Reduction Method.

c) The post fault admittance matrix: The post fault admittance matrix can be calculated by removing the line i-k from the new admittance matrix $Y_{n*n}$and the element admittance of linei-kis subtracted from both diagonal elements Y_{ii} and Y_{kk} .The new admittance matrix are reduced to post fault admittance matrix Y_{m*m} according to the Kron Reduction Method [8].

7) Swing equation of multi machine can be expressed as:

$$\frac{H_i}{\pi f}\frac{d^2\delta_i}{dt^2} = P_{mi} - P_{ei} \tag{10}$$

where$P_{mi}$is the output active power of the generator i (mechanical power);$P_{ei}$is the electrical active power of the generator iand equal to equation (2|);δ_i is the rotor angle of the generator i;H_i is the inertia constant of the system; f is the system frequency;$\frac{d^2\delta_i}{dt^2}$is the Acceleration factor.

The transient stability include two state variables

$$\frac{d\delta_i}{dt} = \Delta w_i \tag{11}$$

$$\frac{d^2\delta_i}{dt^2} = \frac{d\Delta w_i}{dt} = \frac{\pi f}{H_i}(P_{mi} - P_{ei}) \tag{12}$$

whereΔw_i is the rotor velocity of the generator i.Many techniques are used to solve these two state equations (11 & 12). One of them is the Modified Eulers Method, where

$$\delta_{t+1} = \delta_t + \left(\frac{\left.\frac{d\delta}{dt}\right|_{\Delta w_t} + \left.\frac{d\delta}{dt}\right|_{\Delta w_{t+1}}}{2} \right)\Delta t \tag{13}$$

$$\Delta w_{t+1} = \Delta w_t + \left(\frac{\left.\frac{d\Delta w}{dt}\right|_{\delta_t} + \left.\frac{d\Delta w}{dt}\right|_{\delta_{t+1}}}{2} \right)\Delta t \tag{14}$$

Using the derivatives ($\frac{d\delta}{dt}$ and $\frac{d\Delta w}{dt}$) at the beginning of the interval (at t location) and at the end of the interval at (t+1), where the location $t + 1 = t + \Delta t$; Δt is step size in sec. [7]

The rotor swing equation can be classified into three equations according to the three cases of fault (pre, during and post fault).

4. Particle Swarm Optimization PSO

PSO is one of the most important evolutionary stochastic optimization techniques that can search the optimal value for a complicated system and undefined regain. It is inspired from the social behaviors of bird flocking or fish schooling for searching the food or runway from the enemy. The word particle means a bird or fish in the swarm. Each particle have a specific position and velocity in the searching space. The particle change its position at each times and moves in this searching space towards the optimal solution according to the modified velocity.PSO has the ability to control the local and global best solution in the search space and make a balance between them. This feature improve the search ability and overcomes the problems of convergence. PSO has the capability of developing into the global optimum instead of the local optimum with a random velocity by its memory experiences.PSO is very effective and useful in the practical system because it used the actual objective function without any assumption and approximation like the linearity or differentiability.PSO can treat with the discrete parameter in the practical system like the shunt capacitance and transformer tap changing. The searching space can be chosen arbitrary but in this article, it taken as a rectangular area of n×D dimension to search the optimal solution with a little time, wheren is the number of control variables and D is the number of candidate (particles) for each control variable.
The modified velocity of the particle *id*at iteration *k+1*are presented as the following equation:

$$v_{id}^{k+1} = wv_{id}^{k} + c_1 \times rand_1 \times (pbest_{id}^{k} - x_{id}^{k}) + c_2 \times rand_2 \times (gbest_{i}^{k} - x_{id}^{k}) \quad (15)$$

where *i*(1, 2,…, n), *d*(1, 2,…, D). The modified velocity consists of three important parts. The first part is the currently velocity (v_{id}^{k}).The second part is the local searching position $pbest_{id}^{k}$which related with self-experience of particle. The third part is global searching position $gbest_{i}^{k}$ whichrelated with the whole neighbourhood experience of particle; *w* is the weighting function; c_1&$c_2$are the acceleration positive constants for individual particles;*rand*is the regularly distributed random value between 0 and 1; $x_{id}^{k}$is the current position of particle *id* at $(k)^{th}$ iteration.
The new position x_{id}^{k+1} of particle *id* at $(k+1)^{th}$ iteration are modified according to the following equation

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \quad (16)$$

Inertia weight (w) that presented in equation (15) can be formulated according to the following equation

$$w = w_{max} - \left[\frac{w_{max} - w_{min}}{t_{max}}\right] * t \quad (17)$$

where w_{max}= initial or maximum weight = 0.9;w_{min} = final or minimum weight = 0.4;t_{max} = maximum iteration number; *t* is the currently iteration number.
For each iteration of the search, local position ($pbest_{id}^{k}$) and global position ($gbest_{i}^{k}$) are update as follow:

1. Local position:

a) If objective function$f(x_{id}^{k+1}) < f(pbest_{id}^{k})$ then $pbest_{id}^{k+1} = x_{id}^{k+1}$&$f(x_{id}^{k+1}) = f(x_{id}^{k+1})$

b) If objective function$f(x_{id}^{k+1}) > f(pbest_{id}^{k})$ then $pbest_{id}^{k+1} = pbest_{id}^{k}$&$f(x_{id}^{k+1}) = f(pbest_{id}^{k})$

2. Global position

a) If objective function$f(gbest_{i}^{k+1}) < f(gbest_{i}^{k})$then$gbest_{i}^{k+1} = gbest_{i}^{k+1}$)& $f(gbest_{i}^{k+1}) = f(gbest_{i}^{k+1})$

b) If $f(gbest_{i}^{k+1}) > f(gbest_{i}^{k})$) then $gbest_{i}^{k+1} = gbest_{i}^{k}$)& $f(gbest_{i}^{k+1}) = f(gbest_{i}^{k})$

The stopping condition is satisfied if the algorithm research the maximum iteration. The flow chart of the PSO technique can be presents as shown in Fig. 1 [10,11]

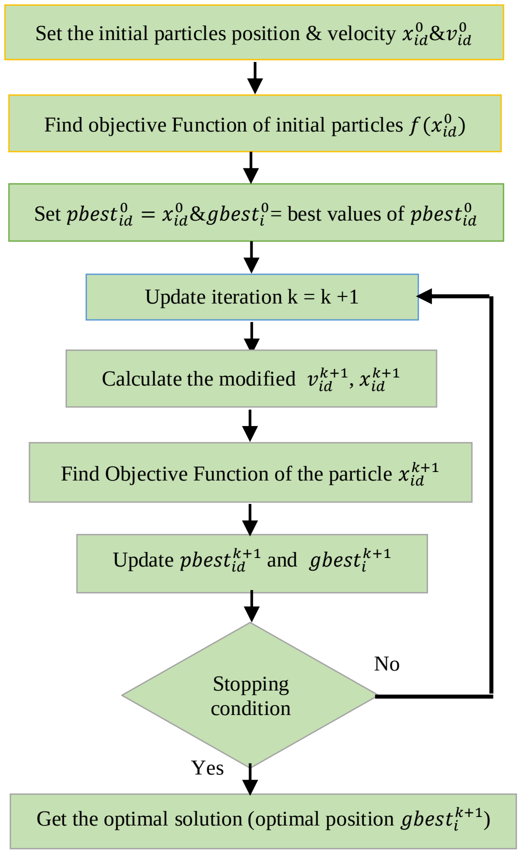

Fig. 1: Flow chart of PSO technique

5. Transient Stability Optimization of Multi Machine Based on PSO Technique

Transient Stability Optimization based on increasing the critical clearing time tcc can be achieved according to minimize the maximum generator rotor swing angle.PSO has been used for this purpose by optimization the control variables of the system such as the generator voltage magnitude, transformer tap changer, shunt injection capacitance and generator active power at the PV bus. The steps of transient stability optimization can be illustrate in the following steps:
1) The algorithm of this article has been prepared to calculate the generator internal voltage including the slack generator from equation (1)and the electrical power from equation (4).Due to equation (11), the initial rotor velocity of the generator Δw_{0i} are equal to be zero
2) In the first of operation at the pre fault case, the electrical power for each machine are equal to the mechanical power according to the stability of the system ($Pm = Pe$) and the acceleration factor is zero as in equation (12). In the during and post fault case, two state equations are presented as equations (11&12). From these two state equations the rotor angle of each machine with respect the slack generator has been calculated according to Modified Euler Method.
3)After cleared the fault at a delay time tc sec, the system may be stable or not. If the system has the ability to return the rotor to its

pervious position before the fault and decreasing the swing of the rotor towards the steady state condition, the system is stable. If its not, the swing of the rotor will be increase further and the system will be unstable.
4) Increasing the clearing time tc leads to increase the maximum rotor angle of the generators and make the system go towards the instability. The clearing time before the instability of the system is called the critical clearing time. In order to make the system stable after the critical clearing time tcc, an artificial intelligence of PSO technique has been used to minimize the objective function. The objective function in this article is the maximum rotor angle of the generators (phase difference between rotor angle of the generator and slack). Minimization the objective function can be achieved according to optimize the control variables.
6) After minimize the maximum rotor angle of the generator using PSO technique. The system has the ability to increase the clearing time and obtains a new critical clearing time tcc higher than the old one. The whole process is shown in the flow chart at the Figure (2)

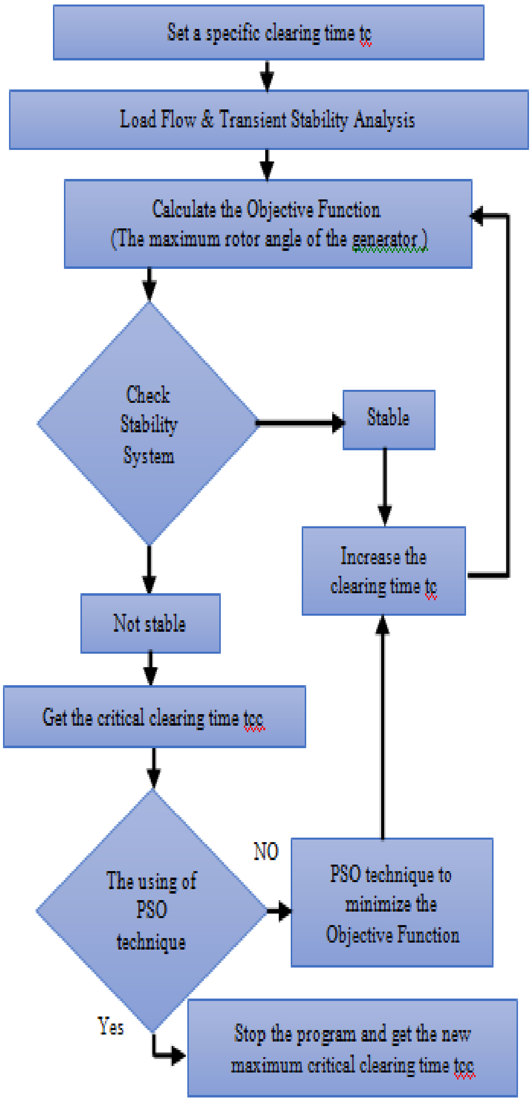

Fig. 2: Flow chart of PSO technique

6. The Result and Calculation

In this article, the IEEE 9 bus system [2] are used to test the application of the transient stability optimization under fault condition based on PSO technique. This system contains three generators, one of them are the slack (Generator one) as shown in the Fig.3.

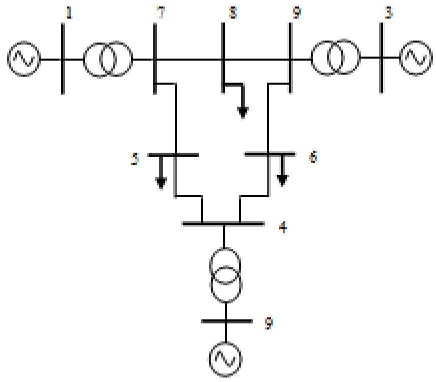

Fig. 3: IEEE 9 bus system

The algorithm of this article used the magnitude of the generator internal voltage as a constant value before, during and after the fault. Also this algorithm has not used the damper system. The fault are choosing in the line (5-7) near the bus 5. Figure 4show the response of the system at clearing time 0.32 sec. When the system increase the clearing time tc, the maximum rotor angle will be increase until the system became unstable as in figurer 5 at tc=0.33 sec. Therefore the critical clearing tcc time before the system became unstable is 0.32 sec and the critical maximum rotor angle of the generator 2 is 145.63 degree as shown in table 1. This article used PSO to minimize the objective function (maximum rotor angle) and increase the critical clearing time. One control variable, the magnitude voltage of the generator is used in this article for the system IEEE 9 bus. This system has no tap change of the transformer and no shunt injection capacitance therefore this article used only the magnitude voltage of the generator as a control variable. According to PSO technique and after 30 iteration at tc=0.33 sec, the system will best able and the optimize control variables became as follow:
$V_{G1} = 1$ pu; $V_{G2} = 1.1$ pu&$V_{G3} = 1.1$ pu.
The maximum rotor angle of the generator 2 is 110.13 degree as shown in figure 6.
In order to knew the critical clearing time after PSO technique. The clearing time tc will be increase until the system became unstable. In this case the new critical clearing time is 0.41 sec and the instability clearing time is 0.42 as shown in the figure 7. Table 1 show the maximum rotor angle of the generator 2 at different cases of clearing time. PSO optimization technique minimize the objective function (maximum rotor angle) and increase the stability critical clearing time from 0.32 sec to 0.41 sec.

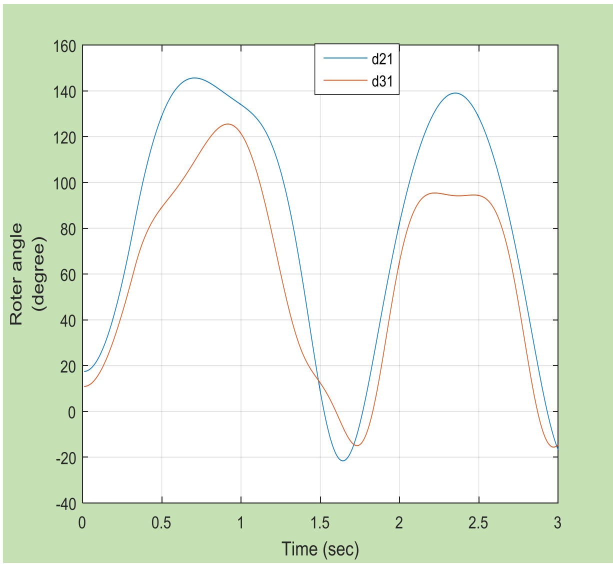

Fig. 4: Response of rotor angle of G2 & G3 with respect to slack at tc 0.32 sec

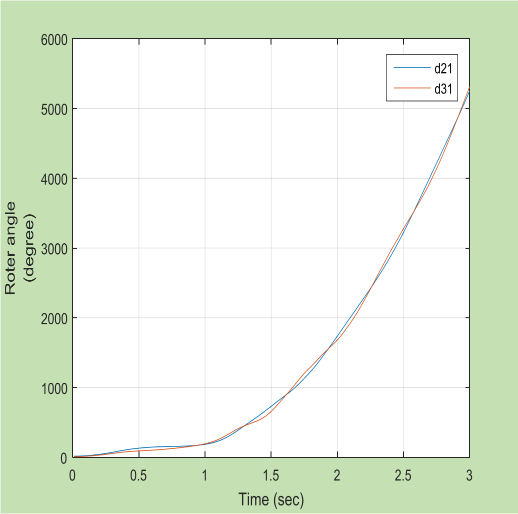

Fig. 5: Response of rotor angle of G2 & G3 with respect to slack at tc 0.33 sec (unstable system)

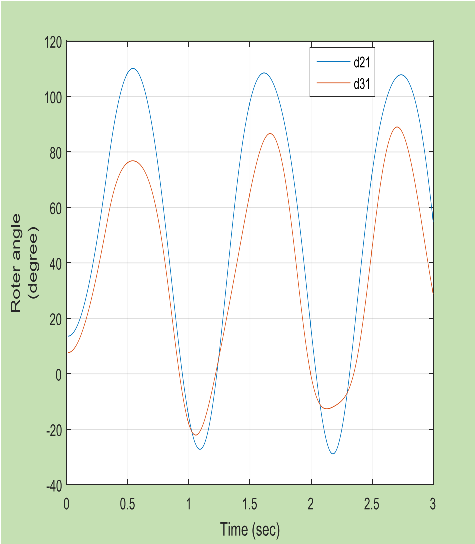

Fig. 6: Response of rotor angle of G2 & G3 with respect to slack at tc 0.33 sec after PSO technique

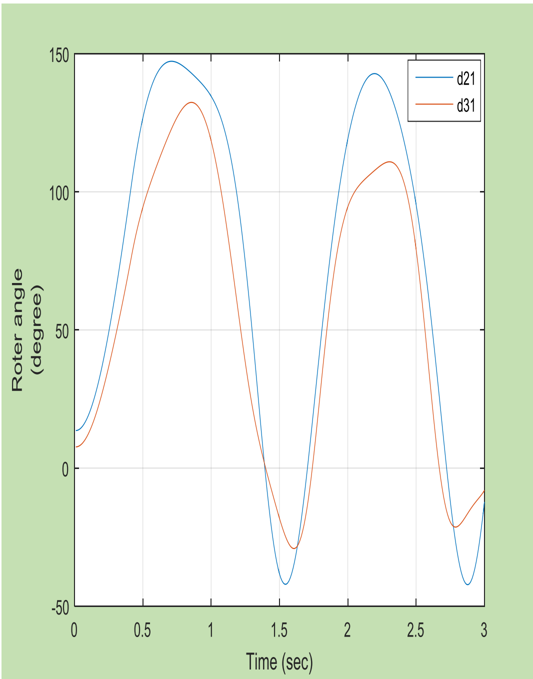

Fig. 7: Response of rotor angle of G2 & G3 with respect to slack at tc 0.41 sec after PSO technique

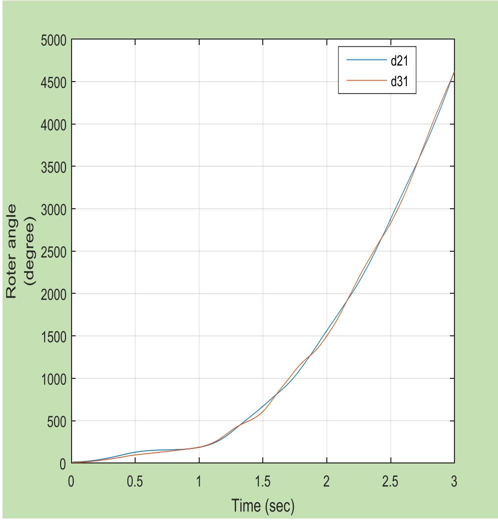

Fig. 8: Response of rotor angle of G2 & G3 with respect to slack at tc 0.22 sec after PSO technique (unstable system)

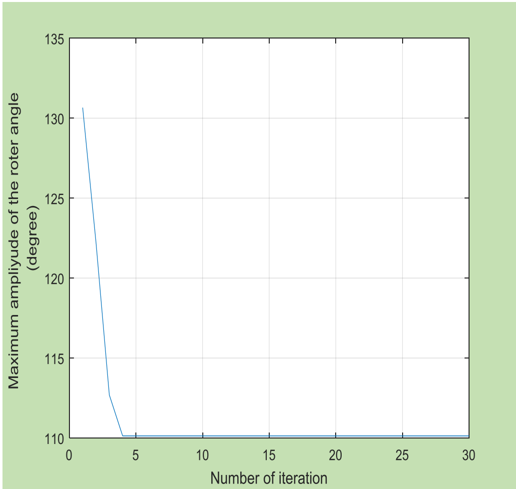

Fig. 9: The maximum rotor angle of G2 according to PSO optimization technique

Table 1: Maximum Rotor Angle of G2 with Clearing Time

tc (clearing time) sec	Max. phase angle (degree) according to G2
0	68.34
0.1	74.68
0.2	92.46
0.3	131.47
0.32tcc	145.63
0.33	Un stable
0.33 using PSO	110.13
0.38	130.4
0.41tcc after PSO	147.25
0.42	Unstable

6. Conclusion

Transient stability under fault condition is one of the most important topics in the power system, where any delay time to cleared the fault and remove the line will be affected on the stability system. It is important to access the critical clearing time in order to ovoid instability system. This article prepared a new technique to increase the critical clearing time under stability condition by minimization the maximum rotor angle of the generator using particle swarm optimization. This can be achieved by optimize the control variables. The control variables in this article is only the magnitude voltage of the generator. The IEEE 9 bus system are used for this test. The propose algorithmimprove the transient stability by increasing the critical clearing time from 32 to 41 sec (28%).

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