An Adaptive Pole Placement Controller on STATCOM with Genetic Algorithm to Improvement Power System Transient Stability

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Abstract: STATic synchronous COMpensator (STATCOM) is a device capable of solving the power quality problems at power systems. These problems happen in milliseconds and because of the time limitation; it requires the STATCOM to have continuous reactive power control with fast response. Therefore optimal exploitation of STATCOM by classical controllers has been a controversial issue in recent years. The most common controlling devices in the market are Pole Placement (PP). In this article, the STATCOM is controlled by Pole Placement controller. A new control method that is Model Reference Adaptive Control method (MRAC) based on the combination of Pole Placement control and the Genetic Algorithm (GA) is introduced. Genetic algorithm is employed to find the best values for location of poles controllers' parameters in a very short time. The simulation results show an improvement in current control response.

Keywords: Adaptive Control, Genetic algorithm, Pole Placement, STATCOM.

1. INTRODUCTION

In recent years, it has become more difficult to construct new generation facilities and transmission lines due to energy and environment problems. Hence it is advisable to enhance the power transfer capability of the existing transmission lines instead of constructing new one. Recently, flexible AC transmission system (FACTS) devices have revived more attention in transmission system operations as they can be utilized to alter power system parameters in order to control power flows and stabilize the system, in addition to the fact that the FACTS devices have the capability of increasing transmission capabilities to the required level [1]-[3].

The first swing stability of the system is greatly influenced by choice of different models of the transmission line [4]. For long transmission lines, when the actual model of the line is considered, the results may deviate significantly from those found for the simplified model. With pre-defined direction of real power flow, the shunt FACTS devices need to be placed slightly off-center towards the sending end for maximum benefit from the transient stability point of view [5]-[7]. Series and shunt fixed capacitors have been widely used to improve the small signal stability of power systems [8]-[9]. How ever, the series and shunt fixed capacitors provide fixed reactive power.
Static Synchronous Compensator (STATCOM) is a voltage source converter based FACTS controller. It is a shunt controller mainly used to regulate voltage by generating/absorbing reactive power. The reactive power is varied by varying the magnitude of the converter output voltage. A small phase difference exists between the converter output voltage and STATCOM bus voltage so that real power is drawn from the lines to compensate for the losses.

In order to study the stability of FACTS controllers with detailed model, it is necessary to determine the steady state solution. The steady state solution can be obtained either by system simulation till the transients are damped out or by solving a set of algebraic equations. The method of determining steady state solution by solving a set of algebraic equations has been proposed for HVDC converters [5]-[6].

The remainder of the paper is organized as follows. Detailed modeling of STATCOM is describes in Section 2 and the design of the proposed control algorithm in Sections 3 and 4. Genetic algorithm is shown in Section 5. The computer simulation results are presented and discussed in Section 6. Finally Section 7 concludes this paper.

2. POWER SYSTEM MODEL WITH STATCOM

Fig. 1 is a single machine infinite bus power (SMIB) system installed with a STATCOM. In this paper, the controller design is based on the third order generator model, the excitation voltage E_{fd} is input. We assume that the input mechanical power P_m is constant regardless of the function of the motor drive.

The STATCOM can be represented by a shunt current source as shown in Fig. 1. Note that STATCOM model is always in quadrature with its terminal voltage.

Controller design for power system stability studies requires proper and adequate mathematical representation of power system so as to include all significant components of the power system. Dynamic models, both non-linear and linearized, for single machine infinite bus as well as multi machine systems installed with STATCOM are presented in this Section [11] and [12].

The magnitude of the STATCOM voltage depends on m, which is a product of the AC/DC voltage ratio and the modulation ratio defined by the PWM. The

dynamics of the generator and the excitation system are expressed through a fourth order model given as

$$\dot{\delta} = \omega_0 \omega$$

$$\dot{\omega} = \frac{1}{M}[P_m - P_e - (x_d - x'_d)I_d]$$

(1)

$$\dot{e}'_{fd} = [E_{fd} - e'_q - (x_d - x'_d)I_d]\frac{1}{T_{do}}$$

$$\dot{E}_{fd} = -\frac{1}{T_A}(E_{fd} - E_{fdo}) + \frac{K_A}{T_A}(V_{to} - V_t)$$
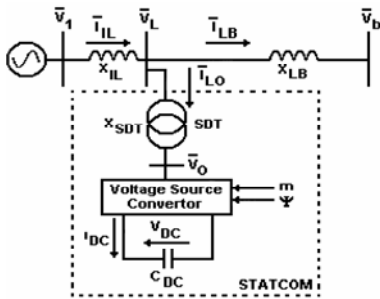

Fig. 1 STATCOM installed in a single-machine connected to infinite bus power system.

By linearizing, the full-state linearized model of the power system installed with STATCOM for small perturbation around a nominal operating condition is expressed as:

$$
\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{e}'_q \\ \Delta\dot{E}_{fd} \\ \Delta\dot{V}_{DC} \end{bmatrix} =
\begin{bmatrix}
0 & \omega_0 & 0 & 0 & 0 \\
-\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & \frac{K_{pDC}}{M} \\
\frac{K_4}{T_{do}} & 0 & -\frac{K_3}{T_{do}} & -\frac{1}{T_{do}} & -\frac{K_{qDC}}{T_{do}} \\
-\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{VDC}}{T_A} \\
K_7 & 0 & K_8 & 0 & K_9
\end{bmatrix}
\begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta e'_q \\ \Delta E_{fd} \\ \Delta V_{DC} \end{bmatrix}
$$

$$
+ \begin{bmatrix}
0 & 0 \\
-\frac{K_{pm}}{M} & -\frac{K_{p\psi}}{M} \\
-\frac{K_{qm}}{T_{do}} & \frac{K_{p\psi}}{T_{do}} \\
-\frac{K_A K_{Vm}}{T_A} & -\frac{K_A K_{V\psi}}{T_A} \\
K_{DC} & K_{d\psi}
\end{bmatrix}
\begin{bmatrix} \Delta m \\ \Delta\psi \end{bmatrix}
$$

(2)

3. ADAPTIVE CONTROL

The adaptive control is used for the automatic adjustment in real time of the process parameters. We employ it when the parameters of a process to control are difficult to determine or when the time is varying [13], [14].

The synthesis of an adaptive controller imposes nearly all the time the following phases:

A. Specification of the required performances. We search an indication of performances, when it is possible, to characterize them.

B. Definition of the control structure or the regulator type which will be used in a view to achieve the required performances,

C. Conception of the mechanism of adaptation which will set optimal values to the parameters of the used regulator.

The interest of the adaptive control appears essentially in the level of the parametric disruptions, that is, acting on the characteristics of the process to control. We have noticed that for the realization of the Pole Placement control, the regulator parameters vary with the operation of the STATCOM.

4. POLE PLACEMENT DESIGN METHOD

In designing the pole placement controller, the new poles must satisfy a few conditions stated below,

- The overshoot of V_{DC} must be improved.
- The voltage of the capacitor (V_{DC}) should be kept constant by control of the controller.

The new poles locations were selected according to where one of the poles locations is needed to be at the origin to fulfill the requirements stated above. The controller block diagram has been designed using MATLAB application after the new poles locations were found based on Fig. 2.
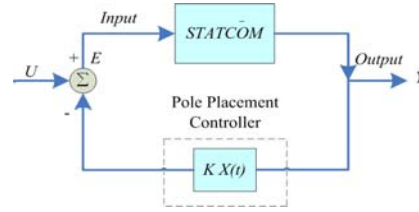

Fig. 2 Block diagram of pole placement.

It shows that the block consists of (5) with a feedback loop from K block which is the value of the gain of the pole placement controller that was found from the locations of the new poles. This feedback gain is also used to minimize the error between the references value with the K gain. The control block diagram using the new poles locations of the STATCOM and the reference currents are shown in Fig. 2. The locations of new poles were found using a program written in MATLAB. This program is needed to determine the outputs for V_{DC} which satisfy the requirement stated when the poles locations were selected. The selection of the poles locations was done in trial and error method [15]. Different poles locations determine different system performance. The program flow format is shown in Fig. 3.

Pole placement is a method that seeks to place the poles of the closed–loop system at some predetermined locations. Although this method has some drawbacks in handling complex systems, it is still fairly sufficient for most small control systems and it gives the best introduction to the design of complex systems.
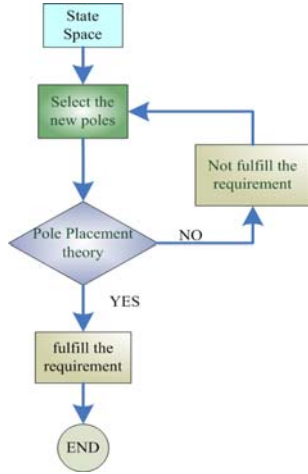
Fig. 3 Flow chart of pole placement algorithm.

The basic concept behind the method is to get K, which will satisfy the closed–loop transfer function at desired pole locations s_i , $i = 1,2,...n$. Implementation of the method will be described here, through the following illustrative example in which a regulator is assumed, i.e., no reference input. (The reference input will be added after some discussion on the state estimators) [16]. Suppose the system as (3).

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3}$$

System is to be controlled by full state feedback such that (4).

$$u(t) = -Kx(t), \tag{4}$$

Where the closed–loop poles are placed at locations $p_1, p_2, ..., p_n$. This means that the required closed–loop transfer function of the controlled system is given by (5).

$$\psi(s) = (s - p_1)(s - p_2)(s - p_3)...(s - p_n) = 0 \tag{5}$$

This can be expanded as (6).

$$\psi(s) = S^n + q_n S^{n-1} + q_{n-1} S^{n-2} + ... + q_3 S^2 + q_2 S + q_1 = 0 \tag{6}$$

Let the matrix A and input matrix B respectively, as (7).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad , \quad B = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix} \tag{7}$$

Therefore, if the feedback matrix K is as (8)

$$K = \begin{bmatrix} k_1 & k_2 & \cdots & k_n \end{bmatrix} \tag{8}$$

Then the closed-loop system has (9), system matrix.

$$A - BK = \begin{bmatrix} a_{11}-b_1k_1 & a_{12}-b_1k_2 & \cdots & a_{1n}-b_1k_n \\ a_{21}-b_2k_1 & a_{22}-b_2k_2 & \cdots & a_{2n}-b_2k_n \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1}-b_nk_1 & a_{n2}-b_nk_2 & \cdots & a_{nn}-b_nk_n \end{bmatrix} \tag{9}$$

Whose characteristic function is shown in (10).

$$\psi(s) = |sI - A + BK| = \begin{bmatrix} s-a_{11}+b_1k_1 & -a_{12}+b_1k_2 & \cdots & -a_{1n}+b_1k_n \\ -a_{21}+b_2k_1 & s-a_{22}+b_2k_2 & \cdots & -a_{2n}+b_2k_n \\ \vdots & \vdots & \vdots & \vdots \\ -a_{n1}+b_nk_1 & -a_{n2}+b_nk_2 & \cdots & s-a_{nn}+b_nk_n \end{bmatrix} = 0 \tag{10}$$

Comparison of this characteristic equation and

demanded in (3) can lead to the determination of the values of k_i and hence matrix K .However, as it can be seen, the algebra behind such a problem is very cumbersome and might in some cases be insoluble. On the other hand, however, if system (A, B) is controllable, the closed-loop system can be expressed in its controllable canonical form as (11).

$$A^* - B^* K^* = \begin{bmatrix} a^*_{11}-b^*_1k^*_1 & a^*_{12}-b^*_1k^*_2 & \cdots & a^*_{1n}-b^*_1k^*_n \\ a^*_{21}-b^*_2k^*_1 & a^*_{22}-b^*_2k^*_2 & \cdots & a^*_{2n}-b^*_2k^*_n \\ \vdots & \vdots & \vdots & \vdots \\ a^*_{n1}-b^*_nk^*_1 & a^*_{n2}-b^*_nk^*_2 & \cdots & a^*_{nn}-b^*_nk^*_n \end{bmatrix} \tag{11}$$

In this case, the closed-loop transfer function becomes (12).

$$|sI - A^* + B^* K^*| = \begin{bmatrix} s & -1 & \cdots & 0 \\ 0 & s & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -a_1-k^*_1 & -a_2-k^*_2 & \cdots & s-a_n-k^*_n \end{bmatrix} \tag{12}$$

Whose expansion can easily be determined to be (16).

$$\psi(s) = s^n + (a_n + k^*_n)s^{n-1} + (a_{n-1}+k^*_{n-1})s^{n-2} + ... + (a_2+k^*_2)s + (a_1+k^*_1) \tag{13}$$

Comparison of this equation with the demanded one in (4) shows the (14).

$$a_i + k^*_i = q_i \quad , \quad i = 1, 2, ..., n \tag{14}$$

From which the elements of the feedback matrix can be computed as (15).

$$k^*_i = q_i - a_i \quad , \quad i = 1, 2, ..., n \tag{15}$$

Or in vector form as (16)

$$K^* = q - a \tag{16}$$

Where

$$q = \begin{bmatrix} q_1 & q_2 & \cdots & q_n \end{bmatrix} \tag{17}$$

$$a = \begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix} \tag{18}$$

In the emphasized again that this procedure applies only for SISO systems in controllable canonical form, and that order of the elements in vectors a, q and K are as shown above. Improper order of the elements will give wrong results. This matrix K is the feedback gain for the system in controllable canonical form, the effort is such that is express in (19).

$$u(t) = -K^* x^*(t) \tag{19}$$

Where

$$x^*(t) = P^{-1} x(t) \tag{20}$$

Therefore, for the original system (not in control canonical form) this control effort becomes as (21).

$$u(t) = -K^* P^{-1} x(t) \tag{21}$$

So that the corresponding feedback gain matrix K is;

$$K = K^* P^{-1} \tag{22}$$

5. GENETIC ALGORITHM

In 1960 the first serious investigation into Genetic Algorithms (GAs) was undertaken by John Holland. Genetic algorithms have become popular due to several factors. They have been successfully applied to self-adaptive control systems and to function optimization problems. They are a powerful search technique, yet are computationally simple. The search method they use is robust since it is not limited like other search methods with regard to assumptions about the search space.

The use of natural evolution method for the optimization of control system has been of interest for the researchers since a long time. The control system parameters are considered as the genes of one chromosome in this system and then with the formation of a random population of different chromosomes and calculation of the target function similar to any other chromosomes by using the promotion generation methods to reach the best response are obtained to satisfy the minimum target function [17].

5.1 Genetic algorithm procedure

i. The formation of initial population
A definite number of chromosomes are randomly selected with regard to the type of the problem.

ii. Evaluation
Each chromosome from the initial population is processed on the basis of the initial goal of the problem.

iii. Production of new population
In this stage a new population is selected on the basis of the previous one. The stages for the manufacture of this population are:

Transmit: in this stage the chromosomes with high efficiency are directly transmitted to the new population.

Selection: Two pairs of the remaining chromosomes from the previous population are selected according to their rate of efficiency (each with higher efficiency has in fact higher chance for being selected). Different methods can be selected for the selection of the chromosomes according to their efficiency values.

Crossover: By selecting two chromosomes from the present population, it is tried to improve the efficiency rate of one of the produced chromosomes by employing crossover method. These operations are accompanied with a reduction probability and can happen in one or several points of chromosomes.

Mutation: in this stage it is tried to correct the gene in a chromosome which has caused a reduction in the competence rate of the chromosome. With regard to the kind of the employed encoding the type of this functioning is determined. This functioning is also accompanied with a reduction probability.

Reception: the obtained chromosome is placed in the new population according to the previous states.

iv. Replacement
The newly obtained population is replaced with the previous population and then we return to stage *ii*.

v. Stoppage
This factor determines the stoppage method of the algorithm, which can be based on the rate of competence proximity of the chromosomes to each other in the new population or is determined on the basis of the number of the produced population in the algorithm. After specifying the critical sections in this article we embark on the formation of chromosomes by binary encoding.

After the determination of the amount of the processing function related to each of the chromosomes, we get on the production of a new population on the basis of the previous population.

Then produce a new population and determine the optimization function rate of the produced chromosomes in the new population. Then, with regard to the amount of optimization function we continue to produce a new population until we reach to the desired point.

5.2 Genetic Algorithm Based On the Model Reference Adaptive Control

Therefore we have decided to realize an adaptive Pole Placement control. The best values for location of poles controllers are laboriously obtained through trial and error, although time consuming. Genetic algorithm is employed to find the best values for location of poles controllers' parameters in a very short time [13].

Because our controlled system is a very complex nonlinear system .As a linear control methods, Pole Placement control method can not get a good control effect when it is used in controlling a nonlinear system. But Pole Placement control method is a simple control method that is wildly used in various controlled systems, Considering GA is a global optimization search algorithm and can be applied in linear and nonlinear problems, we wonder whether Pole Placement control method can control a nonlinear system and obtain a good control result, when Pole Placement control method combines with GA [14]. In this control method reference model supplies the expected performance of system; GA optimizes Pole Placement. Pole Placement control can be expressed stated in (25).

In this system, optimized parameters are location of poles of the Pole Placement control. They are encoded to binary bit string. If every parameter is encoded to 6 bits, then a chromosome that represents a group of parameters is expressed as shown in Fig. 4.
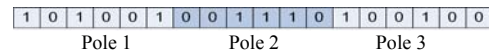
1	0	1	0	0	1	0	0	1	1	1	0	1	0	0	1	0	0
Pole 1						Pole 2						Pole 3					

Fig. 4 Chromosomal representation of location of poles.

The indexes of the active current characteristics are required as: Mp<1%, tr<0.001, ts<0.002, where Mp is overshoot, ts is settling time and tr is rise time. The reference model takes the form as (23):

$$G(s) = \frac{1}{s^2 + 2s + 1} \tag{23}$$

To design the Pole Placement, it is necessary to specify the poles with regard to the system converting function at points -99.509, $-0.35576 \pm 4.0736i$, -0.1005, -0.60547. The new location of the poles in complex coordinate plan which are obtained by the system stability increase index, and reinforcement of the system responding speed in transient conditions through trial and error.

Population size M=18, Crossover rate Pc=0.9, Mute rate Pm=0.01; The numbers of generation is 1000.The

fitness of Pole Placement parameters is applied to the controlled system, and a good control result is obtained. In this control method .The system control block diagram is shown as Fig. 5.
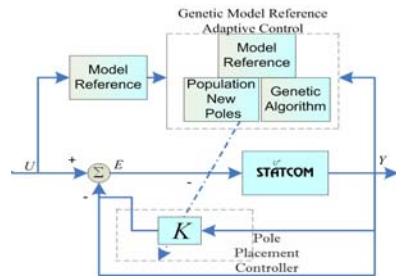

Fig. 5 Genetic Model Reference Adaptive Control.

6. THE RESULT OF SIMULATION POWER SYSTEM STUDIES

The primary function of a STATCOM is to provide voltage regulation within the power system. To provide the best performance, a STATCOM should be placed at those buses which provide high voltage response for incremental changes in reactive power injection. To verify the effectiveness of the proposed damping control, a digital simulation study of a single-machine infinite-bus power system installed with a STATCOM is carried out [18]. Parameters of a single-machine infinite-bus, shown in Fig. 1, are listed below in pu.

$H=3.0s$, $D=4.0$, $T_{d0}=5.044s$, $x_d=1.0$, $x_q=0.6$, $X_d=0.3$, $x_{tL}=0.3$, $X_{SDT}=0.15$, $K_A=10.0$, $T_A=0.01s$, $T_C=0.05s$, $C_{DC}=1.0$, $V_{DC0}=1.0$, $P_{e0}=0.8$, $Vt0=1.0$, $V_{B0}=1.0$, $V_{L0}=1.0$, $c_0=0.25$, $\Psi_0=52^0$.

Simulations are carried out to show how the system recovers after a major disturbance. In this study, while the system was operating at its normal condition, the step increase in torque reference at t=5 sec. After the clearance changed load at t=100 sec, the system resumed to its original operating status.

6.1 Without Controller on STATCOM

Power angle of the machine without controller on STATCOM is shown in Fig. 6. In This figure, it has seen that, in the power angle there is some oscillation, and it is harmful for the machine shaft.
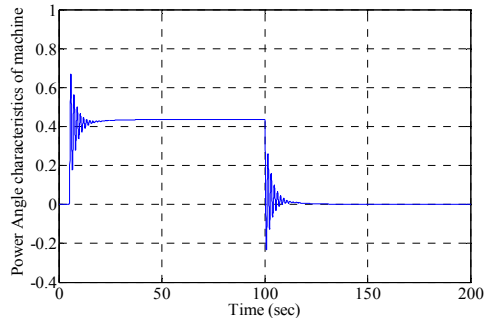

Fig. 6 Power angle of machine without controller on STATCOM.

The STATCOM bus DC voltage in the network is shown in Fig. 7. In This Figure, the voltage of the capacitor (V_{DC}) deviation is very large and this is harmful to the capacitor.
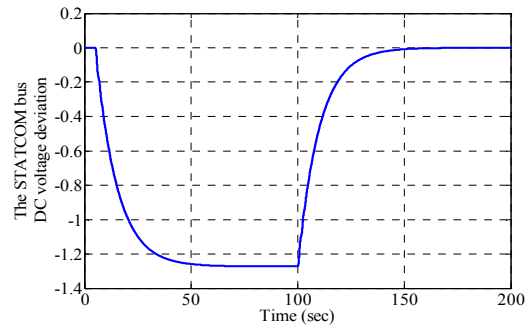

Fig. 7 The STATCOM bus DC voltage without controller.

6.2 With Controller on STATCOM

Power angle of the machine with controller on the STATCOM is shown in Fig. 8, and it has seen the improvement in the oscillation and steady state time of the system. The improvement of the STATCOM bus DC voltage is shown in Fig. 9. In This Figure, the voltage of the capacitor (V_{DC}) deviation is controlled and this is not harmful so large to the capacitor.
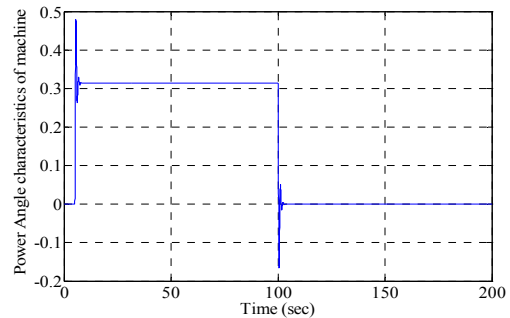

Fig. 8 Power Angle characteristics of machine with controller on STATCOM
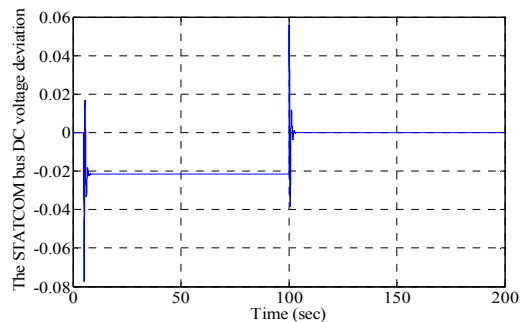

Fig. 9 The STATCOM bus DC voltage with controller

6.3 Compare Between System With Controller and Without Controller

There is are compare between system with controller and without controller in power   angle of the machine and STATCOM bus DC voltage are shown in Fig. 10 and Fig. 11.
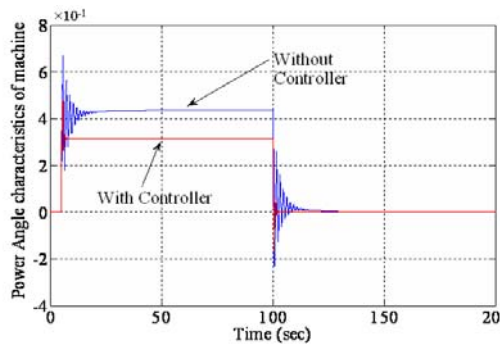
1516

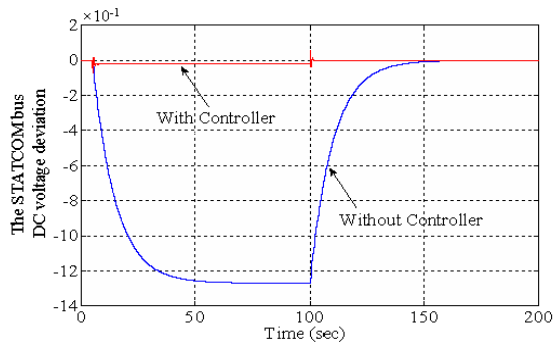Fig. 10 Power Angle characteristics of machine.

Fig. 11 The STATCOM bus DC voltage.

7. CONCLUSION

In this paper the stability of the single machine is studied and the capacitor voltage of STATCOM is controlled by a new Model Reference Adaptive Control method (MRAC) based on the combination of pole placement control and the Genetic Algorithm (GA) is introduced. Also the stability of power angle deviation of rotor is damped with this method. Genetic algorithm is employed to find the best values for new places of the controller in a very short time. The results demonstrate the improvement in dynamic behavior of power system control response compared with simple Pole Placement method.

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