Coordinating the Multivariable State-feedback Controller on Static Synchronous Compensator with Genetic Algorithm

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***Abstract*- In this paper, a Linear Quadratic Regulator (LQR) and Pole Placement method for Static Synchronous Compensator (STATCOM) control is introduced. STATCOM is a device capable of solving the power quality problems at the power system. These problems happen in milliseconds and because of the time limitation; it requires the STATCOM that has continuous reactive power control with fast response. The former controller designing needs to positive definite matrix selection and the later is relative to desired pole places in complex coordinate. In this article, matrixes coefficients and dominant poles of closed loop transfer function are selected based on Genetic algorithm method. These methods are tested in MATLAB, and their results are obtained.**

I. Introduction

Reactive power control is a critical consideration in improving the power quality of power systems. Reactive power increases transmission losses, degrades power transmission capability and decreases voltage regulation at the load end. In the past, Thyristor-Controlled Reactors (TCR) and Thyristor-Switched Capacitors were applied for reactive power compensation. However, with the increasing power rating achieved by solid-state devices, the Static Synchronous Compensator (STATCOM) is taking place as one of the new generation flexible AC transmission systems (FACTS) devices. It has been proven that the STATCOM is a device capable of solving the power quality problems. One of the power quality problems that always occur at the system is the three phase fault caused by short circuit in the system, switching operation, starting large motors and etc. This problem happens in milliseconds and because of the time limitation, it requires the STATCOM that has continuous reactive power control with fast response [1].In order to increase the stability of the system and damping response which makes the inverter in the STATCOM to inject voltage or current to compensate the three phase fault [2].

With only excitation control, the system stability may not be maintained if a large fault occurs close to the generator terminal, or simultaneous transient stability and voltage regulation enhancement may be difficult to achieve. With the development of power electronics technologies, several Flexible AC Transmission System (FACTS) devices [3] at present or in the further can be used to increase the power transfer capability of transmission networks and enhance the stability of the power system. A STATCOM provides better dynamic performance and minimal interaction with the supply grid. The STATCOM is a shunt connected device. The STATCOM consists of voltage source inverter such as Gate Turn Off (GTO) Thyristor, a DC link capacitor and a controller [4]. The STATCOM is normally designed to provide fast voltage control and to enhance damping of inter-area oscillations. A typical method to meet these requirements is to superimpose a supplementary damping controller upon the automatic voltage control loop [5]. Many of the methods focus on decoupling the system variables and designing PI controllers. A STATCOM is a Multiple Input Multiple Output (MIMO) system. It is not possible to totally decouple the system variables. Therefore, the control performance may sometimes be poor. Other control methods apply state feedback control techniques [2], [6], however, very little detail is given in the literature about how to choose the optimal parameters. Some control methods apply state feedback control techniques [1], [7].

Two basic controls are implemented in a STATCOM. The first is the AC voltage regulation of the power system, which is realized by controlling the reactive power interchange between the statcom and the power system. The other is the control of the DC voltage across the capacitor, through which the active power injection from the STATCOM to the power system is controlled [8]. With the help of robust control theory and the Direct Feedback Linearization (DFL) technique, the nonlinear coordinated control of generator excitation and the STATCOM is investigated in [9]. The modeling and control design are usually carried in the standard synchronous d–q frame [10].

The remainder of the paper is organized as follows. Describes modeling of STATCOM and the design of the proposed control algorithm is detailed in Section II, Genetic algorithm is shown in Section III. The computer simulation results are presented and discussed in Section IV. Finally Section V concludes this paper.

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II. System Description and Modeling

A. System Configuration

In this section, a simplified IGBT based STATCOM system is described [11]. Fig. 1, shows a STATCOM configuration. For simplicity, the STATCOM circuit is connected to a stiff bus, which can be substituted by utility grid or any other power network. The mathematical model of the STATCOM has been derived in the literature. Therefore, only a brief description of the system is given here for the readers' convenience. In Fig. 1, a DC bus voltage is built up across the DC capacitor. By firing the three-phase IGBT bridge appropriately, a requested bridge side voltage can be generated and the current through line impedance R_s and L_s is controlled.

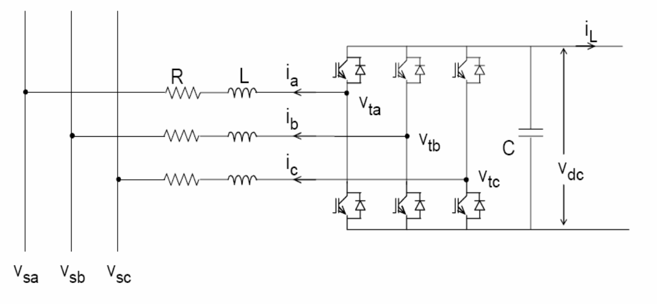


Fig. 1, STATCOM system configuration.

One convenient way for studying balanced three-phase system (especially in synchronous machine problems) is to convert the three phase voltages and currents into synchronous rotating frame by *abc/dq0* transformation. The benefits of such arrangement are: the control problem is greatly simplified because the system variables become DC values under balanced condition; multiple control variables are decoupled so that the use of classic control method is possible, and even more physical meaning for each control variable can be acquired.

Equations (1) to (4) give the mathematical expression of the STATCOM shown in Fig. 1. The variable ω is the angular power frequency, and subscripts d, q represent variables in rotating d-q coordinate system.

$$\frac{di_d}{dt} = -\frac{R}{L} i_d + \omega i_q + \frac{1}{L}(V_{td} - V_{sd}) \tag{1}$$

$$\frac{di_q}{dt} = -\omega i_d - \frac{R}{L} i_q + \frac{1}{L}(V_{tq} - V_{sq}) \tag{2}$$

$$\frac{dV_{dc}}{dt} = -\frac{3(V_{td} i_d + V_{tq} i_q)}{2CV_{dc}} - \frac{i_L}{C} \tag{3}$$

$$Q = \frac{3}{2}(V_{sq} i_{sd} - V_{sd} i_{sq}) \tag{4}$$

Given a linear system,

$$\dot{x} = Ax + Bu$$
$$y = Cx \tag{5}$$

Writing equations (1) and (2) in the state space format as (5), the corresponding matrix can be found as,

$$A_{dq0} = \begin{bmatrix} \frac{-R}{L} & \omega & 0 & -K_1 \sin(\alpha) \\ -\omega & \frac{-R}{L} & 0 & K_1 \cos(\alpha) \\ 0 & 0 & \frac{-R}{L} & 0 \\ \frac{3}{2} K_2 \sin(\alpha) & -\frac{3}{2} K_2 \cos(\alpha) & 0 & 0 \end{bmatrix}$$

$$B_{dq0} = \begin{bmatrix} \frac{1}{L} & 0 & 0 & 0 \\ 0 & \frac{1}{L} & 0 & 0 \\ 0 & 0 & \frac{1}{L} & 0 \\ 0 & 0 & 0 & \frac{1}{C} \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \tag{6}$$

Where the states x, the inputs u,

$$X_{dq0} = \begin{bmatrix} i_d & i_q & i_0 & v_{DC} \end{bmatrix}^T$$
$$U_{dq0} = \begin{bmatrix} e_d & e_q & e_0 & 0 \end{bmatrix}^T \tag{7}$$

B. Pole placement design method

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. The basic concept behind the method is to get K, which will satisfy the closed–loop transfer function at desired pole locations s_i , $i = 1, 2, \ldots n$. 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) [12].

Suppose the system as (8).

$$\underline{\dot{x}}(t) = Ax(t) + Bu(t) \tag{8}$$

System is to be controlled by full state feedback such that (9).

$$u(t) = -Kx(t) \tag{9}$$

Where the closed–loop poles are placed at locations $p_1, p_2, \ldots p_n$. This means that the required closed–loop transfer function of the controlled system is given by (10).

$$\psi(s) = (s - p_1)(s - p_2)(s - p_3)\ldots(s - p_n) = 0 \tag{10}$$

Which can be expanded as (11).

$$\psi(s)=S^n+q_nS^{n-1}+q_{n-1}S^{n-2}+...+q_3S^2+q_2S+q_1=0 \quad (11)$$

Let the matrix A and input matrix B respectively, as (12).

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

Therefore, if the feedback matrix K is as (13).

$$K=[k_1 \quad k_2 \quad \cdots \quad k_n] \quad (13)$$

Then the closed-loop system has (14), system matrix.

$$A-BK=\begin{bmatrix} a_{11}-b_1k_1 & a_{12}-b_1k_2 & \cdots & a_{1n}-b_1k_n \\ a_{21}-b_2k_1 & a_{22}-b_2k_2 & \cdots & a_{2n}-b_2k_n \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1}-b_nk_1 & a_{n2}-b_nk_2 & \cdots & a_{nn}-b_nk_n \end{bmatrix} \quad (14)$$

Whose characteristic function is shown in (15).

$$\psi(s)=|sI-A+BK|$$
$$=\begin{bmatrix} s-a_{11}+b_1k_1 & -a_{12}+b_1k_2 & \cdots & -a_{1n}+b_1k_n \\ -a_{21}+b_2k_1 & s-a_{22}+b_2k_2 & \cdots & -a_{2n}+b_2k_n \\ \vdots & \vdots & \vdots & \vdots \\ -a_{n1}+b_nk_1 & -a_{n2}+b_nk_2 & \cdots & s-a_{nn}+b_nk_n \end{bmatrix}=(\quad (15)$$

Comparison of this characteristic equation and demanded in (11) 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 (16).

$$A^*-B^*K^*=\begin{bmatrix} a^*_{11}-b^*_1k^*_1 & a^*_{12}-b^*_1k^*_2 & \cdots & a^*_{1n}-b^*_1k^*_n \\ a^*_{21}-b^*_2k^*_1 & a^*_{22}-b^*_2k^*_2 & \cdots & a^*_{2n}-b^*_2k^*_n \\ \vdots & \vdots & \vdots & \vdots \\ a^*_{n1}-b^*_nk^*_1 & a^*_{n2}-b^*_nk^*_2 & \cdots & a^*_{nn}-b^*_nk^*_n \end{bmatrix} \quad (16)$$

In this case, the closed-loop transfer function becomes (17).

$$|sI-A^*+B^*K^*|=\begin{bmatrix} s & -1 & \cdots & 0 \\ 0 & s & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ -a_1-k^*_1 & -a_2-k^*_2 & \cdots & s-a_n-k^*_n \end{bmatrix} \quad (17)$$

Whose expansion can easily be determined to be (18).

$$\psi(s)=$$
$$s^n+(a_n+k^*_n)s^{n-1}+(a_{n-1}+k^*_{n-1})s^{n-2}+...+(a_2+k^*_2)s+(a_1+k^*_1) \quad (18)$$

Comparison of this equation with the demanded one in (11) shows the (19).

$$a_i+k^*_i=q_i \;, \; i=1,\ 2,\ ...,\ n \quad (19)$$

From which the elements of the feedback matrix can be computed as (20).

$$k^*_i=q_i-a_i \quad , \; i=1,\ 2,\ ...,\ n \quad (20)$$

Or in vector form as (21).

$$K^*=q-a \quad (21)$$

Where

$$q=[q_1 \quad q_2 \quad \cdots \quad q_n] \quad (22)$$

$$a=[a_1 \quad a_2 \quad \cdots \quad a_n] \quad (23)$$

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 (24).

$$u(t)=-K^*x^*(t) \quad (24)$$

Where

$$x^*(t)=P^{-1}x(t) \quad (25)$$

Therefore, for the original system (not in control canonical form) this control effort becomes as (22).

$$u(t)=-K^*P^{-1}x(t) \quad (26)$$

So that the corresponding feedback gain matrix K is;

$$K=K^*P^{-1} \quad (27)$$

C. LQR Design

It is possible to improve the STATCOM response by employing the LQR control method. Application of the LQR involves choosing the positive definite state and control input matrices, Q and R that provide satisfactory closed-loop performance. The closed-loop eigenvalues are related to these weighting matrices. Many methods are available for determining weighting matrices, with the closed-loop poles placed in a specified region of the complex plane. A sequential procedure which selects the weighting matrix Q and degree of relative stability to position individually and arbitrarily the real parts of the eigenvalues of the optimal LQR system has been presented.

A sequential method uses the classical root-locus techniques has been developed for determining the weighting matrices in the frequency domain to retain closed-loop eigenvalues in a desired region in the complex plane, but the main method is based on trial and error, although time consuming. In this method, the feedback gain matrix is determined if J energy function is optimized. To achieve equilibrium among range control parameters, response speed, settling time, and proper overshoot rate, all of which guarantee the system stability, the LQR is employed.

C. LQR algorithm

For a system in the form of $\dot{X} = AX + BU$ the LQR method determines the K matrix of the equation $U(t) = -KX(t)$ to minimize the $J = \int_0^\infty (X^T QX + U^T RU)dt$ function. R and Q matrices express the relation between error and energy expense rate. R and Q are also the definite positive matrices. From the above equation, we have.

$$J = \int_0^\infty (X^T QX + X^T K^T RKX)dt = \int_0^\infty X^T (Q + K^T RK)Xdt \quad (28)$$

i. Weight Matrix Selection

In LQR design, R and Q weight matrix which determines the quotient related to the closed loop feedback system within the least time is determined. The selection of R and Q has the least dependence on the specification of system administration and requires a long range of trial and error.

ii. Flow chart of LQR controller

Statement of the Problem

Given the plant as x(t) = Ax(t) + Bu(t) .
the performance index as

$$J = \int_0^\infty (X^T QX + X^T K^T RKX)dt = \int_0^\infty (X^T (Q + K^T RK)X)dt$$

and the its conditions $x(t_0) = x_0; x(\infty) = 0,$
Find the optimal control, index.

Solution of the Problem

Step 1 Solve the matrix algebraic Riccati equation

$$A^T P + PA - PBR^{-1}B^T P + Q = 0$$

Step 2 Solve the optimal state x* (t) from

$$X^*(t) = (A - BR^{-1}B^T \overline{P})X^*(t)$$

with initial condition x(t_0) = x_0 .

Step 3 Obtain the optimal control u* (t) from

$$u^*(t) = -R^{-1}B^T PX^*(t)$$

Step 4 Obtain the optimal performance index from

$$J^* = \frac{1}{2} e^{2at_0} x^{*'}(t_0) \bar{P} x^*(t_0)$$

III. Genetic algorithm and its application in determining the controlling parameters

A. 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. GA as a powerful and broadly applicable stochastic search and optimization techniques is perhaps the most widely known types of evolutionary computation method today.

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 [13].

B. Use of Genetic Algorithm for Adjusting the State Feedback Coefficients in Pole Placement Method

To design the Pole Placement, it is necessary to specify the poles with regard to the system converting function at points -5±314i. 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. The object function is selected as

$$Fobj = \{(E_{SS}^{-1} + 10M_P)^{1.25} + (1000t_s + 10t_r)\} \quad (29)$$

C. R and Q design by genetic algorithm

The target function is as follows.

$$Fobj = \{(E_{SS}^{1.5} + M_P^{0.25})^{0.5} + (10t_s + 0.1t_r)\} \quad (30)$$

That t_s is settling time, M_p is overshoot and E_{ss} is steady state error.Through this method the time-consuming stage of determining Q and R matrices is performed with great precision and the system is optimized to reach the intended specifications in closed loop automatically and at the end, the output of the system is optimized with less overshoot, less oscillation, low settling time, and little steady error stage.

V. The result of simulation

With regard to the state Equations of the STATCOM and using the parameters in Table I, the STATCOM open loop response is shown in Fig. 2. The system stability is related to the dominate pole position in complex coordinate plan. The system parameters chosen are listed below [11].
The members of every individual are Q , R and dominant pole:
Population size M=20, Crossover rate Pc=0.9, Mute rate Pm=0.01, The numbers of generation is 1000.

TABLE I
STATCOM PARAMETERS

Source line-line voltage	460 V	*DC linkage voltage dc*	800 V
Rated power	140 KVA	*Frequence*	50 Hz
Line resistance	2 m•	*Line inductance*	400 µH
DC linkage capacitance	7.8 mF	α	0

The STATCOM open loop response will be in the form of Fig. 2.

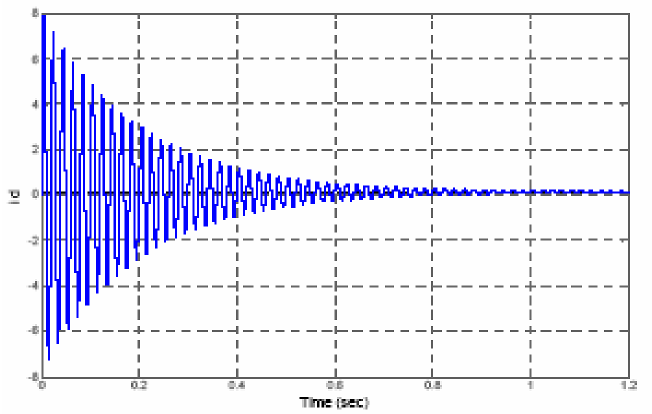


Fig. 2. STATCOM open loop response.

As it is evident from the study of outputs, the open loop system has not a good dynamic response, and ideal conditions, for example Mp is higher than 200%. Of course, the outputs will eventually approximate ideal rate with regard to the stability of the system.

A. The Result of Simulation With Pole Placement Method

The system response to this manual displacement is depicted in Fig. 3.

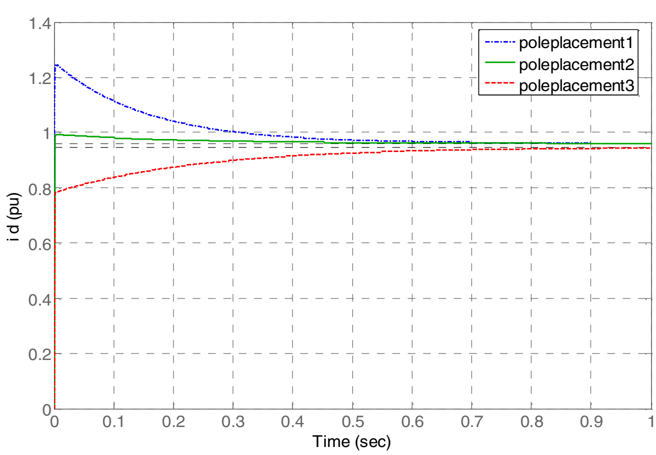


Fig. 3. STATCOM response of Pole Placement.

By applying genetic algorithm for placement optimization of the system poles in order to the improvement of STATCOM response, we obtain the conclusions in Fig. 4.

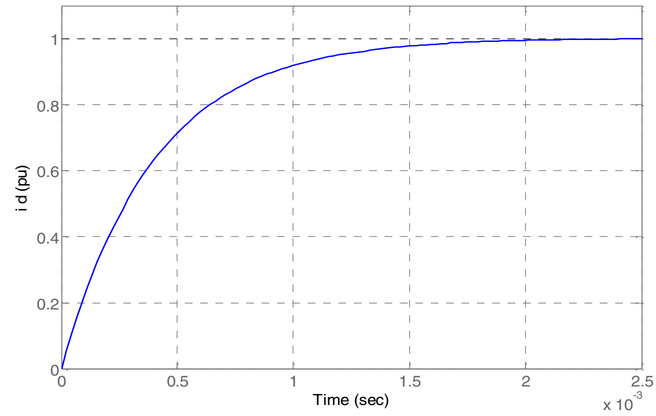


Fig. 4. STATCOM response of Pole Placement-genetic algorithm.

B. The Result of Simulation with LQR Controller

In the design of LQR weight matrices, R and Q are the determining elements for the quotient related to closed loop feedback system. Paying close attention to Fig. 5, this result is obtained that with fluctuation of R and Q matrix amounts.

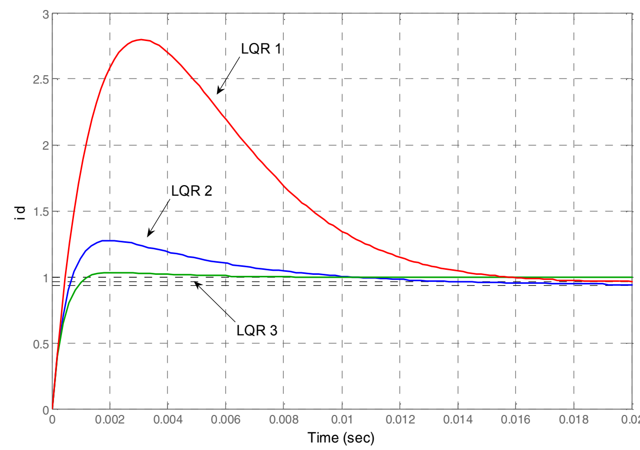


Fig. 5. STATCOM response with LQR controllers.

The result of genetic algorithm is shown Fig. 6.

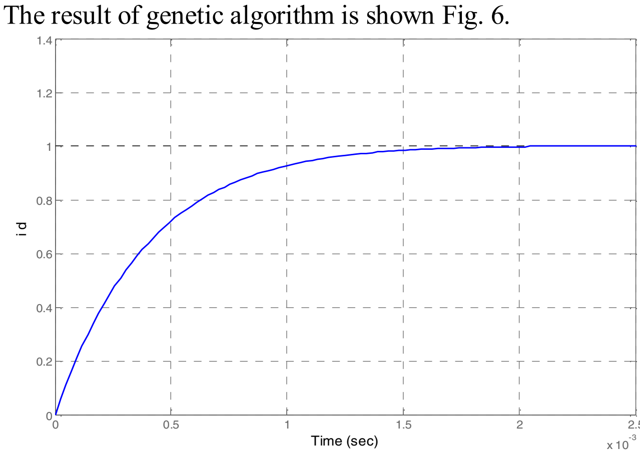
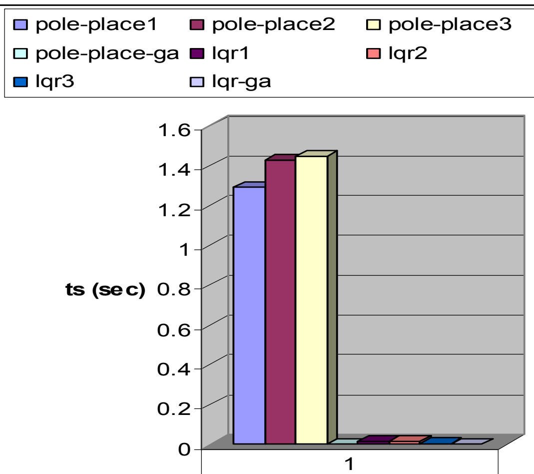


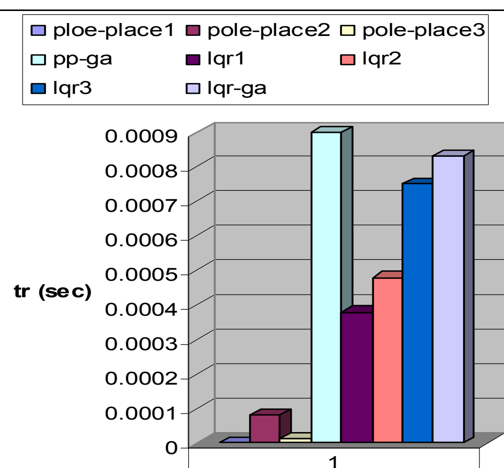
Fig. 6. System response with LQR controller based on genetic algorithm.

With regard to the results presented in Fig. 7~8, it is observed that by applying genetic algorithm, both LQR Controller and Pole Placement controller responses will be improved, but system response will be faster and more precise by employing LQR controller. For this purpose the genetic algorithm on the system, within several successive seasons, has improved the convergence of the system and has generated the best chromosome of that generation into optimum amount from generation to generation.



	1
pole-place1	1.29
pole-place2	1.43
pole-place3	1.45
pole-place-ga	0.00134
lqr1	0.0155
lqr2	0.0165
lqr3	0.0043
lqr-ga	0.0013

Fig. 7. Settling time of STATCOM response with LQR& Pole Placement controllers.



	1
ploe-place1	0
pole-place2	0.0000804
pole-place3	0.0000134
pp-ga	0.0009
lqr1	0.00038
lqr2	0.00048
lqr3	0.00075
lqr-ga	0.00083

Fig. 8. Rise time of STATCOM response with LQR& Pole Placement controller.

VI. CONCLUSION

Reduction of output current ripple of the STATCOM is very important. The optimum method for linear controller design is able to control the dynamic behaviour of the STATCOM. Dynamic performance of STATCOM output current can be controlled by two methods of LQR and Pole Placement. Genetic algorithm can be used to design the LQR matrixes and dominant pole places of closed loop system to achieve the optimum dynamic response. The simulation results demonstrate the improvement in currents control response compared with simple LQR and Pole Placement methods.

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