COMPARISON OF GA AND LQR TUNING OF STATIC VAR COMPENSATOR FOR DAMPING OSCILLATIONS

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ABSTRACT

Static VAR Compensator (SVC) is added to the excitation system of a generator in order to enhance damping during low frequency oscillations. In this article Linear Quadratic Regulator (LQR) tuning approach and Genetic Algorithm (GA) are used to obtain supplementary controller parameters for oscillation damping. The performances of SVC without controller, SVC with LQR controller and SVC with GA controller are compared. Eleven bus two area four machine system is used for the study. The performance of the GA controller is found to be better than the LQR controller and without controller under different operating conditions. A comparison between the effect of SVC alone and the proposed GA and LQR is made.

KEYWORDS: *Static VAR Compensator (SVC), GA, LQR, Power system oscillation*

I.   INTRODUCTION

Power system oscillations are as a result of lack of sufficient damping torque at the generators rotors .This situation may happen as a result of heavy load in the lines, weak interconnection, high gain excitation systems etc[1]. The oscillation of the generators rotors cause the oscillation of other power system variables such as transmission line active and reactive powers, bus voltage, bus frequency, etc. Depending on the number of generators involved, the frequency of the oscillation is usually between 0.1 and 2Hz [2]. There are several types of oscillations: Local mode, Inter area mode, Control mode and Torsion mode[3,12]. Many devices can be used as damping controllers for power system oscillation such as flexible ac transmission system (FACTS) devices, power system stabilizers (PSS), high voltage dc (HVDC) links, static var compensators, etc. PSS is applied on selected generators to damp the local mode oscillation but for inter-area mode oscillation a supplementary controller is applied to the SVC devices. In most cases the design of these controllers are based on a linearised model which, for wide range of operating points and under large disturbances, will not provide satisfactory performance[1]. The main objective of this paper is to compare the performances of supplementary SVC controller, genetic-algorithm-based controller and LQR on oscillation damping. SIMULINK is used for the simulations in MATLAB environment.

The remaining sections of this paper are arranged as follows. Section 2 discusses static var compensating model. The relevant equations modeling the SVC current and reactance are derived. In Section 3 a small overview of Genetic Algorithm (GA) is given. Similarly, overview on LQR is given in Section 4. Details of the actual power system model and the results are presented in Section 5. The paper is concluded in Section 6.

II.   STATIC VAR COMPENSATOR MODEL

SVC consists of reactors and capacitors, with thyristor control valves which are connected in parallel with a fixed capacitor bank. It is connected to the transmission line via a transformer as shown in fig.

1. The equivalent circuit of the SVC is shown in fig 2. Its position in the transmission line depends on the primary usage (i.e. midpoint of long transmission line or near load center) [2]. The voltage of a bus is regulated by controlling or adjusting the equivalent reactance of the SVC[2]. This constitutes the main function of the SVC. Being an adjustable reactance device, the SVC is capable of performing both inductive and capacitive compensation.
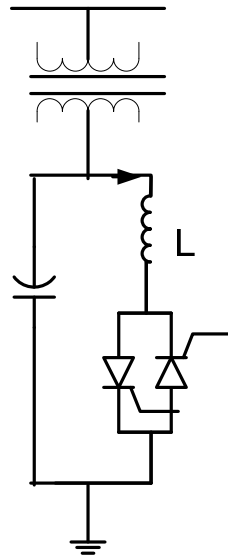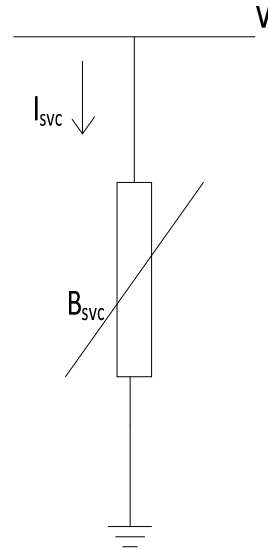

Fig. 1 SVC MODEL

Fig 2 SVC equivalent circuit

2.1 Reactive Power Flow Model

The thyristors conduct during the alternating half-cycles of the voltage waveform depending on the firing angle α, which is measured from a zero crossing of the voltage. Full conduction is obtained with a firing angle of 90°. The current is essentially reactive and sinusoidal. Partial conduction is obtained with firing angles between 90° and 180°. Firing angles less than 90° are not allowed as they produced asymmetrical current with a dc component. The effect of increasing the firing angle is to reduce the fundamental harmonic components of the current. This is equivalent to an increase in the inductance of the reactor, reducing its reactive power as well as its current[6]. The conduction angle σ can be defined as a function of the firing angle α.

$$\sigma = 2(\pi - \alpha) \tag{1}$$

The instantaneous current in the Thyristor-Controlled Reactor (TRC) is giving by

$$I(t) = \begin{cases} \dfrac{\sqrt{2V}}{X_L}(\cos\alpha - \cos\omega t) & \alpha < \omega t < (\alpha + \sigma) \\ 0 & (\alpha + \sigma) < \omega t < (\alpha + \pi) \end{cases} \tag{2}$$

Where ω is the supply voltage frequency, V is the voltage r.m.s applied to the TRC and $X_L = \omega L$ is a fundamental-frequency reactance of the reactor. The fundamental component is found by Fourier analysis and is given by

$$I_L = \frac{V}{X_L}\frac{\sigma - \sin\sigma}{\pi}[A]r.m.s \tag{3}$$

We can write equation (3) as

$$I_L = B_L(\sigma)V \tag{4}$$

Where $B_L(\sigma)$ is an adjustable fundamental-frequency susceptance controlled by the conduction angle according to the following law

$$B_L(\sigma) = \frac{\sigma - \sin\sigma}{\pi X_L} \tag{5}$$

This can also be written as a function of the firing angle as

$$B_L(\alpha) = \frac{2(\pi - \alpha) + \sin 2\alpha}{\pi X_L}$$

(6)

The maximum value of the variable susceptance is $1/X_L$, obtain with $\sigma = 180°\,(\alpha = 90°)$ and the current on the reactor is maximum. The minimum value is zero, obtained with $\sigma = 0°\,(\alpha = 180°)$. This control principle is called phase control [7]. The equation of the equivalent susceptance is given by

$$B(\sigma) = B_C - B_L(\sigma)$$

(7)

Where B_C is the capacitor susceptance, B_L is the reactor susceptance. The reactive power injected at the SVC node is then given by

$$Q(\sigma) = -(B_C - B_L(\sigma))V^2$$

(8)

2.2 System Dynamic Model

The SVC model with supplementary controller is shown in fig.3. In this model, a total reactance B_{SVC} is assumed and the following differential equation holds [2].

$$\dot{B}_{SVC} = (K_R(V_{ref} - V_T) - B_{SVC})/T_R$$

(9)

The regulator has an anti-windup limiter, thus the reactance B_{SVC} is locked if one of its limits is reached and first derivative set to zero[2]. The supplementary input V_{ref} is to maintain acceptable voltage at the SVC bus. TCR of 150MVAr is connected in parallel with fixed capacitor of 200MVAr correspond to a limit of 2.0pu to -1.5pu at 1.0pu voltage.
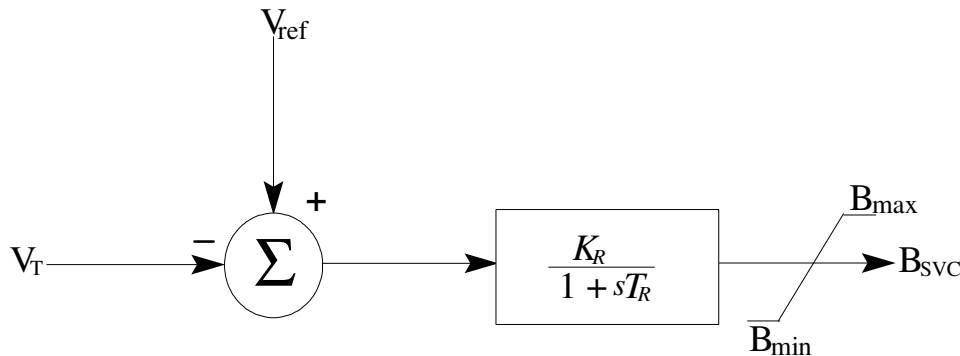

Fig. 3: SVC model with supplementary controller

III.   GENETIC ALGORITHM

Genetic Algorithm (GA) is a heuristic search technique based on the evolutionary ideas of natural selection. It is usually used to solve optimization problem by random search [3]. GA is not restricted by difficult mathematical model and is flexible enough for almost all types of design criteria. GA can easily be integrated with already developed analysis and simulation tools [1].

There are several methods to select parents from the old population, and there are different GA methods that can be used for different selection method. Encoding process is necessary when GA is used to solve an optimization problem (i.e. represent the solution in a string form). In most cases the binary encoding method is used. Crossover and mutation which are the standard genetic operators are operating on the string to search for optimal solutions. The solution to the SVC tuning problem can easily be encoded as binary string.

The most important operator in GA is crossover, and it is applied with probability between 0.6 to 0.9. It takes two strings from the old population and exchange some contiguous segment of their structure to form two offspring. There are many types of crossovers in GA. Another important operator in GA is mutation. In a binary encoded string the mutation operator randomly switch one or more bits with some small probability which is typically between 0.001 to 0.09 [9].

The genetic algorithm toolbox uses MATLAB matrix function to build a set of versatile tools for implementing a wide range of GA methods. The GA toolbox is a collection of routines, written mostly in script files (m-files), which implement the most important function in GA[12]. Fig 4 shows the simple GA flow chart.
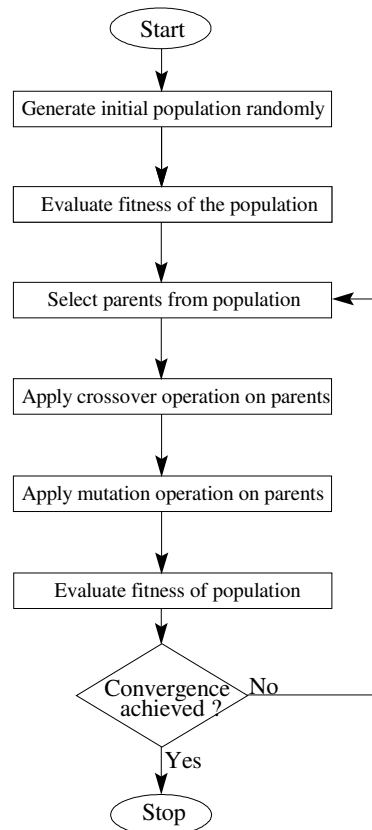
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                              ┌────────┐
                              │ Start  │
                              └────────┘
                                   │
                                   ▼
                    ┌──────────────────────────────┐
                    │ Generate initial population randomly │
                    └──────────────────────────────┘
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                    ┌──────────────────────────────┐
                    │ Evaluate fitness of the population │
                    └──────────────────────────────┘
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                    ┌──────────────────────────────┐ ◄───────┐
                    │ Select parents from population │         │
                    └──────────────────────────────┘         │
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                    ┌──────────────────────────────┐         │
                    │ Apply crossover operation on parents │   │
                    └──────────────────────────────┘         │
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                    ┌──────────────────────────────┐         │
                    │ Apply mutation operation on parents │    │
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                    │ Evaluate fitness of population │         │
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Fig 4 simple GA flow chart.

IV. LINEAR QUADRATIC REGULATOR (LQR)

Liner quadratic regulator (LQR) provides an optimal control law for a linear system. It's a control strategy based on minimizing a quadratic performance index [3, 4]. LQR design problem is that of finding a control input u that minimizes the quadratic cost function J, where

$$J = \int_0^\infty (X^T Q X + U^T R U)\, dt \qquad (10)$$

Q and R are the state and control weighting matrices and are always square and symmetric. It is required that Q be positive semi-definite and R be positive definite. Given a system in state space representation

$$\dot{x} = Ax + Bu \qquad (11)$$

where (A, B) is stable, the optimal control u is define as

$$u = -Kx \qquad (12)$$

The matrix K is giving by

$$K = R^{-1} B^T P \qquad (13)$$

The symmetric definite matrix P is the solution of the algebraic Riccati equation given by

$$PA + A^T P + Q - PBR^{-1}B^T P = 0 \qquad (14)$$

The closed-loop system which has the optimal eigenvalues is given by

$$\dot{x} = A_c x = (A - BK)x \qquad (15)$$

4.1 Selection of Q and R (Weight Matrices)

Weight matrices Q and R are selected such that the performance of the closed-loop system can satisfy the desired requirements. The selection of Q and R is partially related to the performance specifications, and certain amounts of trial and error are required with an interactive computer

simulation before a satisfactory design results. Now given a linear model one can use either pole placement or LQR technique to design full state feedback control given by equation (12).
The MATLAB function *lqr* can be used to find the optimal control gains for a continuous controller. One can use the *lqr* function for choosing **R** and **Q**, which will balance the relative importance of the input and state in the cost function that one is trying to optimize. The simplest case is to assume $R = I$ (identity matrix) and $Q = C' * C$. LQR method allows for the control of all outputs. The controller can be tuned by changing the nonzero elements in the **Q** matrix to get a desirable response.
Finding the matrices **P** and **Q** is difficult for high order systems. In those cases, approximate solutions can be obtained by using a reduced-order model [10]. For convenience a balanced truncation and residualization method is used on the system to reduce it from 41- state to 4- state before applying LQR on it.

V.   RESULTS

In this study, a two area interconnected four machine power system, shown in fig. 5, is considered. The system consists of machines arranged in two areas inter-connected by a weak tie line[10]. The location of the SVC is indicated in the diagram. The system is operating with area one exporting 400MW to area two. Network and generators data can be found in reference [5]. The SVC is treated as a variable capacitance. Simulations were performed in the Matlab using ODE45 solver with a fixed step-size of 1ms.
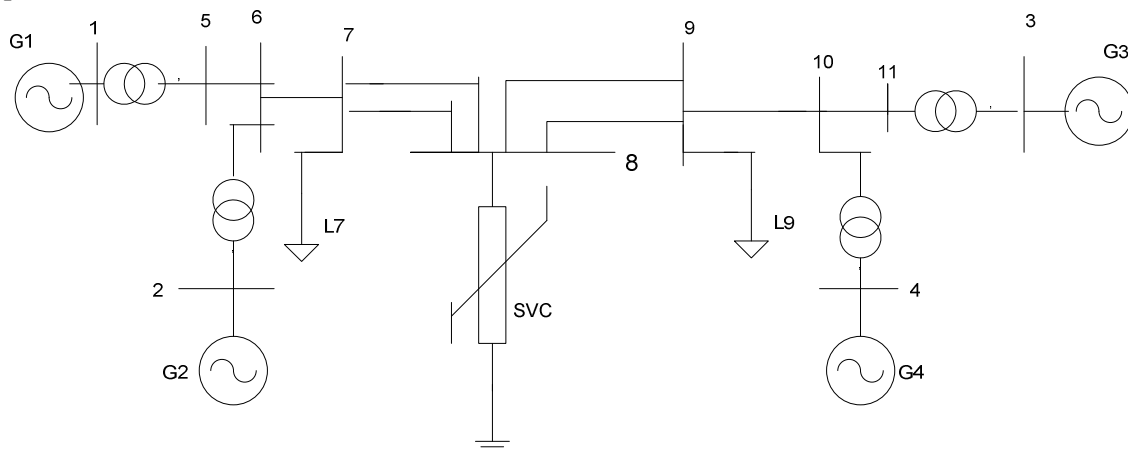

Fig.5: Two area test system with SVC

Case 1: for this case study, SVC is connected at bus 8 with normal load demand from area 2 of 400MW with all the tie line in place. Fig. 6 shows the response for the reactive power at line 7-8 without controller, with GA and with LQR controller. Fig 7 shows the speed deviation response between generator1 and generator 2 without controller, With GA controller and with LQR controller turning the SVC this figure shows the important of LQR and GA turning SVC over SVC alone. Table 1 shows the values of matrix **K** (LQR constants) for different cases and for different lines.

Table 1: LQR Constants.

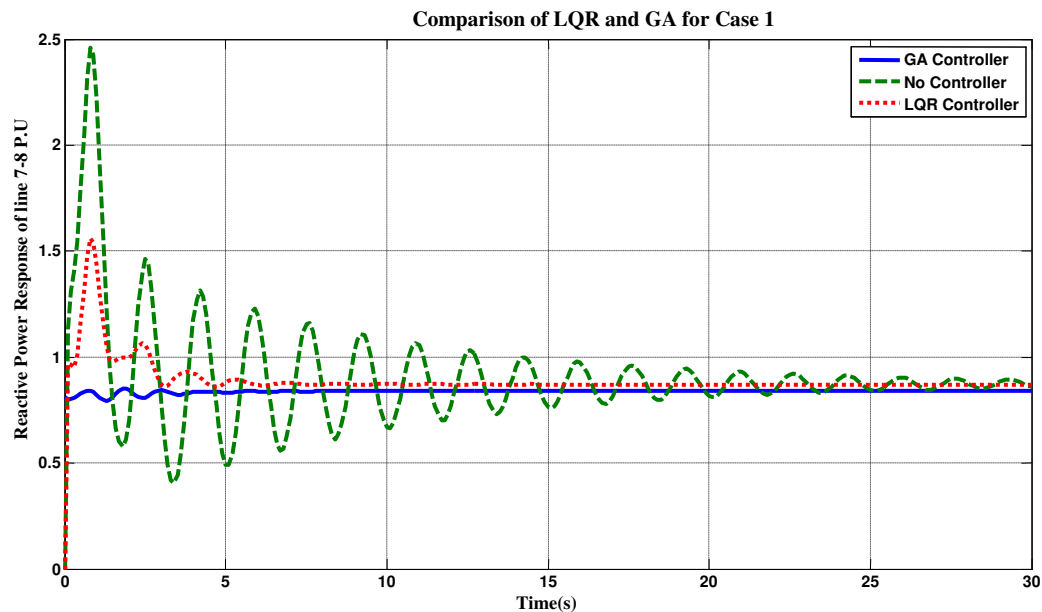| Lines	Case 1				Case 2			
K (Line7-8)	0.00	64.09	-23.90	0.00	0.00	64.09	-23.90	0.00
K (Line8-9)	0.00	17.90	-3.68	0.00	0.00	26.90	-3.85	0.00

Fig 6: Reactive power response for line 7-8, case 1
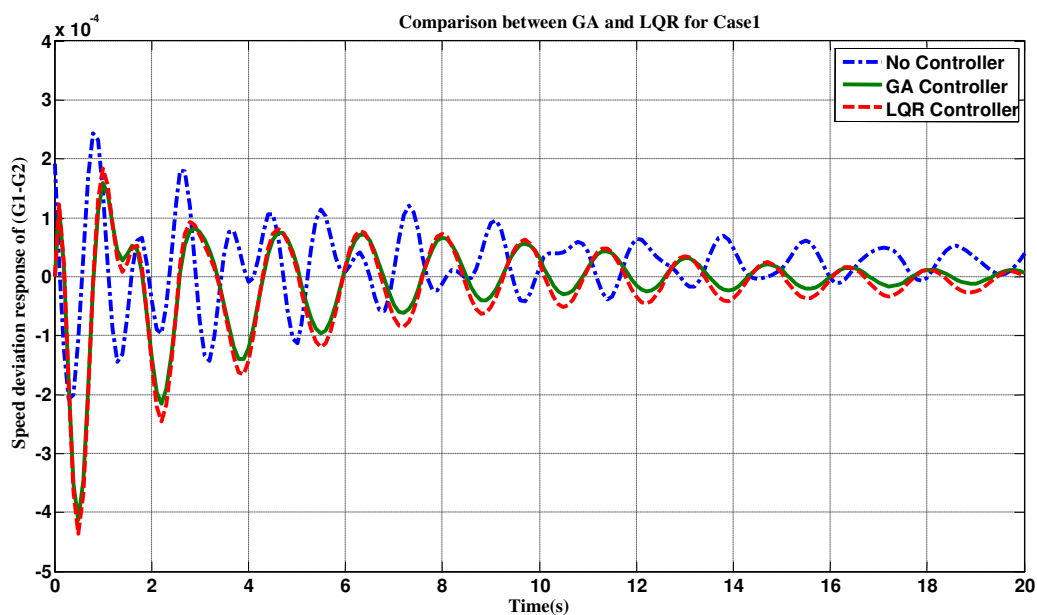

Fig. 6: Speed deviation between generator 1 and generator 2

Case 2: For this case study, a three phase faults is applied at bus 8 for a one second cleared after 1.05s with normal load demand from area 2 of 400MW and all the tie lines in place and SVC connected at bus 8. Fig. 8 shows the response for the reactive power in line 7-8 with GA Controller, without controller and with LQR controller. Fig. 9 shows the response for speed deviation between Generator 1 and 2 with GA controller, LQR controller and without controller. These figures indicate the superiority of GA controller followed by LQR controller over the SVC alone.
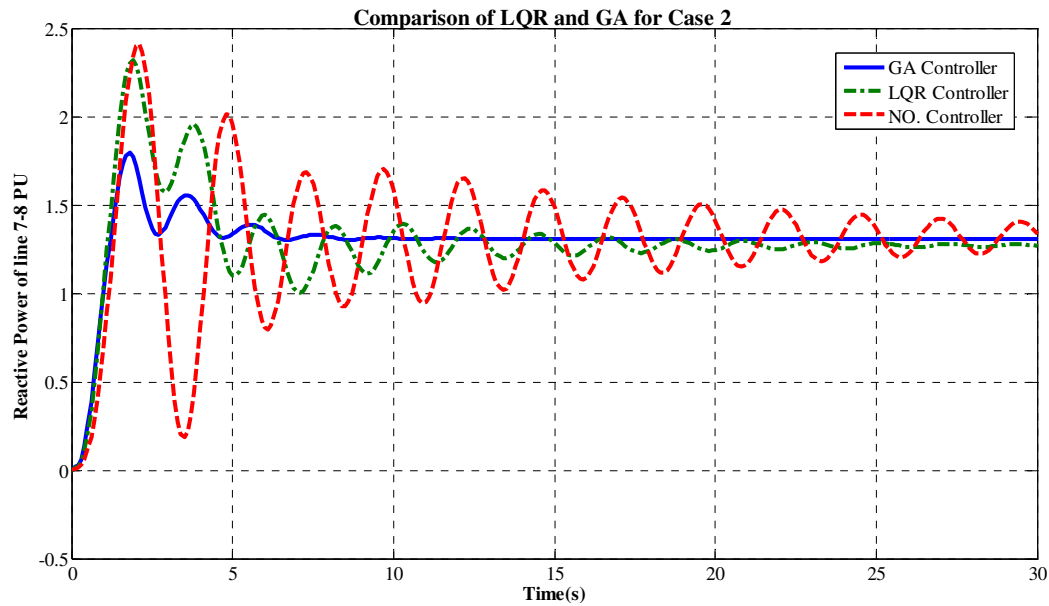
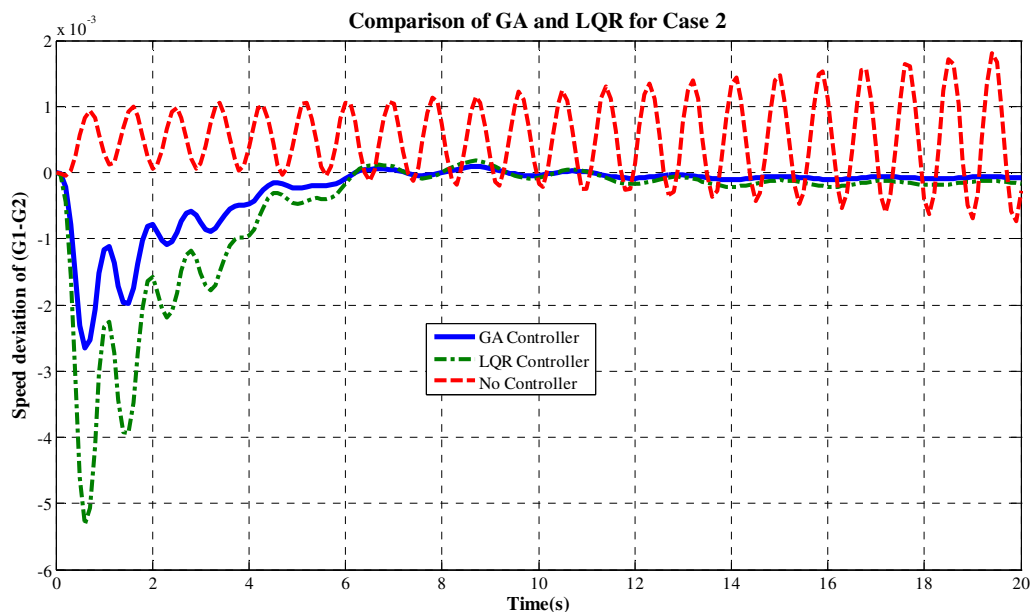**Fig 8:** Reactive power response for line 7-8, case 2

Fig 9: Speed deviation response between G1 and G2, case 2

VI. CONCLUSION

LQR tuning is proposed to obtain a supplementary controller parameter for oscillation damping. The procedure developed identify the most effective use of LQR controller parameters by considering $R = I$ and selecting symmetric matrix Q as product of transpose of output matrix and the output matrix. The simulation results show that the propose LQR under different operating conditions worked effectively and robustly for different signals.

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