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## Design and Analysis of LQR on D-STATCOM

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**ABSTRACT:** This paper focuses on the Distribution Static Compensator (D-STATCOM) device, which is widely used to overcome the power quality problems like voltage sag, voltage swell and power interruption. The concept of this device is to absorb or generate controllable active and reactive power at the point of common coupling (PCC) of load and source. So, it is installed near the load to absorb or generate suitable amount of power so that there is no any effect of sudden load change on the main source. To enhance the performance of D-STATCOM this paper proposes an MATLAB programming of an optimal controller Linear quadratic regulator(LQR).LQR utilizes the benefits of optimal control methods to reach optimum solutions for power quality problems and minimises cost, settling time and maximizing system robustness.It consists of the two weighting matrices i.e. Q and R whose values are set by hit and trial method until steady-state response with minimum settling time is achieved.

**KEYWORDS:** D-STATCOM, LQR, optimal controller, Power Quality, Custom Power Device, MATLAB.

### I. INTRODUCTION

In the present day scenario private power producers are increasing rapidly to meet the increase demand of electricity. In the modern industrial facility, many electrical devices have been incorporated into the processes which are more sensitive to power quality variations than was equipment used in the past [1] The high power quality is requested by manufacturing factories and commercial buildings dealing with information.

Today, new technologies known as Custom Power devices [2],using power electronics-based concepts, have been developed to provide protection from power quality problems. A power quality problem is defined as any power problem manifested in voltage, current, or frequency deviations that result in power failure or disoperation of customer or equipment from the perspective of customers[3].Problems mainly include voltage sag, voltage dip, voltage swell, flicker, harmonics, and power interruption. These power quality problems may cause abnormal operations of electric suppliers or even trip protection devices. Hence, the maintenance of electric power quality have become an important scenario today [4].Hence, the interesting in power quality became a very urgent need in modern era.

Custom power devices are used for this purpose mainly D-STATCOM which is shunt active filter One of the main advantages of custom power devices is ensuring a greater reliability and a better quality of power flow to the load centers in the distribution system by successfully compensating for voltage sags, dips, surges, swell, harmonic distortions, interruptions and flicker, which are the frequent problems associated with distribution lines [5].An optimal controller LQR is used on D-STATCOM. The benefits brought about LQR include improvement of system dynamic behaviour and minimisation of the cost of the system. The objective of this paper is to develop an algorithm to improve the step response of system having D-STATCOM by use of LQR.LQR is an optimal controller which reduces overall cost of the system by reducing settling time of the system having D-STATCOM as compared to the system without having D-STATCOM.

One of the power quality problems that always occur at the distribution system is the three-phase fault that is cause by short circuit in the system, switching operation, starting large motors and etc. This problem happen in milliseconds and because of the time limit, it need the D-STATCOM that has continuous reactive power control with fast response [6].Due to this factor, various topologies for the controllers can be design such as Proportional Integration (PI), pole placement and Linear Quadratic Regulator (LQR) to give high response, low settling time to the system and steady

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operating point. In LQR controller method, it is capable to response high by change of the system by selecting the positive semi definite and positive definite matrix value to give a better performance of the overall system.

Conventional power theory was based on active, reactive and apparent-power definitions were sufficient for design and analysis of power systems. Nevertheless, some papers were published in the 1920s, showing the conventional concept of reactive and apparent power losses its usefulness in non-sinusoidal cases. Then, this method to power definitions under non sinusoidal condition were introduced by Budeanu in 1927 and Fryze in 1932. Fryze defined power in time domain whereas Budeanu did it in frequency domain. Subsequently power electronics was introduced in 1960s, non-linear loads that consume non sinusoidal current have increased significantly. Today everywhere power electronics based equipment are used from domestic purpose to residential purpose. In 1976, Harshima, Inaba and Tsuboi presented, probably for the first time, the term "instantaneous reactive power" for a single phase circuit. That same year, Gyugyi and Strycula used the term "active ac filters" for the first time. A few years later, in 1981, Takahashi, Fujiwara, and Nabae published two papers giving the hint of the appearance of the instantaneous power theory or "p-q theory.

## II. PRINCIPLE OF OPERATION

A distribution Static Synchronous Compensator (D-STATCOM) is a medium power systems (up to 5 MVA) which is installed in distribution systems or near the loads to improve power factor and voltage regulation. It can also use high switching frequencies. The insulated gate bipolar transistor (IGBT), high voltage IGBT (HV IGBT) and gate turn-off thyristor (GTO) are the candidate power semiconductors for D-STATCOMs [6].

It consists of a dc capacitor, three-phase inverter (IGBT), ac filter, transformer and a control technique. The basic block of the DSTATCOM is the voltage-sourced inverter that converts an input dc voltage into a three-phase output voltage at fundamental frequency. The Distribution Static Compensator (DSTATCOM) is a voltage source inverter which is used for the correction of bus voltage sags. Connection to the distribution network is through a standard power distribution transformer. DSTATCOM is capable of generating variable inductive or capacitive shunt compensation. It continuously checks the source current waveforms, and therefore, it can provide the correct amount of leading or lagging reactive current compensation to reduce the amount of voltage fluctuations. The major components of a DSTATCOM are shown in Fig.1. In the DSTATCOM, a voltage-source inverter converts a dc voltage into a three-phase ac voltage that is connected to the ac line through a small reactor and capacitor (ac filter).

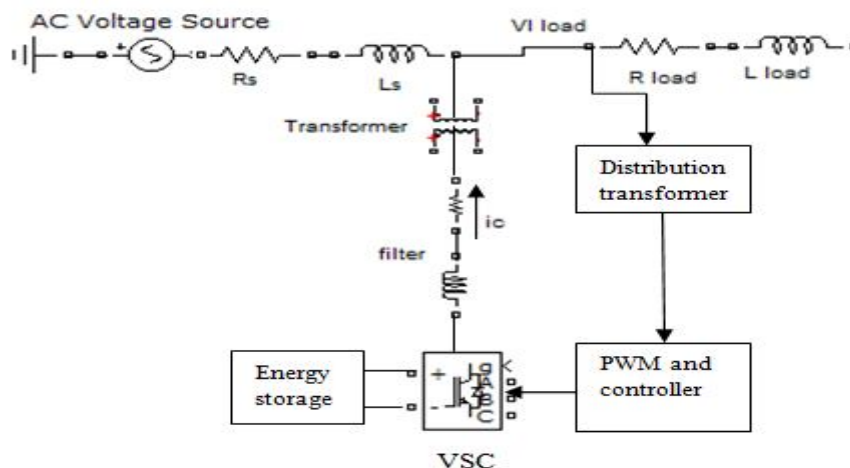


Fig.1 schematic diagram of D-STATCOM

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## III. MODELLING OF D-STATCOM

The structure of DSTATCOM and its operating modes is shown in Figure 1. The main components of DSTATCOM are a VSC (voltage source converter), controller, filter, and energy storage device. These are briefly described as follows:

**Isolation transformer:** It connects the DSTATCOM to the distribution network and its main purpose is to maintain isolation between the DSTATCOM circuit and the distribution network

**Voltage source converter:** A voltage source converter consists of a storage device and switching devices, which can generate a sinusoidal voltage at any required magnitude. DSTATCOM generates the supply voltage which is absent and injects the compensating current into the distribution network depending upon the amount of unbalance or distortion. An IGBT is used as the switching device the D-STATCOM as a shunt compensator is connected to a three-phase grid connected system through a coupling transformer. The configuration of D-statcom may be represented per phase basis as shown in Fig 2.

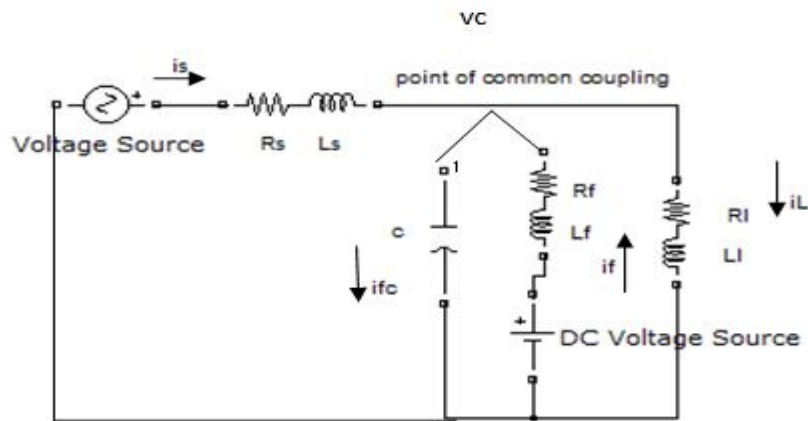


Fig. 2 Single-phase circuit of D-STATCOM system

where,

$V_s$  supply voltage

$R_s$  supply resistance

$L_s$  supply inductance

$V_l$  voltage at load point

$i_l$  load current

$R_l$  load resistance

$L_l$  load inductance

$i_{fc}$  current in C branch of filter

$i_f$  current in L branch of filter

$R_f$  filter resistance

$L_f$  filter inductance

C shunt filter capacitor

$V_{dc}$  source voltage

Referring to Figure 2, the following equations can be written to express the system

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$$V_s = L_s \frac{di_s}{dt} + i_s R_s + V_c \quad (1)$$

$$V_c = -L_c \frac{di_f}{dt} - i_f R_c + V_{dc} \quad (2)$$

$$V_c = L_l \frac{di_l}{dt} + i_l R_l \quad (3)$$

$$i_{fc} = C \frac{dV_c}{dt} \quad (4)$$

The filter capacitor C is connected to the PCC to provide a path for the harmonic currents generated due to switching, while the main branch of the compensated current is the L-branch with its compensated current  $i_f$ . Hence, it is correct to express  $i_{fc}$  as:

$$i_{fc} = i_f + i_s - i_l \quad (5)$$

that is from the currents relation of PCC node:

$$i_f + i_s = i_{fc} + i_l \quad (6)$$

then, by substituting equation (4) in equation (3) we get:

$$i_f + i_s - i_l = C \frac{dV_c}{dt} \quad (7)$$

Equations (1), (2), (3) and (7) can be rewritten as

$$\frac{di_s}{dt} = \frac{V_s}{L_s} - \frac{i_s}{L_s} R_s - \frac{V_c}{L_s} \quad (8)$$

$$\frac{di_f}{dt} = \frac{V_{dc}}{L_c} - \frac{i_f}{L_c} R_c - \frac{V_c}{L_c} \quad (9)$$

$$\frac{di_l}{dt} = \frac{V_c}{L_l} - \frac{i_l}{L_l} R_l \quad (10)$$

$$\frac{dV_c}{dt} = \frac{i_s + i_f - i_l}{C} \quad (11)$$

Here,  $V_c$  is the control voltage

$V_s$  will be considered as the system input  $u$ , while  $V_c$  will be considered as the system output  $y$ .

The states will be chosen as source current  $i_s$ , compensated current  $i_f$ , load current  $i_l$  and the PCC voltage  $V_c$ . Thus,

$$x_1 = i_s, x_2 = i_f, x_3 = i_l, x_4 = V_c \text{ and } y = x_4$$

Therefore, the differential equations can be expressed by linear continuous time system, or state-space model of the form:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \quad (12)$$

$$\begin{aligned} \text{where, } u &= V_s, \\ y &= x_4 = V_s \end{aligned}$$

$$\text{the state variables are: } \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} i_s \\ i_f \\ i_l \\ V_c \end{bmatrix} \quad (13)$$

and the state-space model can be given in equation

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} -R_s/L_s & 0 & 0 & -1/L_s \\ 0 & -R_c/L_c & 0 & -1/L_c \\ 0 & 0 & -R_l/L_l & 1/L_l \\ 1/C & 1/C & -1/C & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 1/L_s \\ 0 \\ 0 \\ 0 \end{bmatrix} u \quad (14)$$

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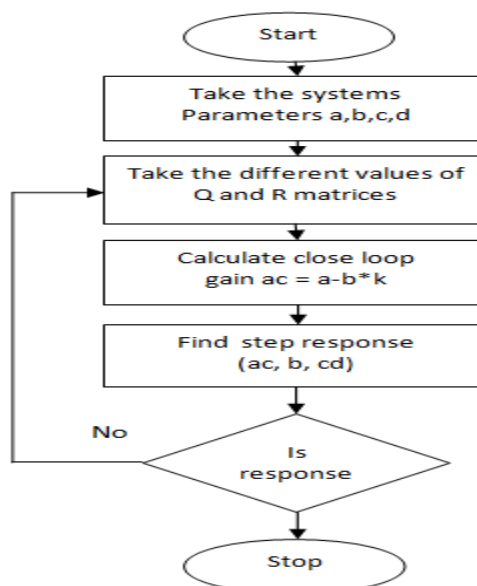
$$y = [0 \quad 0 \quad 0 \quad 1] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

## IV. OPTIMAL CONTRLLERS

Due to the weakness of researches of the robust and optimal control methods for D-STATCOM to improve its performance, the interest in this project is concerned on optimal control methods for D-STATCOM, such that applying LQR, controllers in addition of the PI controller in order to utilize the benefits of the optimal control methods to reach optimum solutions of power quality problems. Optimal is a adjective which means that-there are many ways of doing a particular thing but only one way which requires least effort (least expenditure of energy & money).In contrast to pole placement approach, where desired performance is indirectly achieved through location of closed loop poles, optimal control system directly addresses the desired performance objective while minimizing the control energy. The system which is the end result of an optimal design is supposed to be the best possible system of a particular type and provides the best possible performance with respect to given measure of performance by mean of the cost function.

### LINEAR QUADRATIC REGULATOR (LQR)

LQR optimal control methodology is used and step response will be tested for the system.LQR is a optimal controller which is used for optimization of the cost. Linear quadratic regulator design methods involve the determination of an input signal that will take a linear system from a given initial state  $x(t_0)$  to a final state  $x(t_f)$  while minimizing a quadratic cost functional. The cost functional in question is the time integral of a quadratic form in the state vector  $x$  and the input vector  $u$  such as  $x^T Q x + u^T R u$  where  $Q$  is a non-negative definite matrix and  $R$  is positive definite matrix. The main advantage is that the optimal input signal  $u(t)$  turns out to be obtainable from full state feedback; i.e.  $u = Kx$  for some  $K$  matrix. The feedback matrix  $K$  in question is obtained by solving the Ricatti equation associated with the particular LQR problem you have at hand. The feedback matrix  $K$  in question is obtained by solving the system,  $R$  and  $Q$  matrices themselves, or both to obtain the best possible step response of the system having minimum settling time.  $Q$  and  $R$  matrix is selected by using hit and trial method. The natural formulation of a cost for the system is given directly in terms of states and inputs, rather than inputs and outputs [9].One of the disadvantages of the LQR controller is that obtaining an analytical solution to the Ricatti equation is quite difficult in all but the simplest cases.



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## V. IMPLEMENTAION AND ANALYSIS

To verify the performance of the D-STATCOM with the new controllers, a step response is presented using the state-space model to test its characteristics and performance using different parameters for controller.

Source parameters	Load parameters	Filter parameters
R= 0.2 $\Omega$ L= 0.2mh	R = 10 $\Omega$ L= 80 mh	R = 0.1 $\Omega$ L= 5 mh C = 2200 $\mu$ F

Table 1. System parameters

The step response now is performed for the given system, by applying PI, LQR, controllers for each system. Closed-loop control for D-STATCOM is showed in Figure 4, where the "controller" block represents the PI, LQR, controllers separately.

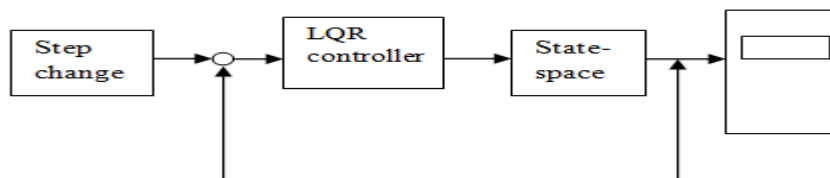


Fig.4 Step response of the system

### STEP-RESPONSE WITHOUT LQR

The step response of the system without using LQR is shown in Fig 5. When LQR controller is not used, the system will not reach its steady state. Settling time is also very large, and overshoot is also present as shown in Fig 5.

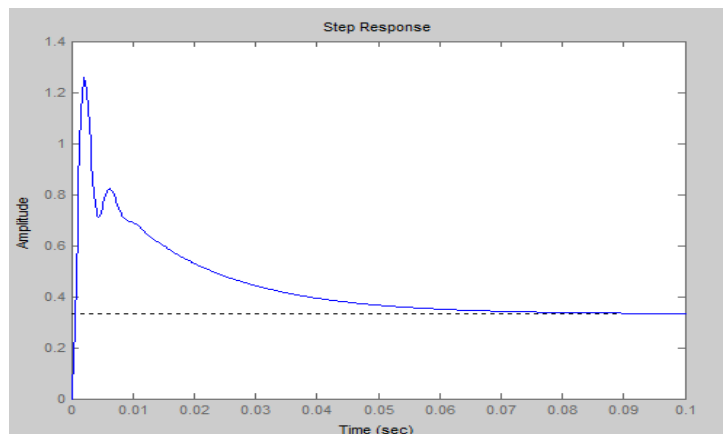


Fig.5 Step response of system without LQR

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## STEP RESPONSE WITH LQR

The key features of LQR design are choosing the weighting matrices Q and R. The LQR gain K is applied to the error of the system states. It is expected that applying the LQR control law  $u=-kx$  to the error of system states will improve the performance of the controlling process. The selection of Q and R is weakly connected to the performance specifications, and a certain amount of trial and error is required with an interactive simulation before a satisfactory design results. For the D-STATCOM system Q is  $4 \times 4$  matrix and R is  $1 \times 1$  matrix, and since Q and R are symmetric, so there are 8 distinct elements in Q and 1 element in R for a total of 9 distinct elements need to be selected. Also, the matrix Q and R should satisfy the positive definitions. One practical method is to set Q and R to be diagonal matrix such that only five elements need to be decided. Hence our aim of better step response is achieved.

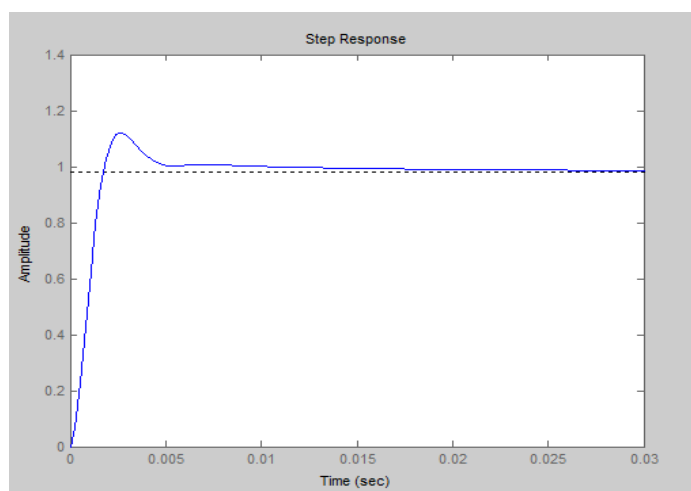


Fig.6 Step response with using LQR

## VI. CONCLUSION

In general, the LQR Controller applied to D-STATCOM has good step response. Its settling time is 0.03 which is much better than without using LQR. The system has settling time of 0.1 when we are not using LQR. Overshoot and rise time is also better. Hence LQR is a good controller to obtain the better step response with the use of LQR controller cost function is also minimized. The objective of this project is to use an optimal controller for D-STATCOM as a power quality solution, to improve the performance of the D-STATCOM within this control. The analysis improves the step response result of the system.

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