A

Project Report

on

DESIGN OF OPTIMAL CONTROLLER FOR A MULTI-TERMINAL VSC-HVDC

Submitted in partial fulfilment of the

requirement for the award of the

Degree of

BACHELOR OF TECHONOLOGY

in

ELECTRICAL ENGINEERING

By

Himanshu Singh (1615105012)

Suyash Singh (1615105022)

Under the Guidance of

Dr. Sheetla Prasad

(Assistant Professor, Electrical Engg.)

GALGOTIAS
UNIVERSITY

SCHOOL OF ELECTRICAL, ELECTRONICS AND COMMUNICATION ENGINEERING

May, 2020

DECLARATION

We declare that the work presented in this report titled "**Design of Optimal Controller for a Multi-terminal VSC-HVDC**", submitted to the Department of Electrical Engineering, Galgotias University, Greater Noida, for the Bachelor of Technology in Electrical Engineering is our original work. We have not plagiarized unless cited or the same report has not submitted anywhere for the award of any other degree. We understand that any violation of the above will be cause for disciplinary action by the university against us as per the University rule.

Place: **Signature of the Student**

Date:

Himanshu Singh (1615105012)

Suyash Singh (1615105022)

GALGOTIAS
UNIVERSITY

School of Electrical, Electronics and Communication Engineering

CERTIFICATE

This is to certify that the project titled **"Design of Optimal Controller for a Multi-terminal VSC-HVDC''** is the bonafide work carried out by **Himanshu Singh**, **Suyash Singh** students, during the academic year 2019-20. We approve this project for submission in partial fulfillment of the requirements for the award of the degree of Bachelor of Technology in Electrical Engineering, Galgotias University.

Dr. Sheetla Prasad
Project Guide(s)

The Project is Satisfactory / Unsatisfactory.

_______________ ________________

Internal Examiner (s) External Examiner

Approved by

____

Dean

ACKNOWLEDGMENT

We would like to express our deepest appreciation to all those who provided us the possibility to complete this report. A special gratitude we give to our final year project mentor '**Dr. SHEETLA PRASAD**, whose contribution in stimulating suggestions and encouragement helped us to coordinate our project especially in writing this report.

Furthermore, we would also like to acknowledge with much appreciation the crucial role of the staff of **Prof. (Dr.) B. Mohapatra**, who gave the permission to use all required equipment and the necessary materials to complete the task "**Design of Optimal Controller for a Multi-terminal VSC-HVDC**". We would like to thanks **Dr. SHEETLA PRASAD** again who invested his full effort in guiding our team in achieving the goal. We have to appreciate the guidance given by other supervisor especially in our project presentation that has improved our presentation skills thanks to their comment and advices.

ABSTRACT

In recent years, incensement of development and deployment of renewable energy resources to meet the ever-increasing electric power demand and also to limit the use of fossil fuels. wind farm had development by spurred offshore, particularly in the North Sea, due to the vast offshore wind farms in the North Sea pose grid integration challenges such as the need for long distance subsea power transmission and managing the variability of wind power variation in the power grid. These challenges can be properly met by the use of multi-terminal voltage source converter high voltage dc transmission (MTDC) grid. Even though the North Sea region is envisioned as the immediate target of application, MTDC can also be used as the highway of power in onshore systems, thereby connecting loads and generation sites involving very long distances.

In that system it consists of three or more HVDC converters stations And it also connected to a common DC transmission network. In this system there are two type of converters are used namely Line Commutated Converter (LCC), Voltage Source Converter (VSC). Now a day's research is mainly based on VSC technology in MTDC systems. Several R&D works is focus on control strategies in MTDC system.

There are mainly three areas of research work namely MTDC control, MTDC operation and MTDC analysis is being done. In the area of MTDC operation precise control of steady states power flow has been proposed and tested. Steady states sensitivity analysis has been done in secondary control of MTDC.

In this paper, author proposed a controller that is VSC MTDC controller. This VSC MTDC controller is used to minimize the oscillations introduced when there is load varying condition.

When power is produced from different generating stations, then it is an undulating in nature. It is not that useful for transmission as it disrupt the electronic components. So, in this paper a five terminal VSC MTDC controller is proposed to design. If controller is not used in the system and there is sudden change in the load. Then voltage and power varies dangerously as it destroys the system. Hence there is requirement of a controller. This controller helps to maintain the voltage and power flow as subsequent level at load varying condition. This VSC MTDC controller used to eliminate the maximum and minimum overshoot and reduced the oscillations. The transient and state space representation is correctly matched. Settling time of the system is reduced. If settling time is reduced it means system reaches to stable state more quickly. Hence, closed loop system stability is improved. The proposed controller helps to reduce the oscillations at load varying conditions. Power sharing capability of the VSC-MTDC terminals enhanced and doesn't affect if there is sudden change in load. We can obtain feedback gain by the solution of series of linear matrix inequality (LMI). We can obtain feedback gain by the solution of series of linear matrix inequality (LMI). LQR helps us to choose performance index of weighted matrix. Linear quadratic regulator or LQR is a method or technique of producing desired and controlled feedback gains and used for the high performance design of the system. Any system can be represented in terms of differential equations. The LMI based technique helps to introduce that system in the differential form. Then LQR based technique helps to produced desired feedback gain enhances the system performance. With the help of LQR the proposed controller is developed which regulates the flow of power and voltages at different load varying conditions. With integration of meshed MTDC system with exsisting AC system had added some economical advantage but there are also major challenges to control the operation of this system .

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 HVDC Transmission:

A high voltage of direct current in an electrical power system in that transmit system used, common AC systems are in contrast way. “The Gotland HVDC link” built in 1954 that is a first transmission system.It’s total length of 816km.For the transmission of large distances a high voltage DC system is used. Day by day demand for power is rising. Hence, grid system stability and quality of power is a challenging task. So, multi terminal DC grids are helpful in providing meshed type interconnections between powers generating stations and far reaching area where electricity is required. It is also helpful in maintaining the reliability between AC and DC system network [1]. It is more economical and efficient in terms of power dispatching and utilization of cables and converters. Although the architecture of LCC MTDC has greater advantages in comparison to HVDC system because it has large capacity of handling of power, simplest design and maintenance cost is also less. Simple HVDC two terminal systems have evolved MTDC system technology but there some challenges also in MTDC system. Current sharing on different terminals in a MTDC system plays an important role in stabilizing dc power flow. Controller used or embedded in MTDC in order to improve system performance.. This paper analyzes the distribution of current and power to various distribution networks after getting passed from the controller. This controller would minimize the oscillations and share equal voltage and power to all the five nodes used [2]. We get transient and undulating power from generating stations. We cannot transmit such power directly to required destination. Because due to transient i.e., high or lower power would affect the devices used such as cables, relays, bus etc. in the transmission system. It is not more efficient and economical for transmission [3]. So, we need to use a controller which controls the unwanted and abrupt flow of power. Multi terminal DC system provides a meshed interconnection of adjoining networks. Also, we are regulator (LQR) system in order to power flow control. Linear quadratic regulator (LQR) gives a technique to provide feedback gains in a controlled manner and enables high performance design and closed loop stable system [4]. When a system dynamics is defined by group of LDE that is linear differential equations and its expense is defined by quadratic equation then it is LQR based system. For linear system, to develop a controller that is linear working. the linear quadratic regulator (LQR) is the widely used method. The minimum gain margin and maximum gain margin of LQR is 6db and infinity respectively. It is more robust. It can reach phase margin of 60degree. at the same time.LQR algorithm minimizes the work done by control system and eliminates the negatively impacted harmonics of a distorted grid system. In this project work, we are designing the LQR based voltage source controller (VSC) for multi terminal DC network system. Our main aim is to reduce the oscillations produced by grid, minimize the distortion and take out reliable power which is suitable for electronics components and load used in network [5]. VSC based MTDC controller can improve initial level frequency and attenuate when there I disturbances occurs. Voltage source controller (VSC) based Multi terminal dc provides more controlled and economic system. Here, we are designing the controller for five terminal dc grid systems. Actually Multi terminal DC grid is considered as dc equivalent of ac grid connecting more the one ac/dc converting station having dc transmission network system. In order to design MTDC there are some challenges which need to considered are stability analysis of a MTDC grid, controlling the dc voltage and power flow, MTDC have an oscillations due to load variations etc. In order to reduce or eliminate these problems we are designing the linear matrix inequality optimization based linear quadratic regulator (LQR) [6]. MTDC grid integration meshed with prior or existing AC grid has some adding economical benefits and important challenges. We will analyze the closed loop system stability and time response against different load variation. This will done with the help of MATLAB software. If we varies the load in any of the five terminal of dc grid, then controller must be design in such a way that there is no or negligibly small power oscillations can occur on each terminal. The main benefit is to protect the other equipments and increases more efficiency [7]. In VSC-MTDC system more than two converters can operate in parallel. Same operating conditions can be find in HVDC system. If a converter is acting in a rectifier mode, it must be connect in ac system whereas and rest of the converter acts as a inverter if they supply to the passive network. In this paper an integrated model of 5 terminal dc grid control system are designed. We are taking small signal into consideration. Because analysis of small signal is easy. Multi terminal dc grid consist of (i) two VSC converters work as rectifying stations.(ii) two voltage source inverting stations(iii) two dc-dc conversion stations.[8]

In MTDC system, there are more than two terminals which can are operating parallel. These systems much more similar to HVDC system. If a converter connects into AC source as a rectifier, rest of the converters are working as inverter when it is supplied for the passive network. Single source multi terminal system operation is simple. In order to regulate the power voltage source control based MTDC is more flexible particularly in instances where power flow reversal can be easily achieved by reversing the direction of DC currents rather than the reversal of DC voltages. MTDC is still a matter of research, for ex. Combined form of LCC and VSC HVDC links into hybrid system. By combining HVDC and HVDC network many technical difficulties can be removed.

In meshed dc grid system, an undulated harmonic will come depending on the load varying conditions and production of power from generating station. Total exchanged power at the converter direct current side is fully controlled where as the dc current of each branch is equal to the voltage difference between the resistance and the two terminal dc branch. The main challenge is how best we can integrate both ac and dc and reduce oscillations. The drawback of LCC-HVDC technique is required to reverse its polarity to enact the change in power flow direction, on the other hand VSC-HVDC doesn't need change in polarity at all, which provides solution for the development of constructing MTDC system. It also helps in the integration of large scale integration of renewable resources into grid. That's why scope of building MTDC transmission network in future is more.

1.2 Advantages of HVDC Transmission

- Low cost of conductor
- Has lower power losses then HVAC
- Lower environmental impact
- Bulk power transfer over long distances.

In that HVDC System is used one or two conductors, that's why, cost of conductor reduces considerably. For bulk transmission of power **over** long distances, it is very economical. The cost of towers and insulators is also reduced.

There are some challenges in developing MTDC system is use of high-power devices and system of high power level. Voltages of bus in dc network are identified by their amplitude and not by their phase angle and the impedances of transmission line, at zero frequency do not present any imaginary components at steady state. That’s why only voltage and current amplitude is to be used in order to control the flow of power in MTDC grid. . The proposed controller helps to reduce the oscillations at load varying conditions. Power sharing capability of the VSC-MTDC terminals enhanced and doesn’t affect if there is sudden change in load. We can obtain feedback gain by the solution of series of linear matrix inequality (LMI). We can obtain feedback gain by the solution of series of linear matrix inequality (LMI). LQR helps us to choose performance index of weighted matrix. Linear quadratic regulator or LQR is a method or technique of producing desired and controlled feedback gains and used for the high performance design of the system. Any system can be represented in terms of differential equations. The LMI based technique helps to introduce that system in the differential form. Then LQR based technique helps to produced desired feedback gain enhances the system performance. With the help of LQR the proposed controller is developed which regulates the flow of power and voltages at different load varying conditions.

1.3 Types of HVDC

- Line Commutated Converter [CLASSICAL HVDC]
- Voltage Source Converter (VSC-HVDC)
    - Line Commutate Converter
    - Thyristor based method
    - Used for very high capacity
    - Used for high efficiency

1.3.2 Voltage Sourced Converter (VSC)

- Self-Commutated Converter

- Transistor (IGBT, GTO etc.)
- Mainly Used for interconnecting weak ac system Ex. wind power.

1.4 Point - Point high voltage direct current System

In different region the converters are located and needed to connect with a transmission line to transmit power.. In Point to Point HVDC System one converter provides power flow which act as rectifier and other receives power that act as an inverter.

1.5 MULTI TERMINAL DC SYSTEM (MTDC)

The MTDC, which is a dc equivalent of ac grid connecting more than ac/dc convertor station having dc transmission network. A MTDC system has more than 2 convertor station. Some of them operating as rectifier and other of inverters. MTDC system consists of two or more than two convertor station. Some of them operating as rectifier and other of inverters. There are two type of HVDC, these sort of DC grid is possible: It can proposed by some researches that's Hybrid MTDC transmission. The main simplest way of building a MTDC system from an existing two terminal system is to introduce tappings and parallel operations of converters and bipoles can also be viewed as multi terminal operation. For decade, it has been studied by LCC technology and it also based on MTDC while VSC is relatively new topic.

Later on, with invention of power elctronic devices and the converters the DC came into the game of long distance transmission again.Because there were many advantages of using direct current over use of the alternating current for example the transmission losses were low ,two conductors were being used in DC instead of three in AC, power transfer is limited because of the limits imposed by power angle and line inductive reactance but the power transfer limit is very high in DC transmission lines(single HVDC link adequates up to 30,000 MW), voltage control is easier in case of direct current transmission, less enviromental impact and limited short circuit current etc. In meshed dc grid system, an undulated harmonic will come depending on the load varying conditions and production of power from generating station. Entire power interchanged at the converter direct current may be totally controlled where as the dc current of and is equal to the voltage difference between the two terminals and the resistance of dc branch. The main challenge is how best we can integrate both ac and dc and reduce oscillations. The drawback of this technology is required to reverse its polarity to compensate the change in the direction of power flow, VSC-HVDC doesn't need change in polarity at all, which provides solution for the development of constructing MTDC system. It also helps in the integration of large scale integration of renewable resources into grid. That's why scope of building MTDC transmission network in future is more.

1.6 Challenges in MTDC System

There are following challenges

- DC voltage controlling.
- Power flow control in DC lines.
- Interaction between converters.
- One of the most important issues is that the DC voltage across the MTDC system must be kept in an acceptable range.

CHAPTER 2

Controlling of DC Voltage

In this topic, we are discussing different control strategy of a MTDC system. Grid connected voltage source converters are connected with ac voltage control that provides ac voltage of constant frequency and constant strength at common coupling point (PCC). Point of common coupling (PCC) is a junction where the ac grid is connected to VSC unit. The ac voltage controller activates the VSC to work as the slack bus of the ac grid connected network. Passive grid is connected to VSC has a relatively simple control scheme. By comparing the passive grid connection, ac grid active connection of VSC requires a more progressive controller. In the wind farm which is connected to vsc-mtdc, each individual wind turbine - converter unit has to synchronize its ac voltage to that of the VSC-HVDC terminal. A SLD of ac grid passive connected to VSC and the corresponding ac voltage control are shown

Next to the ac inductive filter the PCC is located, as in the case of Fig(a). Uc , Ux refer to the ac voltage generated internally by the VSC and PCC ac voltage respectively. Z_L denotes the impedance of passive load and I_L denotes currents in load. A main motto of the voltage controller is to compensate the voltage at point of common coupling close to the given reference .Most commonly proportional-integral (PI) or proportional (P) controller is used to achieve this purpose. Modulating index (mx) can be defines as the output from the controller that is then connected to the pulse - width modulator (PWM).

THERE ARE THREE BASIC CONTROL CONFIGURATIONS ARE AVAILABLE

- DC Droop control
- Constant power
- Constant DC voltage

2.1 DC Droop characteristics

The voltage controller is the sum of both controllers' i.e. Constant power Controller and Constant DC voltage Controller. The slope of characteristic can be given in terms of the dc voltage output as in Fig. The droop constant ρdc is used together with voltage and relation between these two constants is given by:

$$R_{DC} = \frac{-P_{cN}}{U_N \rho_{DC}} \tag{2.1}$$

where,

U_N= power capacity rated
P_{CN}= Rated operating dc voltage

3. Small Signal Stability Analysis

The voltage flow through HVDC terminal (V) is fixed and equivalent to voltage initial (U*) irrespective of the level of the dc voltage (Pc). The HVDC Transmission System uses the PI controller to regulate the converter systems. The constant steady state characteristics of control of dc voltage are U.

Small signal analysis is a very important method by which one can understand easily the dynamic of a complex non-linear system. This method helps to analyze a complex non-linear system by liberalizing it in such a way that the dynamics of that system can be understood very easily. In this method a small perturbation is given to the system, the perturbation is considered sufficiently small such that it allows the non linear equation which is representing the system can be liberalized by studying the variation in position of operating point on the system response. These liberalized equations are then converted into the state space representation because state space representation helps to see easily the whole picture. [9]

3.1 Diagram of 5 terminal VSC-MTDC

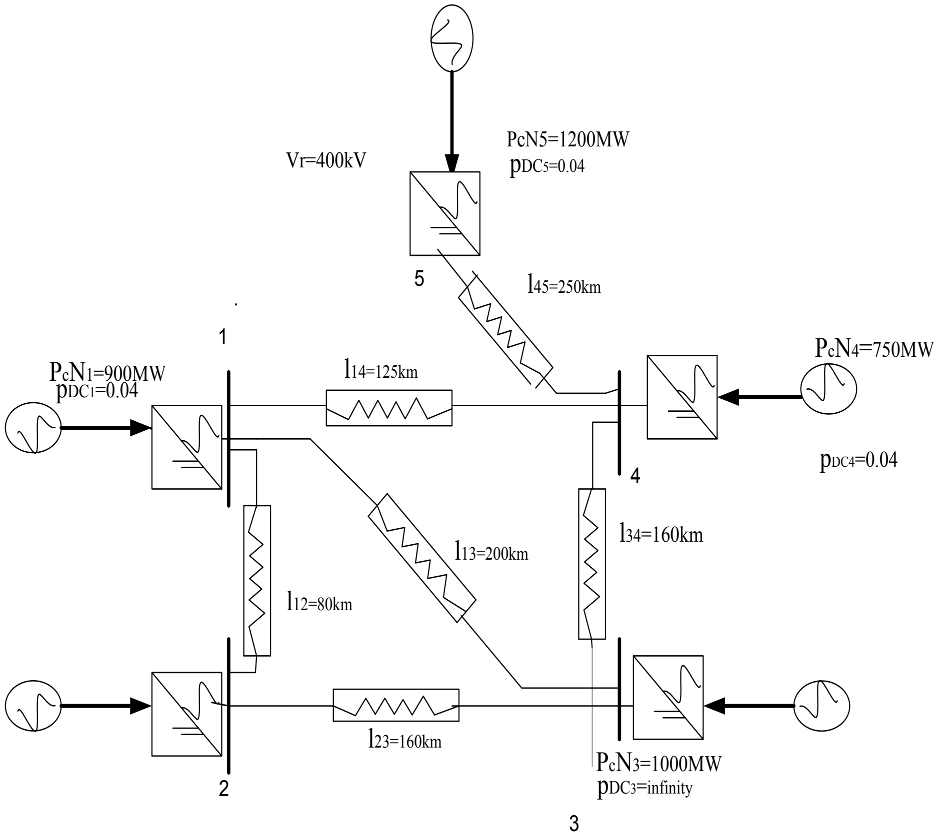


Figure 1 : A five-terminal diagram with droop control of dc voltage

3.2 Flow control of power in Multi terminal direct control

The challenge of precise power control in MTDC, let us look at the dc voltage versus power (V vs P) characteristic curves of the three types of outer controllers discussed. These are shown in Figure. it is clear that the power injection into the dc grid by a constant power mode terminal is always the same as the reference P*c. Similarly, a VSC-HVDC terminal equipped with integral control of dc-bus voltage . will always have the same dc-bus voltage as the reference V*. The power injection of such a terminal, however, is determined by the net power injection of all other terminals in the dc grid as well as the sum total of the power losses in the dc lines. This is what we refer to as the master terminal. The master terminal (if there is one in the dc grid) provides the net balance of power (deficit/surplus) with in a certain time constant. This time constant is dependent upon the control parameters (i.e. proportional and integral constants) used as well as on the total capacitance of the dc grid (i.e. the sum of all dc filter capacitances and line capacitances in the dc grid).

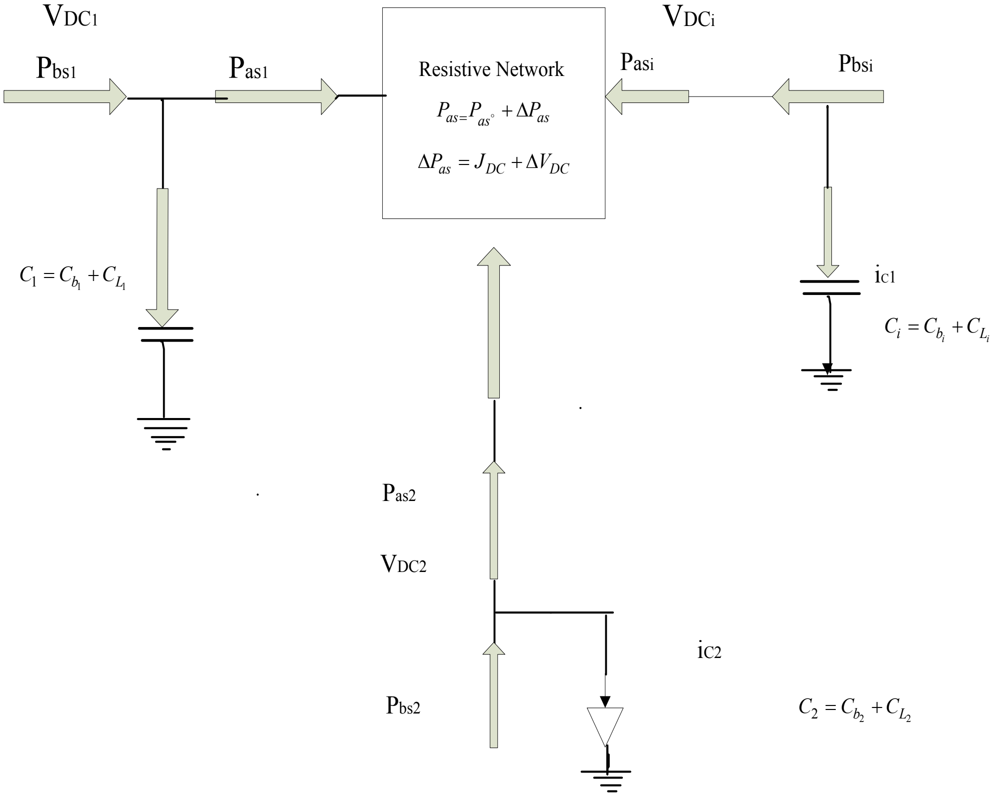


Figure 2 : Power flow of VSC-MTDC

Hence in master-slave or master-slave with dc droop control configurations, the issue of precise power flow control may not be a challenge since power flow at individual terminals, except the master terminal, will be determined by the respective power references. It should be noted that in the presence of master terminal, dc voltage droop-controlled converters appear almost as constant power-controlled terminals due to little dc-bus voltage changes.

Description of dc grid

The dc link of continuous line parameters can be constructed as single or multiple pi equivalent which consists of lumped parameters. Where there is more numbers of pi lines the chance of a model accuracy increases but computational complexity also increases. We are not taking inductances into consideration. Since by ignoring inductances our transmission network are working as cable and not as overhead lines. That's why capacitances are larger and inductances are tends to zero. So, the study of this paper are restricted only to all cable grid network system.

3.3 Abbreviations used

Here is some of the explanation of abbreviations used

l is transmission line length in km,

r represents total resistance per unit line length in ohm/km

c represents line capacitance line length per unit of line in microfarad/km, where as CLi represents aggregate connected dc line bus. N is the total number of terminals in the dc grid.

.

3.4 Generalized Mathematical Representation of VSC-HVDC Controllers

A VSC ac grid connected to HVDC terminal any one of the control methods. Passive grid is connected to VSC-HVDC and is used to power flow and control ac voltage is determined by the ac loads connected to the passive ac grid, VSC-HVDC connected to passive grid also appears as a constant power-controlled terminal (with ac power feedback) when looked from the dc grid side. Therefore, passive grid is connected to the VSC-HVDC can be represented connection to an active ac grid, with the load in the ac grid replacing the converter power reference, P^{*}_{c}. Hence,.

The progress of all methods of VSC-HVDC controller can be represented as generalized expression given by:

The DC terminal voltage V and the dc bus power behind and after the shunt capacitance are given by P_{bs} and P_{as} respectively.

Mathematically it can be represented as

$$V = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix}, P_{bs} = \begin{bmatrix} P_{bs_1} \\ P_{bs_2} \\ P_{bs_3} \\ P_{bs_4} \\ P_{bs_5} \end{bmatrix}, Pas = \begin{bmatrix} P_{as_1} \\ P_{as_2} \\ P_{as_3} \\ P_{as_4} \\ P_{as_5} \end{bmatrix} \tag{1}$$

Resistive dc network power flow after shunt capacitances, given by

$$P_{as} = P_{as^{\circ}} + \Delta P_{as} \tag{2}$$

$$\Delta P_{as} = J_{DC} \Delta V \tag{3}$$

Where JDC represents dc network of Jacobean matrix

$$J_{DC} = \frac{\partial P_{as}}{\partial V} \tag{4}$$

Equation (4) can be written in the vector form as

$$\Delta \dot{V} = diag(F)\Delta P_{bs} - diag(F)\Delta P_{as} \tag{5}$$

Where diagramme represents matrix diagonalization operator. Substituting equation (3) in equation (5) , we get

$$\Delta \dot{V} = diag(F)\Delta P_{bs} - diag(F) J_{DC} \Delta V \tag{6}$$

Generalized control dynamics expression for small signal equivalent is given by

$$\Delta \dot{P}_{bs} = diag(a)\Delta P_{bs} + diag(b)\Delta V + diag(c)\Delta P_{as} + diag(d)\Delta P_{c*} + diag(e)\Delta V*$$

using equation (3) in equation (6) , we get

$$\Delta \dot{P}_x = diag(a)\Delta P_{bs} + (diag(b) + diag(c)J_{DC})\Delta V + diag(d)\Delta P_{c*} + diag(e)\Delta V*$$

State space denotion for full multi terminal Direct Current system can becomes

$$\frac{d}{dt}\begin{bmatrix} \Delta P_{bs} \\ \Delta V \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\begin{bmatrix} \Delta P_{bs} \\ \Delta V \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}\begin{bmatrix} \Delta P_c^* \\ \Delta V^* \end{bmatrix} \tag{7}$$

where

$A_{11} = diag(a)$, $A_{12} = diag(b) + diag(c)J_{DC}$ $\qquad$ $A_{21} = diag(F)$, $A_{22} = -diag(F)J_{DC}$

$B_{11} = diag(d),\ B_{12} = diag(e)$ $\qquad$ $B_{21} = [0]_{n\times n}$, $B_{22} = [0]_{n\times n}$

State space dynamics equation (7) can be represented as follows:

$$\begin{aligned} \dot{x} &= A\,x + B_1\,u + D_1\,\Delta V^* \\ y &= C\,x \end{aligned} \tag{8}$$

$u = \Delta P_c^*$, $\qquad$ $B_1 = \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix}$, $D_1 = \begin{bmatrix} B_{12} \\ B_{22} \end{bmatrix}$

$x = \begin{bmatrix} \Delta P_{bs} \\ \Delta V \end{bmatrix}$, $A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$

3.5 Linear Quadratic Regulator (LQR)

Linear quadratic regulator or LQR is a technique of producing desired and controlled feedback gains and used for the high progress design of complete system. The complex system like differential equations is linearzed into linear system. We can obtain feedback gain by the solution of series of LMI.[12] . LQR helps us to choose performance index of weighted matrix. any in the entire control process. In order to get satisfactory results, we need to modify several times repeatedly. This paper proposed controller, based on small signal analysis of steady space system. In order to speculate or analyze the small signal analysis and progressive output of the system the time response and Eigen value method are used [13]. All the results will be simulated using MATLAB/SIMULINK and controller proves better as compared to old classical LQR. A detailed representation of the LQR controller for MTDC system is represented in Fig.

In this fig. MTDC produces system output(y), and the state(x). these output from MTDC will go to into LQR followed by Linear matrix optimization(LMI). LMI produces controller feedback gain(K). State variables and controlled feedback gain products and generate control input(u) which feedbacks again into MTDC [14].

The equation for state space model is given as

$$\begin{aligned} \dot{x} &= A\,x + B_1\,u + D_1\,\Delta V^* \\ y &= C\,x \end{aligned}$$

here x is the state vector and control input is represented as u.

$$x = \begin{bmatrix} \Delta P_{bs} \\ \Delta U \end{bmatrix}, \qquad u = \Delta P_c^*$$

Where ΔP_{bs} is change in the dc bus power behind shunt capacitances.

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \qquad B_1 = \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix}$$

The LQR cost equation of the system is given as

$$J = \int_0^\infty (x^T s x + u^T c u)\, dt \tag{9}$$

Where c and s are the control and state of weighting matrices.

Provided u=-Kx is the minimization of the cost function

Controller feedback gain $K = c^{-1}B^{T}P$ (10)

Where matrix P is formed by finding the solution of continuous state of Riccati equation given by

$$A^{T}P + \text{PA-PBc}^{-1}B^{T}P + s = 0 \tag{11}$$

In equation (11), G and H control and state weight matrices

$$G = \begin{bmatrix} G_1 & O \\ O & G_2 \end{bmatrix}, H = \begin{bmatrix} H_1 & O \\ O & H_2 \end{bmatrix}$$

Tuning of LQR weights

In this paper, we are proposing a controller which tunes the LQR weight matrices that is state and control weights. For better results we have to iterate and improve the performance. Control performances can be improves by experiments on balancing weight matrices [15]. Several other authors had worked on tuning of weighting matrices but most of them proposed a technique of taking diagonal elements of the matrix and neglecting all the other elements of the matrix. This paved a simplest way of solving the weight matrices. The functional performance of LQR depends on weighting matrices elements G and H. Due to its robust nature and stability characteristic. LQR technique is a specific controlled method which can be expanded in multi variable system. LQR allows a flawless response time and amount of the total control input. But choice of control and state matrices G and H respectively are the most challenging. It is because the task is mostly dependent on several operational conditions of the system and its dynamic order. The peak LQR performance dependent largely on weight matrices, that's why most of the output has been obtained on the selection of G and H matrices. Although, the parameter have greater dependency and used in the better problem and large speed computation limit the use of solving the problem of real world.[16]

Avoid of weighting matrices:

Suppose there is a matrix of high order and we have optimized it, then it is not a convenient way to calculate for all the elements available in the matrix. Then we simply need to remove all the other elements except all the diagonal elements. We just calculate the diagonal elements and get the result. In order to evaluate the program based on evaluation criteria the weighted criteria matrix is a valuable decision making tool.

Design of controller gain using linear matrix inequality (LMI).

Various kinds of control uncertainties can be resolved using linear matrix inequality. The control system performance specifications can be expressed in terms of performance index of quadratics. Largest gain of across overall frequency can be expressed as $H_\infty . H_2$ Is used to handle stochastic aspects and control over errors in regulation in frequency.[18]

A linear matrix inequality can be expressed as

$$L_{(q)} = L_0 + q_1 L_1 + \ldots . q_n L_n < 0 \tag{12}$$

Where $M_{0,}M_1,....,M_n$ are symmetric matrices, $p=\begin{bmatrix}p_1 & p_2 & .... & p_n\end{bmatrix}^T$ is a column vector of scalar and the matrix inequality $L_q < 0$ means LHS is negative definite.

LMI may be used as constraints for the optimization of minimizing the problem. The single LMI constraints are $\begin{bmatrix}L_{1(q)} & 0 \\ 0 & L_{2(p)}\end{bmatrix} < 0$.

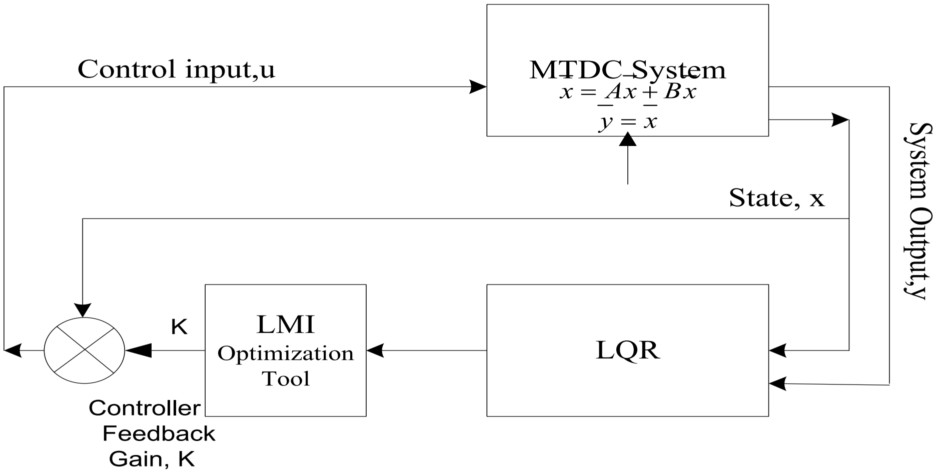
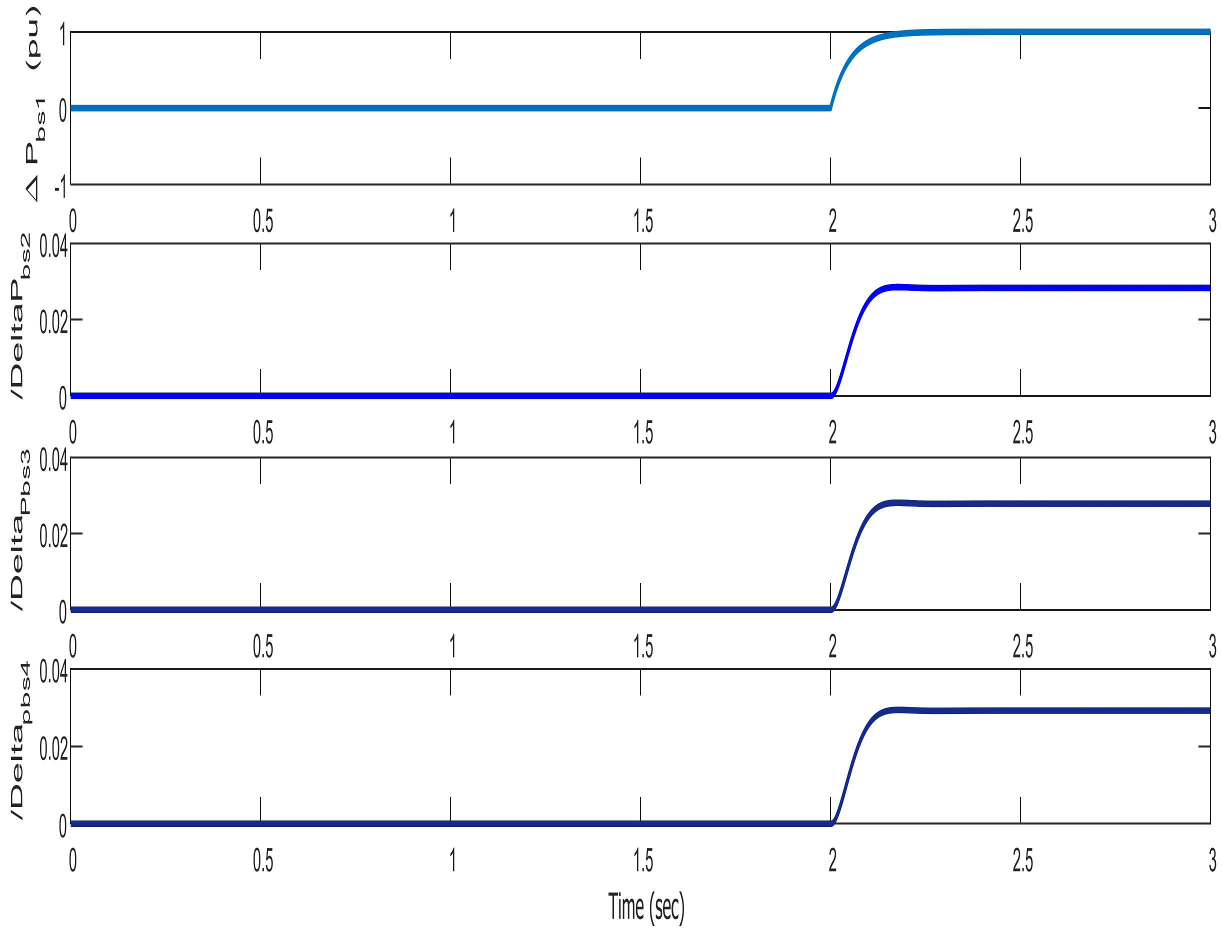


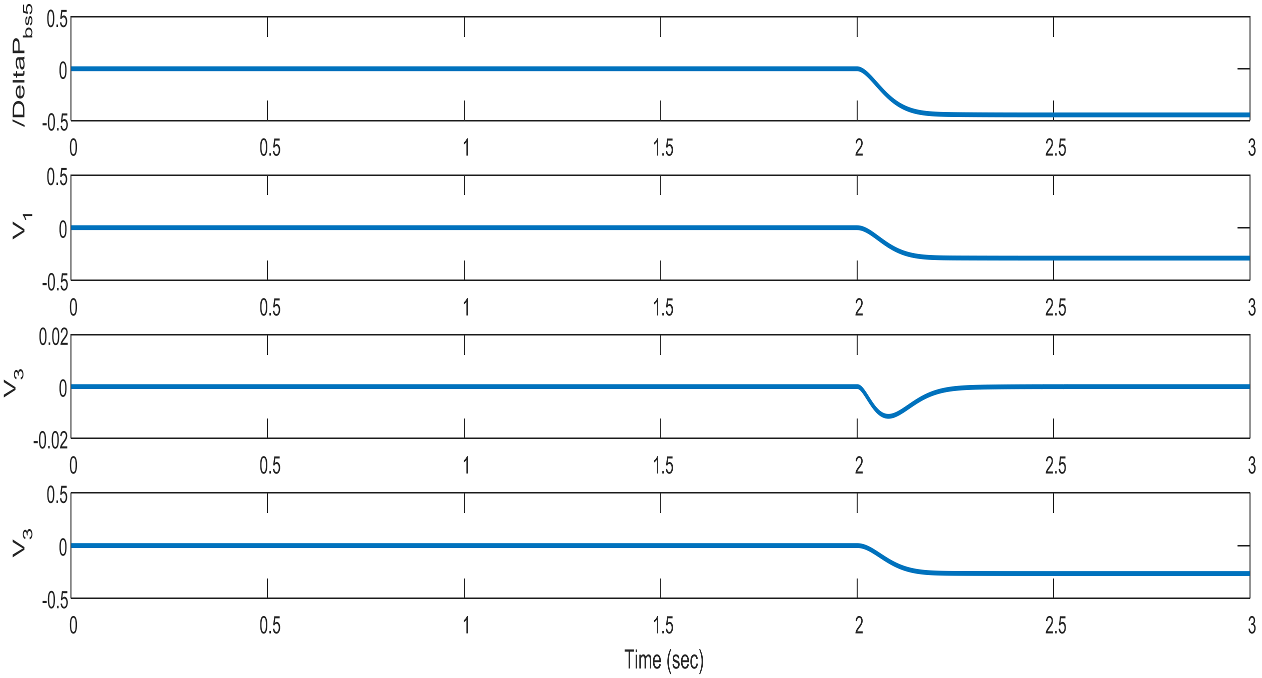
Figure 3 : Linear Matrix Inequality

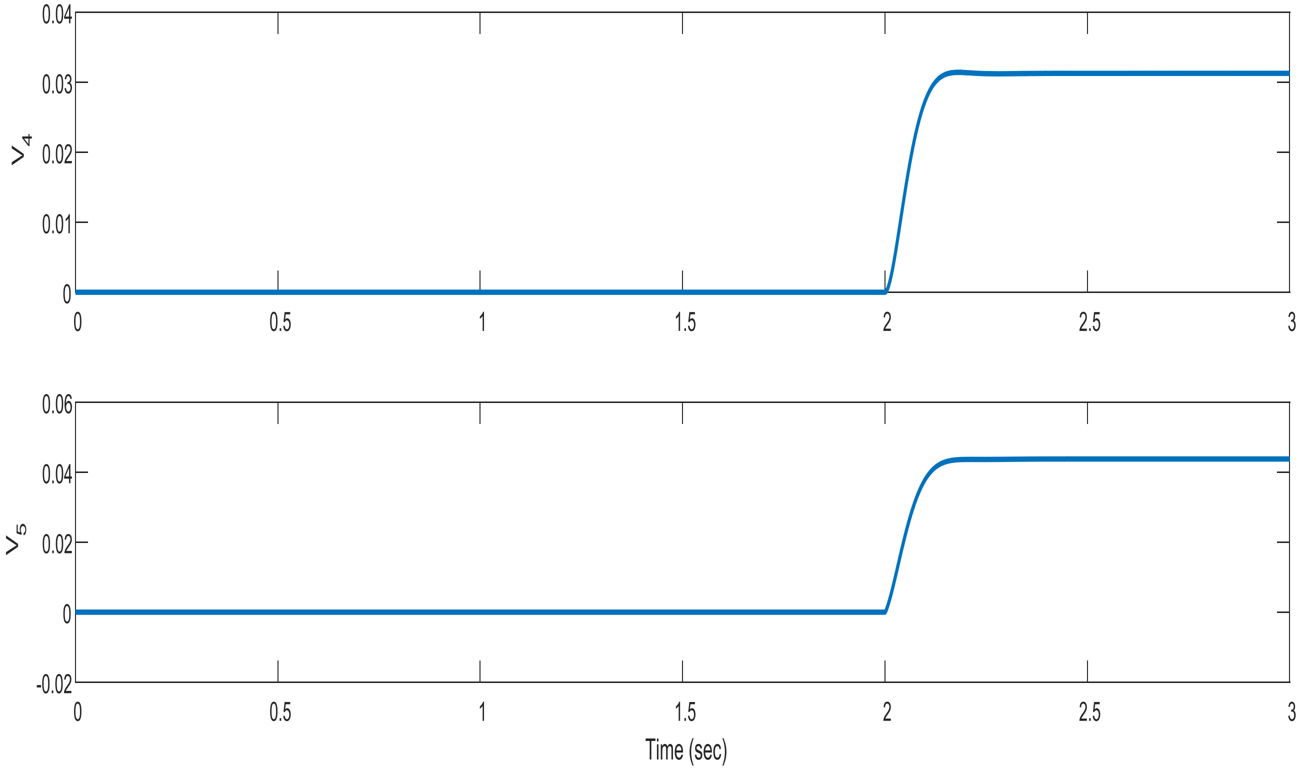
Chapter 4. Results And Discussion

Case-1

In detailed simulation of VSC MTDC model, a change in power reference of $\Delta P_{bs5} = 1MW$ and corresponding response as per change in terminal 5 is given in Fig. 4. This graph is according to input vector $\Delta P_{bs5} = [0 \quad 0 \quad 0 \quad 0 \quad 1]$. The total changes in nodal power and voltages are shown in Fig. 5. It is proved that state space model is correctly matched with time plots. This is the plot between power and voltage of all the five nodes with respect to time. In this proposed control scheme the challenge of overshoot and undershoot at every terminal after sudden change in load is completely removed. As per fig.5 it can be seen that settling time is lies between 2 to 2.5 sec, which is very small. If settling time is small then system stability is more. Hence, close loop system stability is improved. The proposed controller scheme helps to eliminate the load varying oscillations. Power sharing capability of the VSC-MTDC terminals enhanced and doesn't affect if there is sudden change in load. When current passes through proposed controller then controller minimizes its oscillations. Hence, power reserve capacity is also less affected.

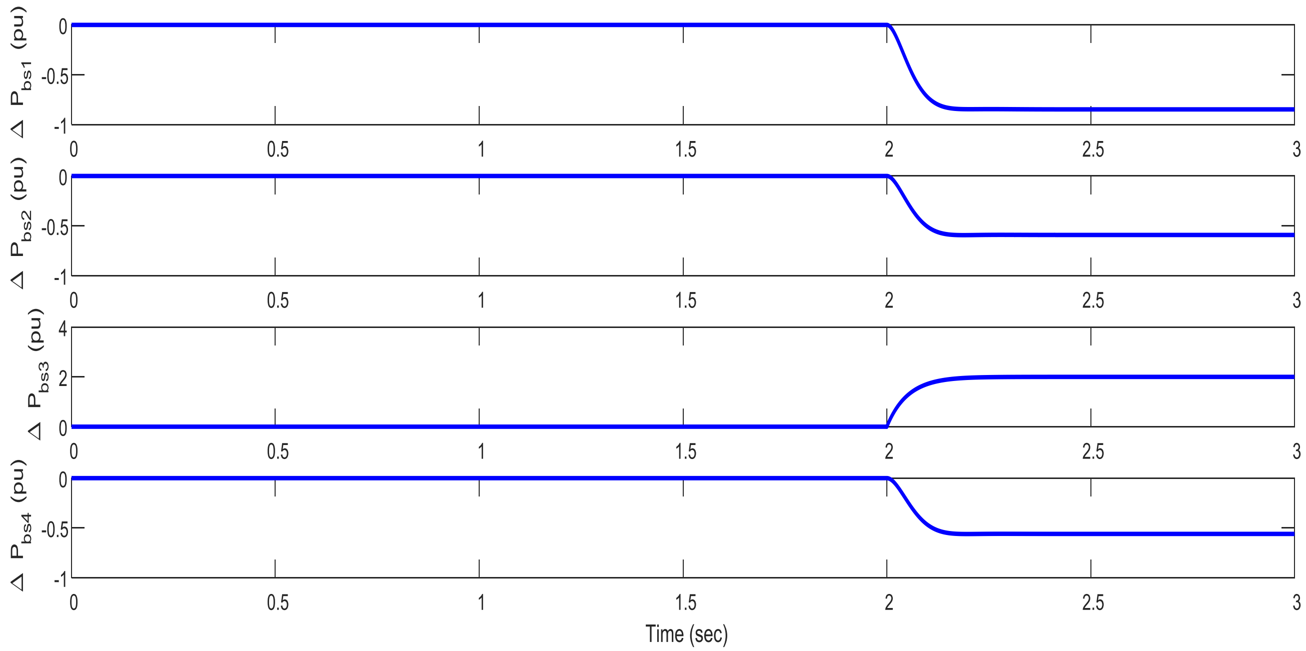


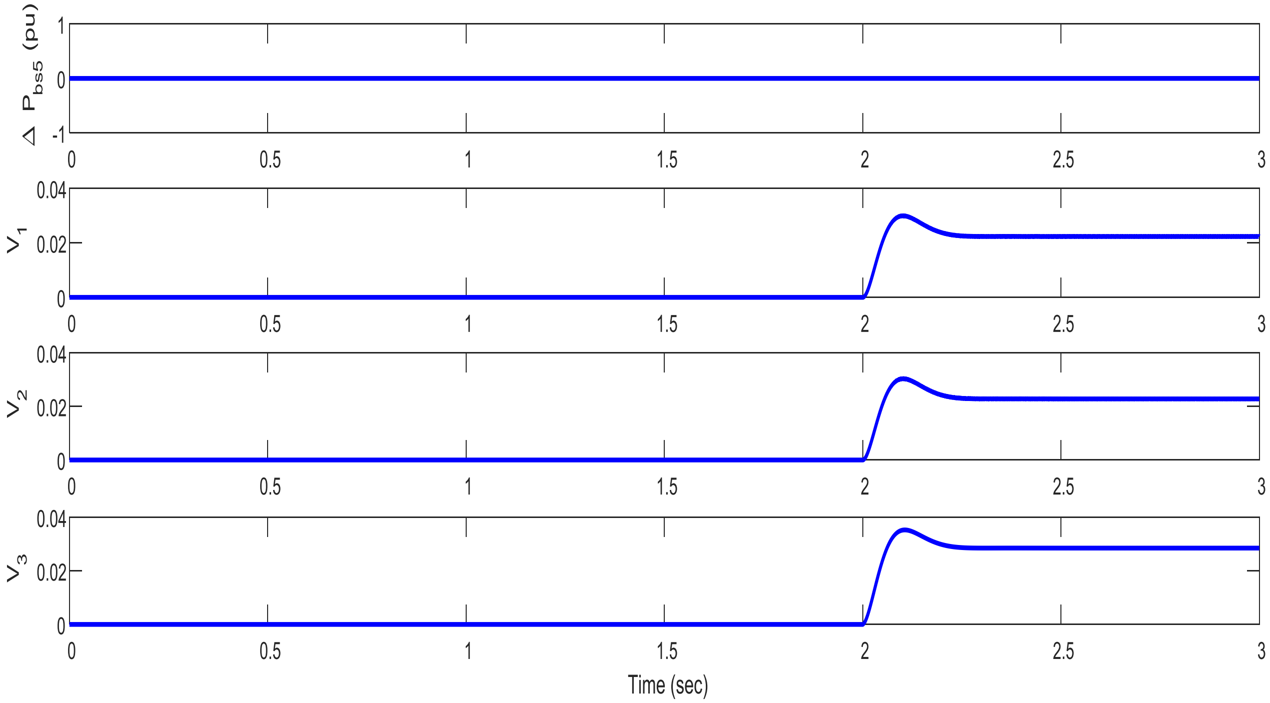

/DeltaP_bs5
V_1
V_3
V_3
0.5
0
-0.5
0.02
-0.02
0
0.5
1
1.5
2
2.5
3
Time (sec)

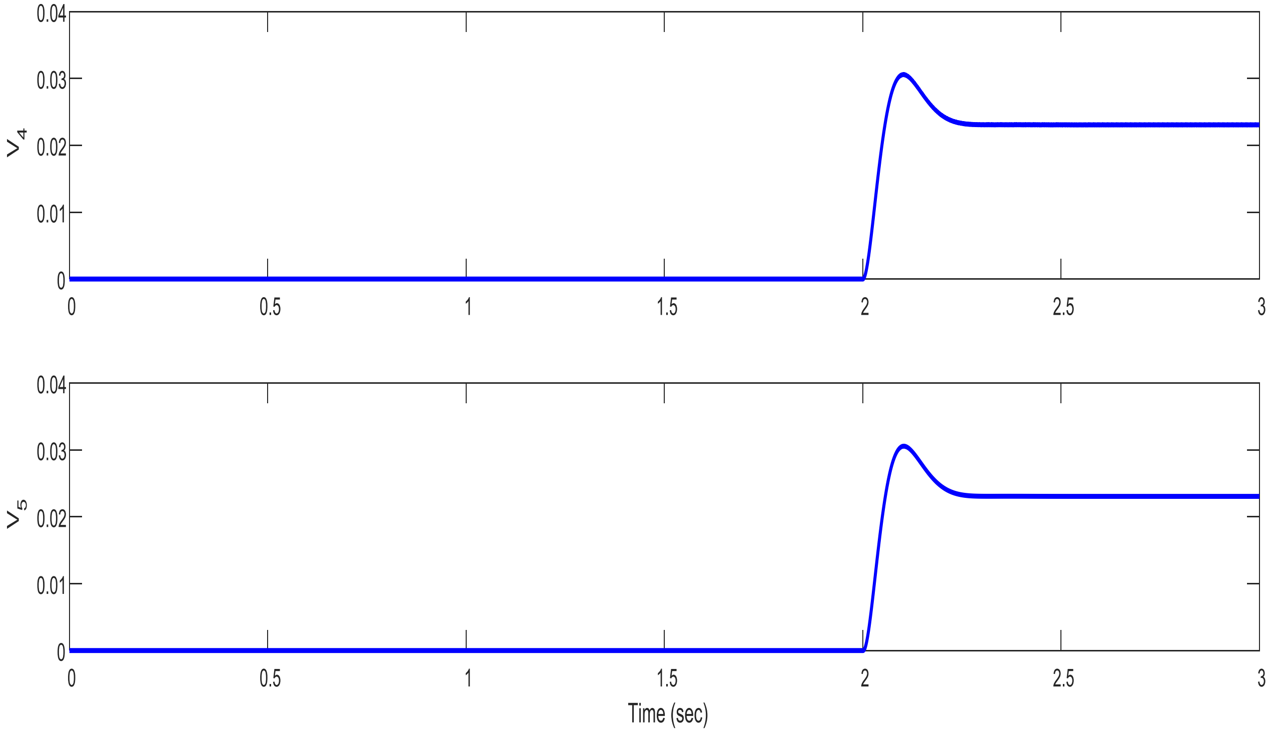

V_4
V_5
0.04
0.03
0.02
0.01
0
0.06
0.04
0.02
0
-0.02
0
0.5
1
1.5
2
2.5
3
Time (sec)

Case-2

In detailed simulation of VSC MTDC model, a change in power reference of $\Delta P_{bs_3} = 2MW$ and corresponding response as per change in terminal 5 is given in Fig. 5. This graph is according to input vector $\Delta P_{bs_3} = [0 \quad 0 \quad 2 \quad 0 \quad 0]$. In this case, the load at terminal 3 is changes to 2MW and corresponding graph is plotted. Voltage and power with respect to time are correctly matched. At terminal 5 power is constant, and at every other terminal there is very small settling time. It means system is more stable and closed loop system stability is improved. There is no variation on any terminals if we change the load condition and capability of power sharing is also enhanced in VSC MTDC system. Power reserve capacity is less affected where as overshoot and undershoot is eliminated.

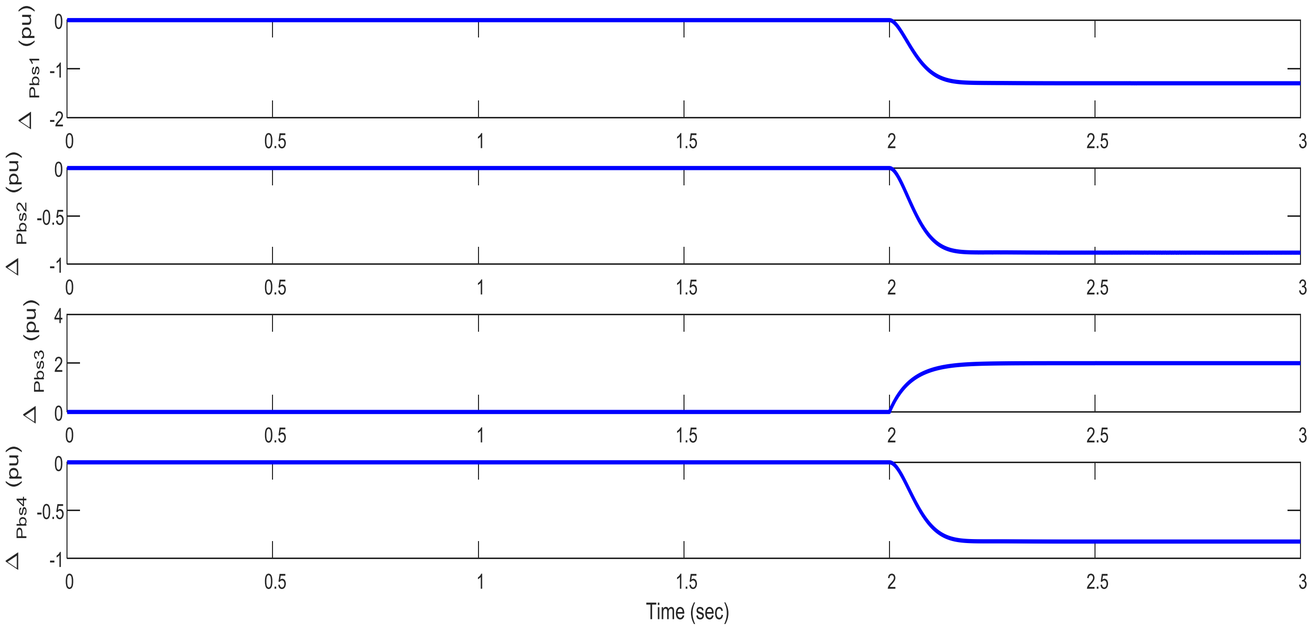


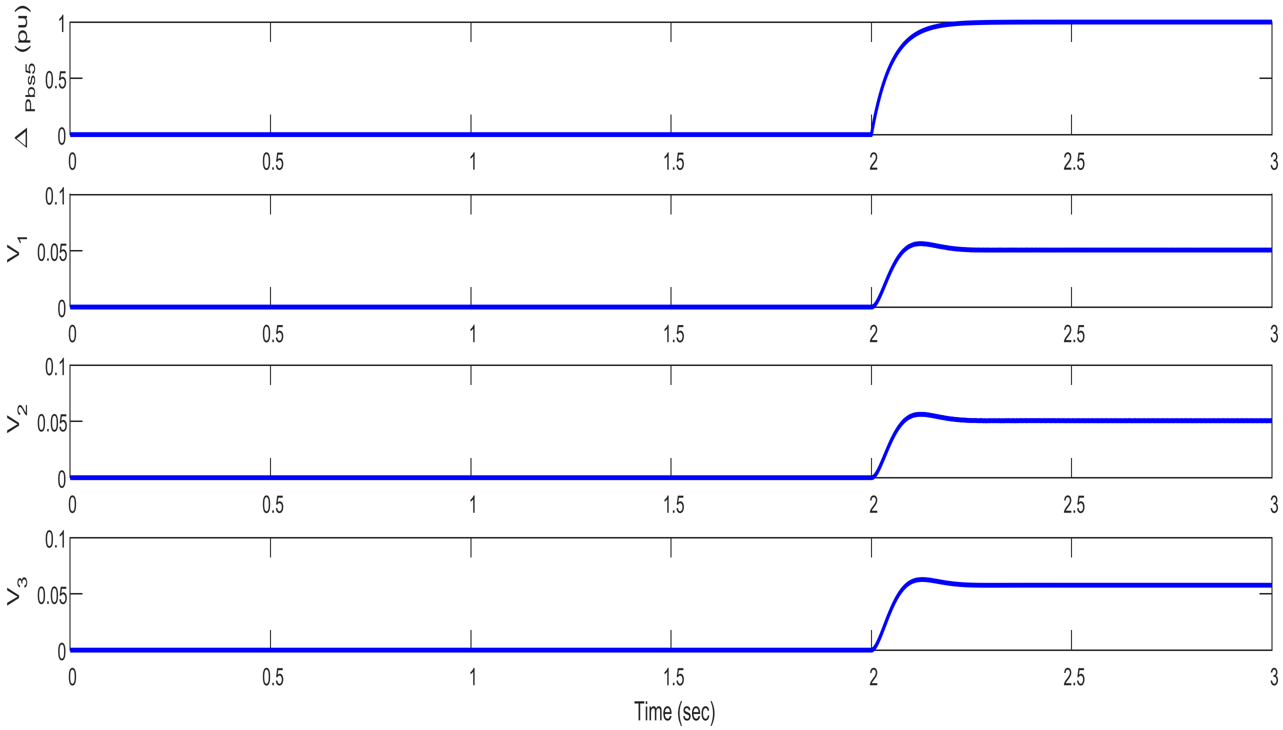

Δ P_{bs5} (pu)
1
0
-1
V_1
V_2
V_3
0.04
0.02
0
0.5
1
1.5
2
2.5
3
Time (sec)


V_4
V_5
0.04
0.03
0.02
0.01
0
0.5
1
1.5
2
2.5
3
Time (sec)

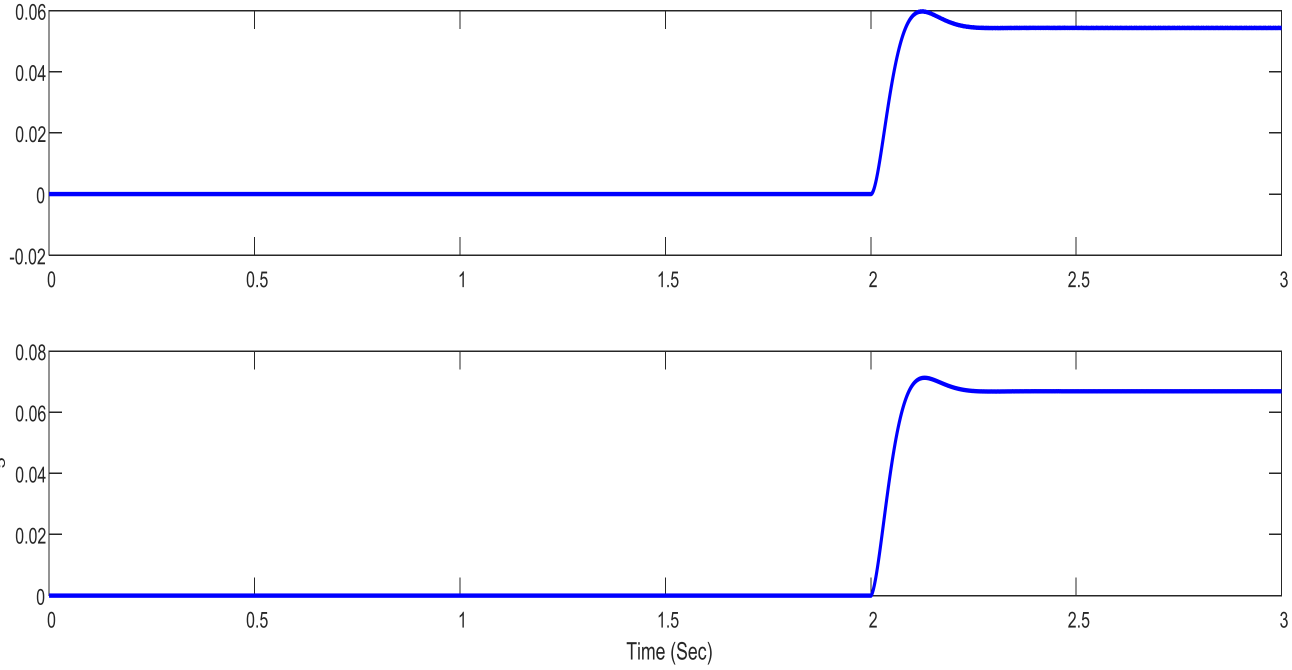
Case-3

In detailed simulation of VSC MTDC model, a change in power reference of $\Delta P_{bs5} = 1MW$ and $\Delta P_{bs_3} = 2MW$ corresponding response as per change in terminal 5 is given in Fig. 6. This graph is according to input vector $\Delta P_{bs5} = \begin{bmatrix} 0 & 0 & 2 & 0 & 1 \end{bmatrix}$. In this case, there are changes in terminal 3 and terminal 5 as 2 MW and 5 MW respectively. It is observed there is no change in any of the terminals when we change the load at other terminals. Proposed controller helps to reduce the oscillations with load varying conditions. Settling time of the system is very small that means, system is more stable. And closed loop system stability is improved. The reserve capacity of power is less affected whereas overshoot and undershoot is eliminated. This shows that there is negligibly small oscillation which would not able to affect our system at all. Power reserve capacity is very less affected.





Δ Pbs5 (pu)
V1
V2
V3
1
0.5
0
0.1
0.05
0
0.5
1
1.5
2
2.5
3
Time (sec)



V4
V5
0.06
0.04
0.02
0
-0.02
0.08
0
0.5
1
1.5
2
2.5
3
Time (Sec)

Terminal	From terminal	To terminal	Length(in km)	Resistance (in ohm/km)	Capacitance (in micro farad/km)	Droop constant	Power(MW)
	1	2	80	0.01	5	0.04	900
	1	3	200				
	1	4	125				
2	2	1	80	0.01	5	0.04	800
	2	3	160				
3	3	1	200	0.01	5	Infinite	1000
	3	2	160				
	3	4	160				
4	4	1	125	0.01	5	0.04	750
	4	3	160				
	4	5	250				
5	5	4	250	0.01	5	Infinite	750

Chapter 5 : Conclusion

In this study, a LQR based controller designed for VSC-MTDC system. LQR controller helps in maintaining the stability of multi terminal DC network. When a current or power generates from generating station, then it is an undulating in nature. It is not useful for supply as it will destroy the electric devices or reduce its life span. Then, we need a regulator which minimizes its oscillations. In HVDC system network there are only two terminals on both sending and receiving end. But in five terminal MTDC systems there are five terminals and we can connect the load at all the five terminals simultaneously. If load changes at any of the five terminals then power flow and current also abruptly changes. Hence, it is necessary to maintain that power changing conditions in such a way that there are minimum oscillations occurs. Hence, linear matrix inequality based LQR controller will control the power flow and balance the voltage and power at all the five terminals. In this paper, authors have done the analysis of three different load varying conditions. Author varies the load at different terminals and studies the graph and corresponding inference has given as per graph. The state space- model and the transient response are correctly matched. Overshoot and undershoot is a challenging task which is eliminated if corresponding load varies. The settling time of the system is reduced. If settling time is reduced then it means system reaches at stable state quickly, which is good for the system. When system undergo in stable state in less time then there is negligibly small oscillations and hence components used in the system is secure and life span increases. When there is sudden change in different terminals, then system is not affected with the use of proposed controller. Hence power reserved capacity of the system is also increases. Power sharing capability of VSC MTDC terminals is also increases

REFERENCES

1. Lei Zhang, Yuntao Zou, Jicheng Yu: ‘Modeling, Control, and Protection of Modular Multilevel Converter-based Multi-terminal HVDC Systems: A Review’ , 2017
2. Bilawal Rehman, Chongru Liu : ‘A Generalized N Terminal Current Order Control Scheme for LCC MTDC’. 2018 IEEE
3. Samy Akkari : ‘Control of a multi-terminal HVDC (MTDC) system and study of the interactions between the MTDC and the AC grids.’. Submitted on 13 Oct 2016
4. YangXi, AiQian, HuangJiantao, and AnYiran: ‘Application of Multipoint DC Voltage Control in VSC-MTDC System’, 29May2013
5. Amir Ghoreishi, Mohammad ali Nekoul, ‘optimal weighting matrices design for lqr controller based on genetic algorithm and pso’. January 2012, Advanced Materials Research Vols. 433-440
6. Ren Wang, Laijun Chen, Tianwen Zheng, Shengwei Mei. ‘VSG-based Adaptive Droop Control for Frequency and Active Power Regulation in the MTDC System’. csee journal of power and energy systems, vol. 3, no. 3, september 2017
7. Peng Ye , Lin Yuan ,Duojiao Guan ,Xingwei Xu ,Kaiyuan Hou : ‘The Modeling and Control Study of VSC-MTDC System’
8. Pedro Rodriguez, Kumars Rouzbehi: ‘Multi-terminal DC grids: challenges and prospects’ Published online: 8 July 2017

9. Amr Ahmed A. Radwan: ‘Small-Signal Stability Analysis of Multi-Terminal DC Grids’. 26 January 2019
10. Ravi Bhushan, Kalyan chaterjee : ‘Modeling and Investigation of Small-Signal Stability of DFIG-based Wind Energy System using Linear Quadratic Integral Controller’ 2016 IEEE
11. Mohammed Mabrook Alharbi: ‘Modeling of multi-terminal VSC-based HVDC systems’2014
12. Cristian Chitu, Jochen Lackner, Martin Horn,Helmut waser. ‘A Robust and Optimal LQR Controller Design for Electric Power Steering System’
13. Xingang Zhao, Zhe Jiang, Jianda Han, Guangjun Liu: ‘Adaptive Robust LQR Control With the Application to the Yaw Control of Small-scale Helicopter’ . Proceedings of the 2006 IEEE International Conference on Mechatronics and Automation June 25 - 28, 2006
14. Kuldeep Singh, Alka Singh: ‘Design and Analysis of LQR based Controller for Reactive Power Compensation’
15. Herbert Werner: ‘Controller design using linear matrix inequalities’, Vol. IX – Controller Design Using Linear Matrix Inequalities.
16. Alonso Marco , Philipp Hennig , Jeannette Bohg , Stefan Schaal, and Sebastian Trimpe: ‘Automatic LQR Tuning Based on Gaussian Process Optimization: Early Experimental Results’
17. Vinodh kumar elumalai , Raaja Ganapathy Subramanian: ‘A new algebraic LQR weight selection algorithm for tracking control of 2 DoF torsion system’. VOL. 66(1), pp. 55-75 (2017)

18. Herbert Werner: ‘Controller design using linear matrix inequalities’, Vol. IX – Controller Design Using Linear Matrix Inequalities.