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VOLTAGE SOURCE BASED HVDC WITH FACTS AS ANCILLARY CONTROLLER USING FUZZY LOGIC CONTROLLER

PRABHAKARA SHARMA. P[1], P. KANTA RAO[2], and K. VAISAKH[3]

[1]Associate Professor, Department of Electrical & Electronics Engineering, Kallam Haranadhareddy Institute of Technology (A), Chowdavaram, Guntur, Andhra Pradesh, India.

[2] Professor, Department of Electrical & Electronics Engineering, SRKR Engineering College (A), Bheemavaram, Andhra Pradesh, India.

[3]Professor, Department of Electrical Engineering, Andhra University College of Engineering (A), Visakhapatnam, Andhra Pradesh, India.

E-mail: [1]prabhakarasharma@gmail.com, [2]dr.pkantarao@gmail.com, [3]prof.dr.vaisakh.k@gmail.com

ABSTRACT

Increasing demand of energy becomes major issue in emerging technology to deliver cost effective electrical power. By using HVDC systems we can achieve transmission of power over long distance with minimal losses with utilization of proper controller like flexible alternating current transmission (FACTS) devices. The main application of HVDC system is large amount of power transfer over long distance with view of reliability, cost and technical performance. FACTS devices are composed of static equipment utilized for increase power transfer capability and enhancing controllability of line. It consists of advance power electronic devices with combination of series and shunt converter called UPFC for facilities fast acting reactive power compensation in tie lines of HVDC network. The proposed system identifies improved power transmission capability through conventional and advance control schemes, simulation study is made with application of PI and Fuzzy logic based UPFC on HVDC network. The conventional controller cannot compensate power fluctuations and time constant of active and reactive power which is integrated in controller of UPFC [2]. The system model is analyzed for various fault conditions by maintain UPFC fixed which reduces the magnitude of the fault current and oscillations in excitation voltage.

Keywords: *High-voltage dc transmission (HVDC), Faults in HVDC system, Flexible ac transmission system (FACTS), PWM Power transfer controllability, Fuzzy Logic Controller.*

1. INTRODUCTION

HVDC system built up with one or two converters with 12 pulse converter. Based on the configuration of system HVDC may begin monopolar or bipolar or homopolar system [1-3]. In certain cases where bipolar system may build by two converters in series configuration for enhancing power transfer capability and improve voltage profile [10]. It is not that easy to connect parallel converter in case of single pole configuration. Each pole is equipped properly with dc filters and reactors to reduce harmonic in lines and improve reliability of the system. Also HVDC system consists of jointly connected converter combination. Fig.1 shows monopolar HVDC system linking both converters with earth electrode, which are installed away from the converter station equipment.

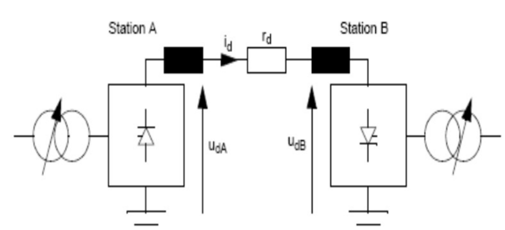

Fig.1. HVDC Transmission System With Monopolar Configuration.

DC transmission line control

The dc current flowing in line can be calculated from Fig.1 which can be obtained by difference of voltage between station A and station B and r_d represents total resistance of the line evaluated dc current

$$i_d = \frac{u_{dA}-u_{dB}}{r_d} \quad (1)$$

Power transmitted to converter station B is denoted by

$$P_d = u_{dB}.i_d = u_{dB}.\frac{u_{dA}-u_{dB}}{r_d} \quad (2)$$

In rectifier unit, firing angle α should normally operates between 3°-5° and should decreased less than α_{min} in order to ensure positive voltage across valve of firing instant. In inverter operation extinction angle normally lie between 17°-19° beyond which there is risk of commutation failure too high. On the other hand both α and γ should be as low as possible to maintain nominal capacity of equipment to lowest. With this low values high chance reactive power consummation and harmonic disturbance in ac network which can be controlled by maintaining γ equal γ_{min} in normal operation [4-5]. The dc voltage of inverter station can be controlled by tap changing transformers and dc currents by controlling dc voltage at rectifier unit. Due to small resistance between the converter stations the voltage difference is small and any variation in voltage gives large variation in current and power transfer of HVDC system. The direction of dc current flow cannot be controlled, so to control the direction of flow by reversing voltage of line. As voltage difference of the line is maintains constant to achieve fixed positive current in the line. The firing angle of rectifier α is maintained as low as possible to control of current [6]. The tap changing transformer of rectifier can be maintained only by controlling α less than α_{min}.

2. V-I characteristics of converter topology

Voltage drop in resistance in transformer and converter as well as non-voltage drop in converter current of thyristor valve are disregarded in practical applications; the magnitude of operating voltage in normal operating voltage is 0.5%. The commutation voltage is 5-10% of normal voltage. The expression for six pulse bridge converter is given by

$$u_d = u_{dio}.[Cos\alpha - d_{xN}.\frac{I_d}{i_{dN}}\frac{u_{dioN}}{u_{dio}}] \quad (3)$$

Where α denotes the firing angle of the converter, during inverter operation it is well known as extension angle γ as in case of rectifier mode of operation. The extension angle is also known as power angles between anti-parallel operations of next converter valves commutation voltage of zero crossing. The relation between firing angle, extension angle and commutation angle is given by

$$\alpha + \mu + \gamma = 180° \quad (4)$$

In inverter mode of operation the equation for dc voltage can be build as give below

$$u_d = -u_{dio}.[Cos\gamma - d_{xN}.\frac{I_d}{i_{dN}}\frac{u_{dioN}}{u_{dio}}] \quad (5)$$

The V/I characteristics of converter operation expressed above can be used to evaluate of i_d and d_{xN} under normal operating condition; however, it is preferable to consider positive voltage on the inverter side and negative voltage on the rectifier side when defining converter characteristics of a complete HVDC system [6]. It would be difficult to control both rectifier and inverter firing angle as fixed controls which may not provide stable operation of HVDC system due to both converter produces same slope characteristics approximately. Also there will be small variation in transformer data and voltage difference. Therefore to achieve better control the characteristics of the converters should be perpendicular to each other as possibly. To achieve such characteristics controller may be fixed to constant value called constant current control [7-9]. When we consider constant current control characteristics in combination with V-I characteristics and steady state response of the rectifier station can be achieved as shown in below Fig.2. Similarly characteristics of inverter can be evaluated by apply reverse polarity of operation. The below diagram represents the rectifier and inverter characteristics with constant current control under steady state operation.

$$\alpha > \alpha_{min} \quad (6)$$

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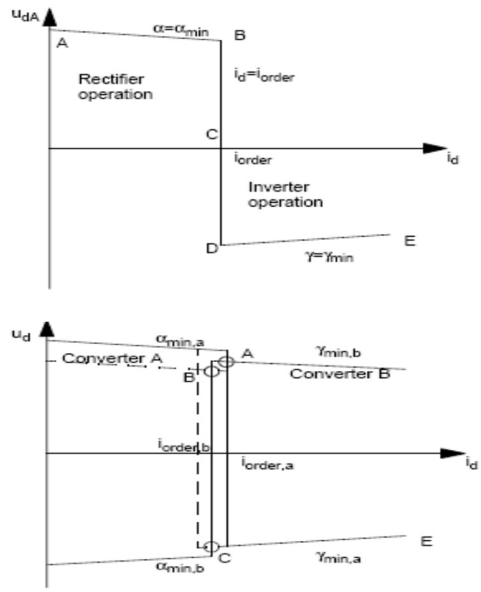

Fig.2.Voltage - Current U_d/I_d Characteristics For Converters Topology Under Steady State Condition.

The voltage of inverter is lower as compared to rectifier and tends to increase opposite voltage with decrease of γ not less than γ_{min}. After evaluating operating point A in Fig. 2 we assumed that the characteristic of inverter at point B is referred to rectifier at point A which improves the voltage drop in transmission line. The magnitude of voltage drop will be between 1-5% of rated value of dc voltage. If any fault occurs at rectifier side result in reduction of voltage difference and sinks dc currents. The constant current controller at rectifier starts to reduce firing angle α, and may possible to meet α_{min}, to current get upheld [8]. On the other side inverter control reduces opposition voltage of inverter to maintain current to its steady state value till it may reach to new stable point. If current at point A decreases to less than point B, then at rectifier unit will generate high currents and tends to increase firing angle α, results in decrease of inverter voltages. Inverter side currents get weakening and can be controlled by variation of extinction angle γ which results decrease of counter voltage. Finally rectifier achieves γ_{min} thresholds and cannot decrease further until new operating point C. Here the current remain positive and voltage becomes negative by which we can say power flow is reversed and point A is operating inverter and point B as rectifier. The variation of thresholds between current value of rectifier and inverter are known as current margins [10]. With this it is possible to vary the power flow in transmission line by reversing the polarity of the current margin. But in real time it is expected to control by different techniques. Therefore inverter is designed in such a way that it operates at an angle between 95°-105° which is less than α_{min} thresholds. To limit current variations between operating points of rectifier and inverter. The small variation at corner points of inverter represents cut off characteristics. Hence we can conclude in HVDC system, it is not permissible to operate with low voltages and high currents and most of the HVDC equipped with voltage dependent current control controllers.

3. Master Control for HVDC System

The master controller explains about the basics and standards of HVDC converter stations under fault operation i.e. master control of HVDC system is used to protect HVDC converter station equipment during fault condition. A master control is designed independent of rectifier control and inverter control. Based on the requirement of transmission master control can be designed for constant power control or constant current control or control any external ac frequency disturbances by properly tuning controller to stabilize system. The controllers are required for both converters for maximum transfer of power, but master controller is active only during fault condition which controls the fault current from damage of converter stations. The calculated transmission line current are designed in such a way that slave communicates fault current to master where it check for pre designed current margins and protects the converter station from fault currents [9]. In order to control both converters with same current control a communication medium is created with converters current control. The communication medium could be telecommunication system with fault free and need would be higher for fast response controllers due to time delay in processing and communicating influences dynamic of the master control system. The following currents for master control can be derived from below equations.

$$I_{dc} = (V_{Rdc} - V_{Idc} - R_{dc}I_{dc})/L_{dc} \quad (7)$$

$$x_r = K_I(I_{RO} - I_{dc}) \quad (8)$$

$$x_1 = K_I(I_{RO} - I_{dc}) \quad (9)$$

$$P_{km} = \frac{V_{ndc}I_{ndc}}{S_n} V_{Rdc}I_{dc} \quad (10)$$

$$Q_{mk} = \sqrt{S_r^2 - [\frac{V_{ndc}I_{ndc}}{S_n} V_{Rdc}I_{dc}]^2} \quad (11)$$

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$$P_{mk} = \frac{V_{ndc}I_{ndc}}{S_n}V_{Idc}I_{dc} \quad (12)$$

$$Q_{mk} = \sqrt{S_1^2 - [\frac{V_{ndc}I_{ndc}}{S_n}V_{Idc}I_{dc}]^2} \quad (13)$$

The assumptions for the algebraic equations are then

$$cos\alpha = x_R + K_p(I_{RO} - I_{dc}) \quad (14)$$

$$V_{Rdc} = \frac{3\sqrt{2}}{\pi}V_k cos\alpha - \frac{3}{\pi}V_k cos\alpha - \frac{3}{\pi_{IR}}I_{dc} \quad (15)$$

$$V_{Idc} = \frac{3\sqrt{2}}{\pi}V_m \cos(\pi - \gamma) - \frac{3}{\pi}X_{tI}I_{dc} \quad (16)$$

$$S_I = \frac{3\sqrt{2}}{\pi}\frac{V_{ndc}I_{ndc}}{S_n}V_m I_{dc} \quad (17)$$

$$I_{IO} = \frac{V_m}{m_I} \quad (18)$$

Above equation denotes dc line circuit with ac to dc conversion and dc to ac conversion connected to RL load [2]. A convention PI controller is proposed to control gate pulse called extinction angle control and control power transfer of HVDC system [1]. A thyristor based HVDC system is designed with converter controllers for enhancement of power transfer in a network. While exchanging power between interconnected lines to different substations with constant or variable power the HVDC converters plays important role in converter controller design and enhance power transfer in transmission line through voltage control [11]. The operation of HVDC system improves power transmission by separately tuning active power control and reactive power control. Importance of HVDC system is consider as component of advance power electronic family designed which are designed in back to back converter implies AC-DC-AC similar like FACTS application [13]. HVDC system are mainly applied for application which are independent of the frequency and phase shift for long and medium overhead transmission systems for bulk power transfer from sending end to receiving end with high speed controllability. It reduces development of underground cable due to less efficiency of ac transmission line for same amount of power but with HVDC system, it overcomes the use of underground transmission system [12]. The HVDC systems are adopted widely on non-synchronous ac system due to its reduced maintenance and greater power transmission. The purpose of smoothing reactor is HVDC systems is to eliminate ac harmonics and compensate reactive power both ends of transmission line as shown in Fig.3 HVDC system is installed on the basis of dc voltage and desired current rating based that optimum converter cost can be yield. The HVDC system used in submarine usually goes with 12 pulse converter [3].

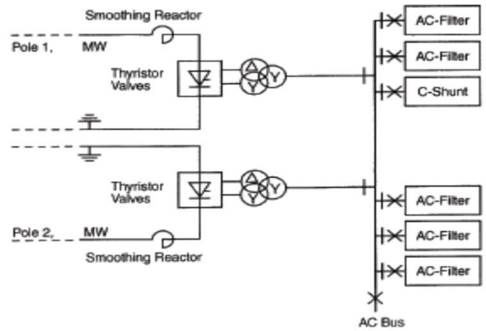

Fig.3. Block Diagram Of 12-Pulse Converter Connected To YY And Y-D Converter Transformers.

The converter transformer winding filter out harmonics in the system using 6 pulse Graetz bridge converter [11]. A passive filter consists of R L C parameter used for filtering operation which reduces the harmonics. The converter designed using IGBT gate turn off thyristors are well known as active filters and passive filter plays vital role in HVDC system.

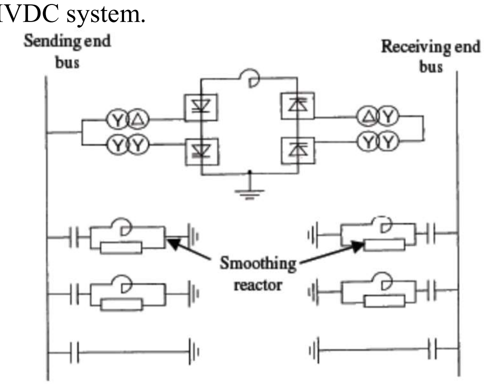

Fig.4. Block Diagram Of HVDC System With Back-To-Back Connection Of Converter Topology.

The function of HVDC system is limited when transmission line short circuit ratio is low. Due to its low short circuit ratio it is necessary to have insulation for HVDC system but will not impact converter operation [3]. The stress produced by ac and dc voltage during HVDC transmission line to withstand HVDC insulation [14]. In addition graetz theory is compensating the harmonics produced in energy conversion of HVDC system.

4. Rectifier operating conditions of HVDC system

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Rectifier of HVDC system filters the sending end voltage- current produces the harmonic and noise in the transmission system. A reactor in the transmission system to filter out the harmonic, noise and transmits the dc power to receiving end voltage as shown in below Fig.5 [3] Inverter of the HVDC system converter the dc voltage-current to ac voltage - current, such operation of simultaneous conversion of AC to DC and DC to AC with filtering circuits forms the HVDC system rectifier controller is to filter and produces the gate pulses of the constant current into the secondary winding of the transformer [15-16]. For such application a special type of three winding transformer is used for transmission current pulse at primary side which has special type of connection and winding ratios also thyristor scheme are used for such type of converter design [20].

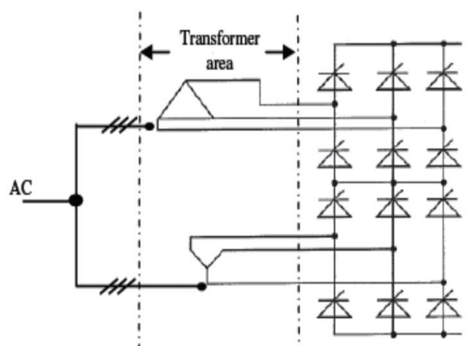

Fig.5. Block Diagram Of Transformers Connection With Valve Based 12-Pulse Converter.

HVDC and FACTS are used for more accuracy and reliable system operation of transmission system where rectifier commutates dc power and inverter converts DC to AC for reactive power control using FACTS controls [17]. For optimal utilization and peak inversion of the voltage across converters a three phase bridge converter is designed and use of simple transformer before converter which control voltage tuning and high direct voltage, the hypothesis of HVDC system with FACTS is developed using matlab equations for (7) to (18). This equation denotes single dc line circuit with rectifier and inverter fed to RL load. A conventional PI controller controls the firing angle and extinction angle of HVDC system. The above expressions represent in singe line dc system with rectifier and inverter connected to RL components. Pulses for converter is controlled by PI control for generating firing angle and extinction angle of HVDC system. The HVDC system using thyristors based are studied and analysis of the same is implemented using Matlab Simulink.

5. FACTS (Flexible AC Transmission System)

The main object of flexible ac transmissions integrating with electrical network is similar like HVDC system but with better provides real and reactive power control, improving power transfer capability, damping power swings and prevents sub synchronous resonance. FACTS devices are well known as series controllers or shunt controller or combination of both unified power flow controller for improving power transmissions capability.

6. HVDC with FACTS

HVDC with UPFC are shown in the Fig.6. The size of the FACTS relays on the loading of the line and utilized in electrical network. The value of the sine wave is depends on the frequency of power electronic devices used, there are three types of FACTS controller for transmission system. (a) Shunt controller: shunt controller are FACTS device which are connected in parallel like variable inductor and capacitor to the transmission line and controls the transmission voltage. This device is mainly limiting the inductive and capacitive reactance in regulating line voltage at sending end point [14]. (b) Series controller: series FACTS device in series with series transformer connected line and controls the current injection of the transmission line. It limits capacitive and inductive reactance of transmission line at receiving end of the transmission system [15]. (c) Shunt- series controller: Shunt series controller are combination of STATCOM and SSSC which is used to control injected voltage and current drawn at receiving end result in compensating reactive power, improved transmission capacity with minimum losses. It is well known as unified power flow controller which requires minimum dc current for exchanging power between shunt series converters as shown in Fig. 6 [3].

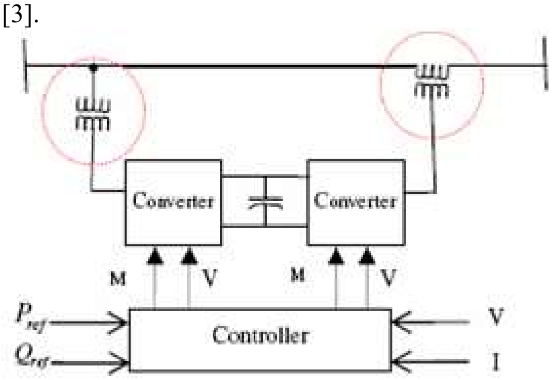

Fig.6. Series-Shunt Compensator UPFC.

7. Control Strategy (Fuzzy Logic Controller)

A fuzzy logic controller is well known as FLC which is one of the adoptive technique used for transforming human knowledge to membership function based fuzzy interface control system [2]. The method used for developing fuzzification input and outputs size, type and rules are based on trial and error. To achieve dynamic response of any system controller gain need to be tuned with respect to system conditions. An adoptive neuro fuzzy logic controller is utilized for increasing gain and decreasing error of the system. For HVDC based UPFC system neuro fuzzy logic controller is used to damp out the oscillations produced by converter stations. Following are steps to develop fuzzy logic controller as adaptive fuzzification approach

- ✓ Building fuzzy logic controller structure
- ✓ Training fuzzy logic to define rules and meet desired control response
- ✓ Operating fuzzy logic controller under different condition for performance evaluation

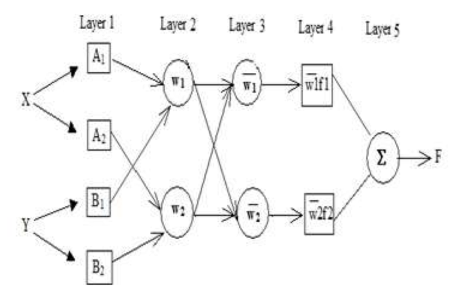

Fig.7. Flc Structure.

In FLC controller input and outputs passes through their respective membership function [15]. By providing input data set and output data set control system toolbox build up fuzzy inference whose membership functions are tuned in such a way it learn form system data and provide dynamic response by modeling system conditions. The rule structure is predefined by the users for calculation of system variable as characteristics.

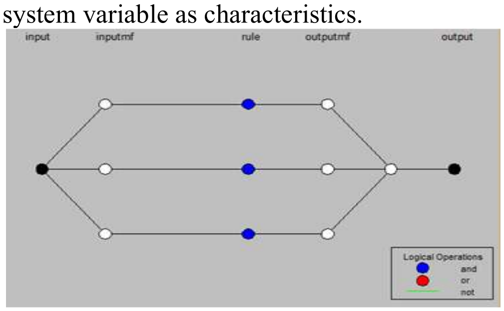

Fig.8. Fuzzification.

FLC applies FIS technique to data modeling, we can choose membership function parameters automatically using FLC tool in MATLAB. Using FLC we can apply fuzzy logic inference to a system for which we already have a collection of input/ output data sets of parameters. Gradient vector reduce some error measures [2]. This error measures is usually defined by the sum of the squared difference between the actual and desired outputs. Collect input/output data in a form that will be usable by FLC for training. GUI includes four distinct areas to support a typical work flow [17] usually FLC are driven by FIS technique for system parameter modeling. By choosing the membership function in FLC toolbox we can tune the controller for fast and dynamic response. If we apply FLC to HVDC based UPFC system where FLC learns the data from system parameter and tends reduce the error and increase gain which result in reduction of fault impact and maintain system fault free as well as improves stability of the network. The collection of input and output data from the system includes four distinct stages of inference development:

- Deploying designing and recreating data
- Importing and exporting of FIS structure
- Exercise the FIS.
- Evaluated the performance of developed FIS.

8. Simulink Implementation of HVDC with FACTS

Fig.7. shows the implementation of HVDC with FACTS controllers where real power is controlled to achieve steady state operation under system impacted with harmonics and other reactive power losses. A weak transmission system is considered in analyzing the performance of HVDC with FACTS controllers using simulation, which shows the implementation of HVDC and FACTS layout for damping harmonics in the system and rectification-inversion of produced dc power at receiving end [18]. Simulation of HVDC and UPFC is carried out and results of line voltages and currents with oscillations before compensation and after compensation results are presented in Fig. 9 to Fig. 19 with different faults (LLG, LLLG and LG), steady state response of the system is captured. By using UPFC system improves transmission efficiency and reduces oscillation in the system. The controller of UPFC is utilized to tune real and imaginary powers in UPFC [19]. Whenever there is fault or any external disturbance due to which system gets degraded at that time feedback controller of UPFC tunes the system and compensates faults and losses in the system. The

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output of the control signal I used as reference for PWM generator for gate pulse creation for series and shunt converter of UPFC. The requires gate pulse for UPFC converter can be modulated by using fuzzy logic controller where it produces several pulses per half cycle of the sine wave which results pulse width modulation of required pulse. The gate pulse can be obtained by comparing reference carrier wave produce by PWM with fuzzy inference.

9. RESULTS AND DISCUSSION

The below figures shows the results of HVDC based UPFC system real and reactive powers obtained under steady state operation with harmonics in the system. Weak power transmission is usual problem when transferred power over long distance. Fig. 5 shows the simulink implementation of HVDC based UPFC system with rectification and inversion operation with their respective controllers. The controller is designed in such a way that it damp out the oscillation of the system at rectification and inversion units. Simulation study is carried out HVDC with UPFC and results are demonstrated as shown below.

Fig. 9 to Fig.19 demonstrates result of HVDC system under different fault conditions like LG, LLG and LLLG faults with and without application of UPFC from the simulation result observation are made that at different faults the system behavior changes i.e. it may take more time in recovering fault and reaching to its steady state value. Also it is observed that by using UPFC reduces the oscillations in the system to greater extent which results increases power transfer capability with minimum losses improves the overall efficiency of the system.

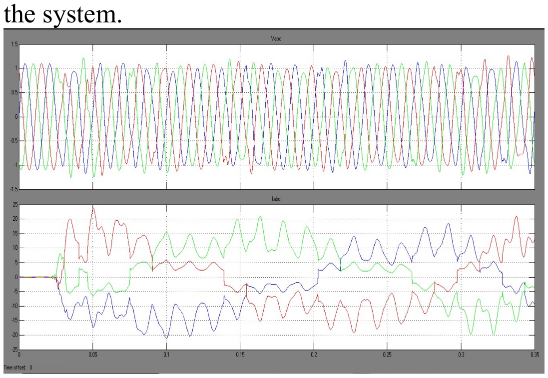

Fig. 9. Line Voltages And Line Currents Without Faults.

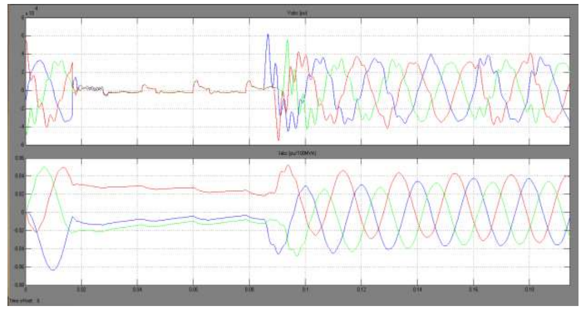

Fig.10. Line Voltages And Line Currents With 3-Phase Fault On Inverter.

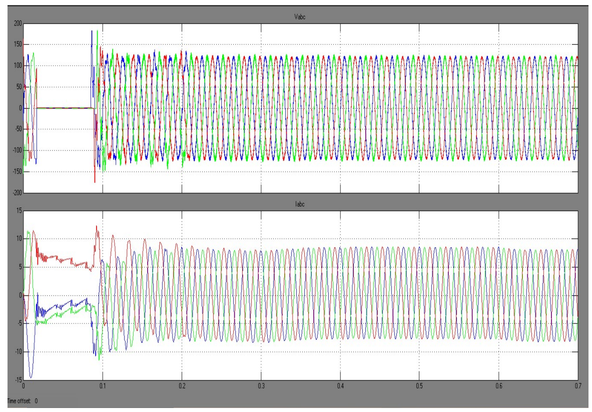

Fig.11. Line Voltages And Line Currents With3-Phase Fault On Inverter Using UPFC With FLC When Three Phase Fault Occurs On Inverter.

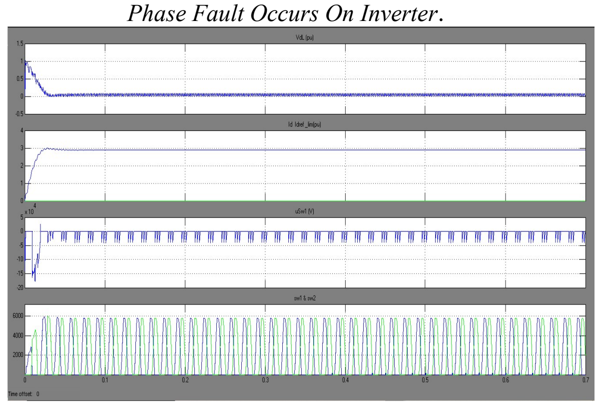

Fig.12. Rectifier Side Performance Under Fault Condition.

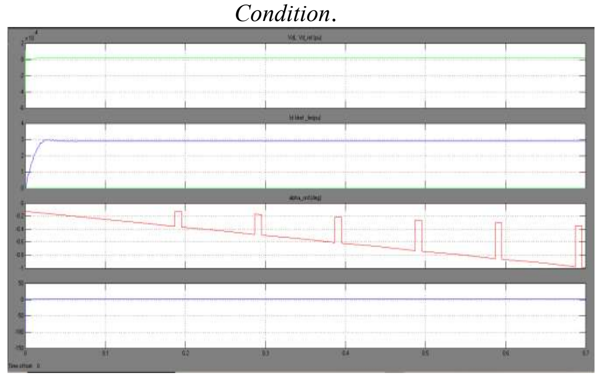

Fig.13. Inverter Side Performance Under Fault Condition.

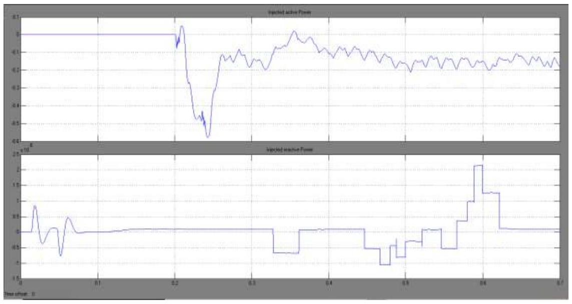

Fig.14. Injected Real And Reactive Powers Of HVDC System.

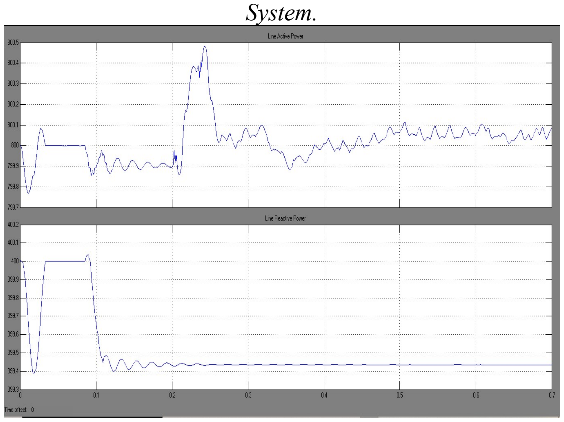

Fig.15. Line Real And Reactive Powers Of HVDC System.

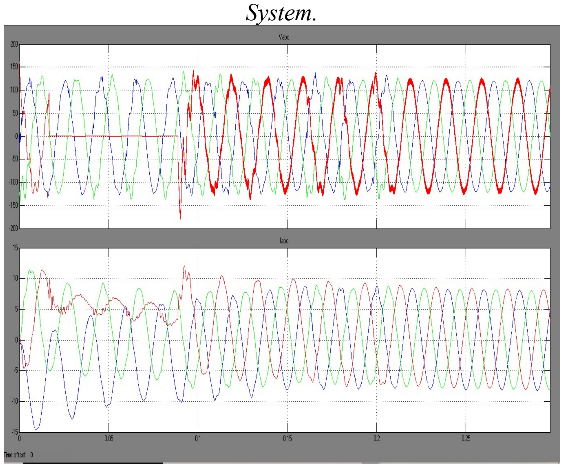

Fig.16. HVDC System With LG Fault On Inverter Side.

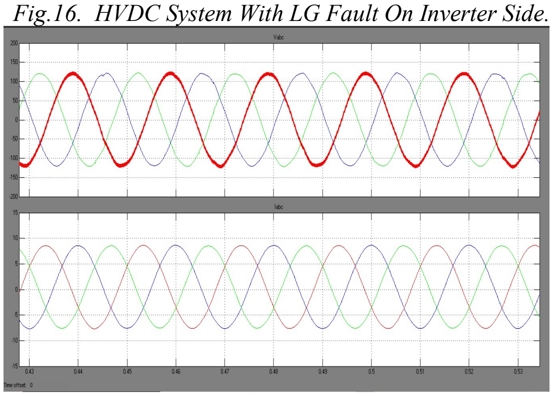

Fig.17. HVDC System With LG Fault And Application Of UPFC Using FLC.

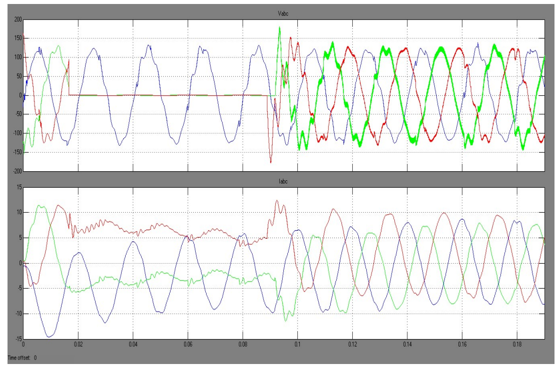

Fig.18. HVDC System With LLG Fault On Inverter Side

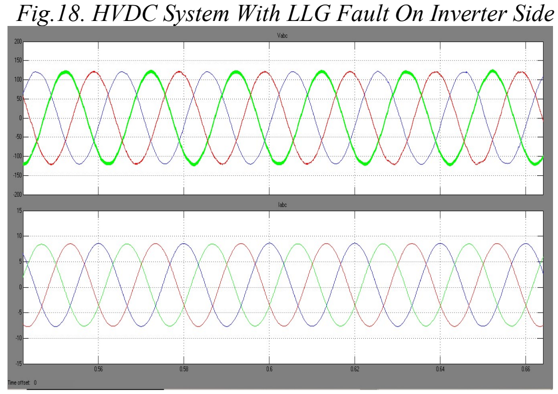

Fig.19. HVDC System With LLG Fault And Application Of UPFC Using FLC.

10. CONCLUSION

From the Matlab Simulation results obtained by simulating HVDC system with UPFC improve HVDC based UPFC system performance under various condition and under normal operation. It concludes that controls the transmission line parameters effectively with reduced losses and increased transmission efficiency under fault conditions. The quantity of fault current and reduction of oscillations achieved by extinction voltage control. The control of current margin results in thyristor valve. AC and DC filters are filters out the harmonics eliminate total harmonic distortion. The performance of current waveforms using PI controller is more dents and crests with continuous oscillations but with proper utilization of fuzzy logic controller for modulation of HVDC system with UPFC for accurate and fast dc current return. Using FLC peak overshoots are compensated unlike conventional controller. Al together the completes seems to be more economical for such HVDC transmission applications with UPFC as improving power transfer which tends to unity power factor with minimum losses. The HVDC system is more flexible for long transmission line and in combination with UPFC case the line congestion and provides controllable power flow. It is more recommended application which line with high variation in the power demand and congested systems with frequency variation. In normal system UPFC is best device in promoting load ability and pool power for interconnected networks. Complete simulation results of voltage, current, active and reactive power waveforms using PI/FLC are compared and detail study is discussed. Thus UPFC is important in deregulation electric system for complete control of active and reactive power economically.

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