Steady State Analysis of Current Source Converter HVDC Transmission Link Connected to a Strong Inverter Side AC system with Rectifier DC Current Control and Inverter DC Current-Voltage Control

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***Abstract*— Transmission of electrical energy with High Voltage Direct Current (HVDC) has provided the electric power industry with a dominant means to transmit huge quantity of electricity over very long distances. To investigate the steady state performance, a well-developed current source converter based twelve pulse HVDC transmission systems is projected, in which the AC system represented as damped LLR equivalent and is equipped with double tuned harmonic filter to mitigate the AC-DC harmonics and the DC system is secured with rectifier current control, inverter current-voltage control. The MATLAB/Simulink based simulation results validate the steady state performance of HVDC transmission system with various controllers.**

***Keywords*— HVDC transmission systems, Double tuned filter, Rectifier DC current control, Inverter DC current-voltage control, Steady state performance.**

I. Introduction

The power transmission through HVDC technology is now mature and experiencing rapid increases in the voltage, power carrying capacity and length of transmission lines. While comparing with three phase HVAC transmission systems, HVDC transmission system is commendable in the following portions: (i) HVDC transmission line cost and operating cost are less, (ii) it need not operate synchronously between two AC systems linked by HVDC and (iii) it is simple to control and adjust the power flow [1].

HVDC transmission system is composed of three major parts: a) rectifier station to convert AC to DC, b) transmission link and c) inverter station to convert back to AC. Most of the HVDC systems have current source converters. Various control techniques are employed for the control and protection of the line and converter against faults [2]. The current source converter based HVDC system naturally absorbs a large amount of reactive power in rectifier stations and inverter stations [3], [4]. By means of filters and/or capacitor banks connected on the primary side of the converter transformer, the reactive power is supplied for HVDC links connected to strong AC systems [5] [6].

Because of the speedy increase in HVDC power transmission schemes, the behaviours of HVDC systems are playing ever greater roles in the performance of entire AC/DC power systems. It is significant to thoroughly understand the mechanisms of the interactions between an HVDC system and an AC network so the HVDC scheme can be operated in a manner that enhances the stability of the entire power grid. The significance of this interaction largely depends on the strength of the AC system at the converter bus [7].

The strength of the AC system is demonstrated by its ability to maintain the voltage at the converter bus during various disturbances in the power system, such as faults etc. Their influence on station design and performance is assessed with reference to the AC-DC system strength, which is generally expressed by the short-circuit ratio (SCR), i.e., the ratio of the AC-system short-circuit capacity to DC-link power: SCR =S/Pdc. Here S is the AC system three-phase symmetrical short-circuit level in megavolt-amperes (MVA) at the converter terminal AC bus with 1.0 p.u AC terminal voltage, and Pdc is the rated DC terminal power in megawatts (MW). The following SCR values can be used to classify AC systems [8]: a) a strong AC system is categorized by SCR >3, b) a weak AC system is categorized by $2 \leqslant SCR < 3$, c) a very weak AC system is categorized by SCR < 2.

A lot of works has been done to know the interaction between AC systems and HVDC link when strong AC system is considered in both the rectifier and the inverter side. Earlier research in [9] investigates the steady state and dynamic performance of the system in MATLAB-Simulink environment by considering few cases of fault conditions. Analysis of dynamic operating characteristics of the HVDC in advanced digital power system simulator (ADPSS) is carried out in [10] but have not been discussed in detail. So, a well-developed detailed model of current source converter based monopolar HVDC transmission system is presented in this paper. The rectifier side is equipped with DC current controller and inverter side is equipped with DC current-voltage controller. The rectifier and inverter controllers are the simplest yet robust fixed gain PI type of controllers. The HVDC transmission system model is developed in the MATLAB/Simulink environment. The steady state operation of the system has been validated by observing AC and DC quantities in rectifier and inverter sides.

II. Modelling of HVDC Transmission system

A current source converter based monopolar HVDC transmission system of 500 kV, 2 kA (1000 MW) shown in the figure 1 is used for the model development.

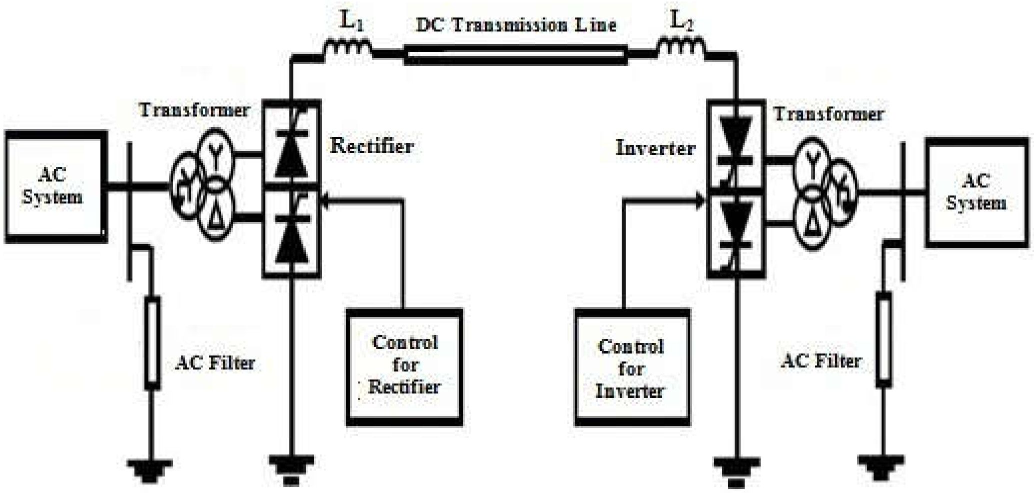

Figure 1: The monopolar HVDC transmission system model

A. The AC Network

The rectifier side AC system of 500 kV, 5000 MVA, 60 Hz network (AC system 1, SCR of 5) to 345 kV and inverter side AC system of 5000 MVA, 50 Hz network (AC system 2, SCR of 5) are represented by damped LLR equivalents [11] with an angle of 80 degrees at fundamental frequency (60 Hz or 50 Hz) and at the third harmonic. This is likely to be more representative in the case of resonance at low frequencies. The passive filters of 300MVAR is connected in the source side to eliminate the 11^{th} and 13^{th} (the double tuned type) [12] order and above 24th (second order high pass filter) order current harmonics and a capacitor (300MVAR) for reactive power compensation.

B. Converter transformer

The 1200 MVA converter transformers (Wye grounded/Wye/Delta) are modelled with three-phase transformer (Three-Winding) blocks. The parameters adopted (based on AC rated conditions) are considered as typical for transformers found in HVDC installation such as leakage: X = 0.24 per unit [13]. The transformer tap changers are not simulated. The tap position is quite at a set position determined by a duplication factor applied to the primary nominal voltage of the converter transformers (0.90 on the rectifier side; 0.96 on the inverter side).

C. Converters

The rectifier and the inverter are 12-pulse converters have been modelled using two universal bridge blocks [14] connected in series. The universal bridge blocks is a compact representation of a DC converter, which includes a built in 6-pulse Graetz converter bridge (can be inverter or rectifier) and series RC snubber circuits are connected in parallel with each switch device.

D. DC network

The DC network model consists of a smoothing reactor for the rectifier and the inverter bridges, a passive filter of double tuned type to mitigate the 12^{th} and 24^{th} order DC voltage harmonics [15] and the DC line. The DC link of 300 km is modelled as distributed parameter line model with lumped losses. In this model, the lossless distributed LC line is characterized by two values namely the surge impedance and the phase velocity.

E. HVDC Control and Protection

The rectifier is equipped with a current controller to maintain the DC system current constant. The DC system current at the rectifier end is measured with the proper transducers and pass through the appropriate filters. After filtering, the measured currents are compared to the reference currents to produce error signals. The error signal from converter side is then passed through the PI controller to produce firing angle order. The firing circuit which is synchronized with the rectifier side AC system through phase locked loop uses the angle order, to produce the necessary equidistant pulses for the valves.

The inverter is provided with a current controller and a voltage controller to maintain the DC system current and voltage constant. The DC system current at the inverter end is measured with the proper transducers and pass through the appropriate filters. After filtering, the measured currents are compared to the reference currents (Also taking the current margin into account) to produce error signals. The error signal from inverter side is then passed through the PI controller to produce firing angle order. Similarly, the DC system voltage at the inverter end is measured with the proper transducers and passes through the appropriate filters. After filtering, the measured voltages are compared to the reference voltages (Also taking the voltage margin into account) to produce error signals. The error signal from inverter side is then passed through the PI controller to produce firing angle order. These two firing angle orders are compared, and the minimum is used to produce the firing pulses for the valves [16]. The firing circuit which is synchronized with the inverter side AC system through phase locked loop uses the angle order, to produce the necessary equidistant pulses for the valves.

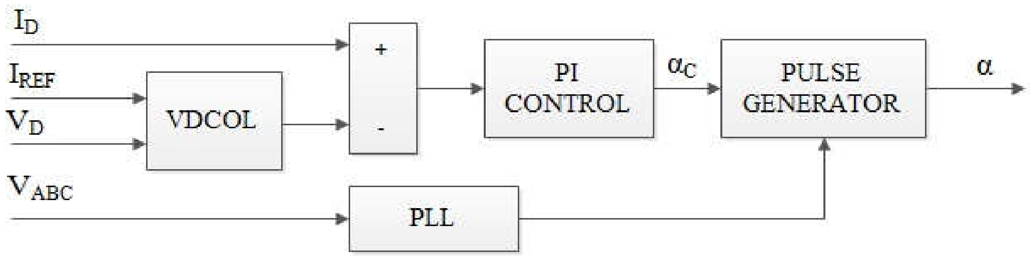

Figure 2: Logic diagram of the rectifier control system model.

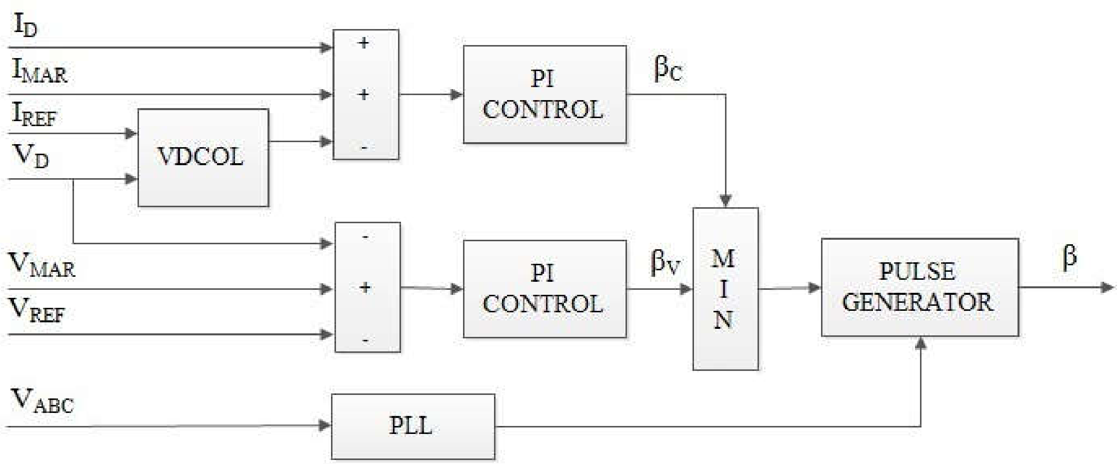

Figure 3: Logic diagram of the inverter control system model.

The reference currents for the constant current controllers are obtained from the master controller outputs through the voltage dependent current order limiter (VDCOL) [17] which can reduce the reference value of direct current (I_{dref}) in case of the large decline in direct voltage, to suppress the over-current and maintain the system voltage. In normal state, there is a small margin (I_{dmarg}) between the direct current references of the two constant-current controllers. Since $I_{dref\text{-}inverter}$ will be smaller than $I_{dref\text{-}rectifier}$, the output of the constant-current controller configured in the inverter side will be regulated to its maximum, and accordingly this controller will not be selected among the two controllers. Then, the inverter's firing angle will be dominated by the constant-voltage controller. To protect the rectifier and the inverter DC protection functions are implemented in each converter. The DC fault protection circuit at the rectifier detects and force the delay angle into the inverter region to quench the fault current. The commutation failure prevention control circuit at the inverter detects various AC fault and reduce the utmost delay angle limit to decrease the risk of commutation failure [18]. The low AC voltage detection circuit at the rectifier and inverter serves to categorize between an AC fault and a DC fault.

III. HVDC MATLAB SIMULATION

The HVDC transmission systems model is implemented in the working platform of MATLAB adapting above mentioned range of features based on the data in [19] with essential modifications.

A. Steady state operation

For steady state analysis, the system has been simulated for duration of 2 sec. in MATLAB-Simulink environment. Figure 2 shows the various AC and DC waveforms during steady state operation. There were some initial transients that subsided within about 0.4 sec and then the system reached steady state.

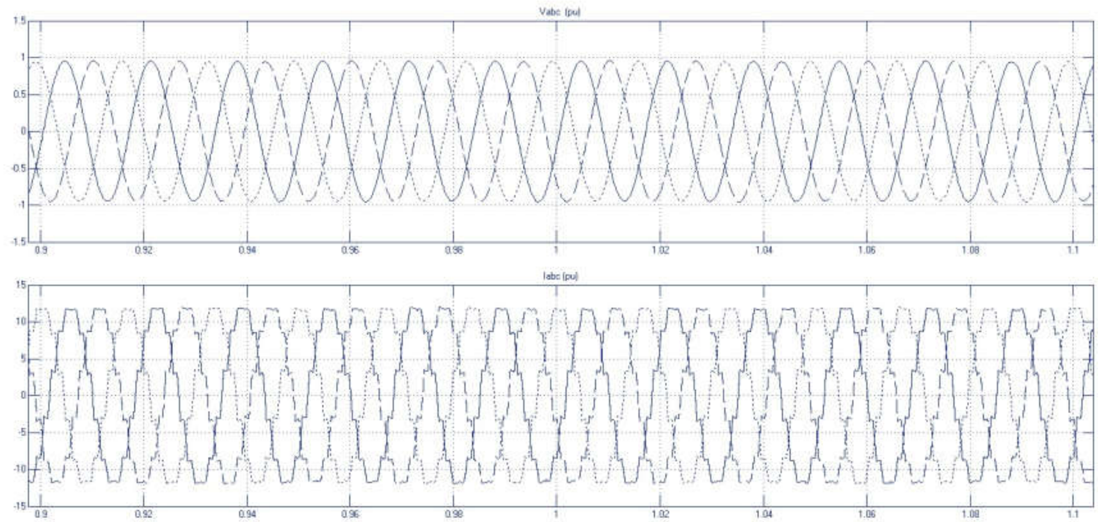

Figure 4: Rectifier side AC quantities

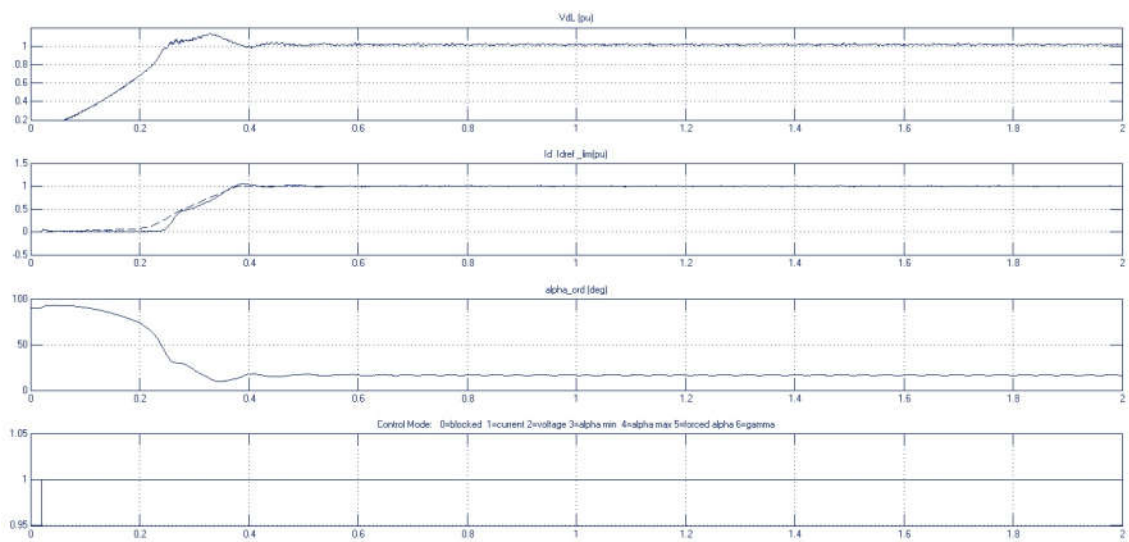

Figure 5: Rectifier DC quantities

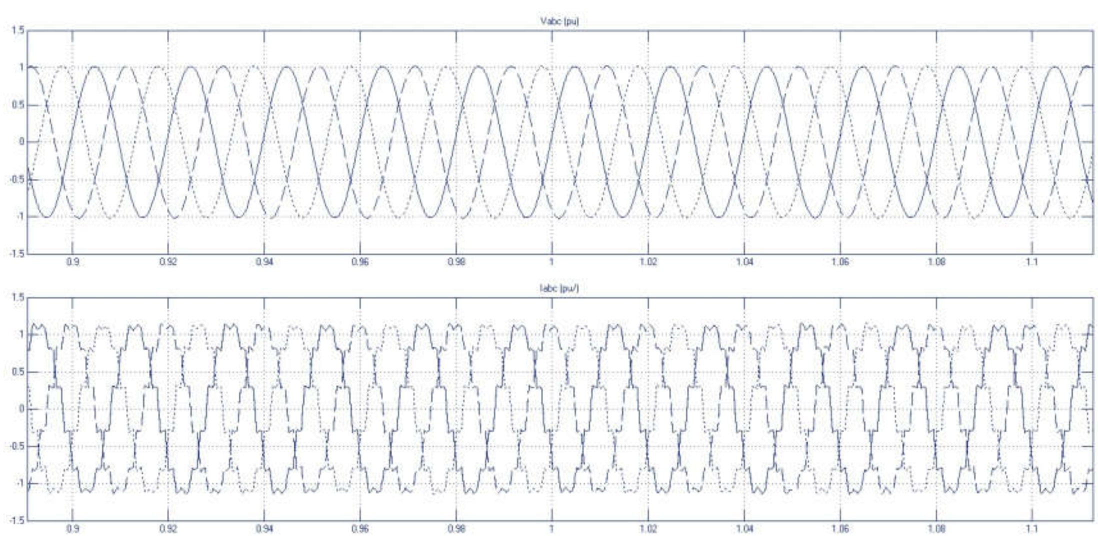

Figure 6: Inverter side AC quantities

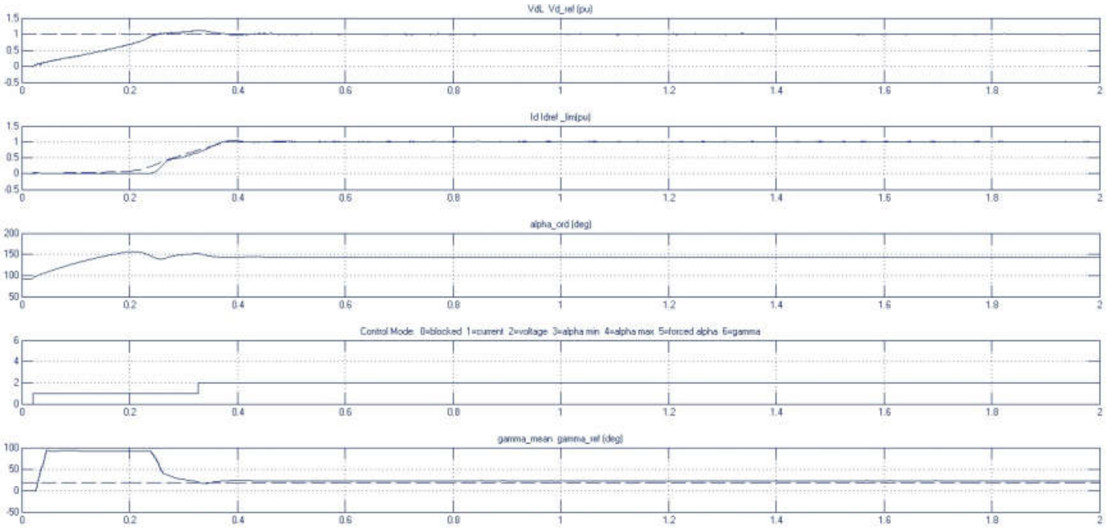

Figure 7: Inverter DC quantities

From the rectifier and inverter side AC waveforms, it is found that voltage and current are equal to 1 p.u. From the DC waveforms on the rectifier and inverter, the DC voltage and current show small oscillations around the reference value (1 p.u.). The mean of output DC voltage and current are 1.0 p.u. At steady state, the measured firing angle is around 9 degrees on the rectifier side and is purely depends on the current controller since the rectifier is controlled by the current controller alone. At steady state, the measured firing angle is approximately 147 degrees on the inverter side. Since the inverter is controlled by two controllers namely current controller and voltage controller. So, the inverter firing angle is decided by the minimum value of firing angle from the two individual controllers. From the inverter firing angle waveform, it is evident that voltage controller has significant role in determining the inverter firing angle.

IV. Conclusions

This paper has evidently established a well-developed detailed model of current source converter based twelve pulse HVDC transmission systems. This involvement can be very useful for designing and safeguarding persons, for analysing the interaction between AC systems and HVDC link under different operating environment. The HVDC transmission system model is implemented in the MATLAB/Simulink environment and steady state operation of the system is investigated by observing the rectifier side AC quantities, rectifier DC quantities, inverter side AC quantities and inverter DC quantities. Simulation results show that detailed model has tolerable accuracy and, validate the steady state performance of HVDC transmission system with rectifier current control, inverter current-voltage control.

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