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Step Response of Rectifier DC Current Controller and Inverter DC Current-Voltage-Extinction Angle Controllers in a Current Source Converter based HVDC Transmission Link Connected to a Weak Inverter Side AC System

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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 a huge quantity of electricity over very long distances. To investigate the performance, a well-developed current source converter based HVDC transmission system model is projected, in which the AC system is represented as damped LLR equivalent and is equipped with a double-tuned harmonic filter to mitigate the AC-DC harmonics, and the DC system is secured with a rectifier current control, inverter current control, inverter voltage control and inverter extinction angle control. The MATLAB/Simulink-based simulation results validate the step response of the HVDC transmission link connected to a weak AC system with various controllers.

Keywords: HVDC transmission systems, Weak AC system, Rectifier DC Current Control, Inverter DC Current-Voltage-Extinction angle Control, Step response.

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, the 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].

The 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 line-commutated converters. Various control techniques are employed to control and protection of the line and converter against faults [2]. The thyristor-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 behaviors 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 $=S/P_{dc}$. 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 ≤ SCR < 3, c) a very weak AC system is categorized by SCR < 2.

In order to know the interaction between weak AC networks and HVDC systems, a lot of work has been done until now. The voltage stability-associated phenomena [9] at HVDC terminals feeding weak AC networks and solutions for eradicating the risks of voltage collapse and for evading control-induced oscillations were discussed. The Nelson River HVDC system is analysed with new synchronous compensators in [10] and also tinted planning requirements and synchronous compensators specification to optimize power delivery by the DC links.

An analysis of the dynamic performance of HVDC systems [11] connected to a weak AC system is carried out for various exciter characteristics of synchronous machines connected to the converter bus. The direct transient stability margin (TSM) prediction method [12] based on the extended equal area criterion is used for the integration of the HVDC transmission system and SVC into the power system. The usage of STATCOM at the inverter end of a classical HVDC system for the reactive power support is deliberated in [13]. The coordination between STATCOM and HVDC classic link feeding a weak AC network is examined in [14] with two different control techniques during various fault conditions.

In this paper, a well-developed detailed model of the current source converter-based monopolar HVDC transmission system is presented. The rectifier side is equipped with DC current controller and the inverter side is equipped with DC current-voltage-extinction angle control. The rectifier and the 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 step response of the various DC side controllers has been validated by observing AC and DC quantities in rectifier and inverter sides.

The rest of the paper is organized as follows. Modelling of the HVDC Transmission System is explained in section II. 3. HVDC MATLAB Simulation results are presented in section III. Concluding remarks are given in section IV.

II. MODELLING OF HVDC TRANSMISSION SYSTEM

A line commutated converter-based monopolar HVDC transmission system of 500 kV; 2 kA (1000 MW) shown in figure 1 is used for the model development.

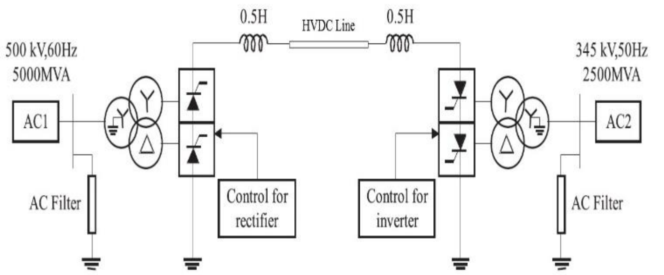

Fig 1. Monopolar HVDC transmission system model feeding a weak AC network

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 2500 MVA, 50 Hz network (AC system 2, SCR of 2.5) are represented by damped

LLR equivalents [15] with an angle of 80 degrees at the 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 are connected in the source side to eliminate the 11^{th} and 13^{th} (the double-tuned type) [16] order and above 24^{th} (second-order high pass filter) order current harmonics and a synchronous condenser (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 [17]. 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 that have been modelled using two Universal Bridge blocks [18] 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 12th and 24th order DC voltage harmonics [19] and the DC line. The DC link of 300 km is modeled 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 passes through the appropriate filters. After filtering, the measured currents are compared to the reference currents to produce error signals. The error signal from the converter side is then passed through the PI controller to produce a firing angle order. The firing circuit which is synchronized with the AC system through a phase-locked loop uses the angle order $_{c}$ to produce the necessary equidistant pulses for the valves.

The inverter is provided with a current controller, a constant voltage controller, and a constant extinction angle controller to maintain the DC system current, voltage, and extinction angle constant. The DC system current at the inverter end is measured with the proper transducers and passes through the appropriate filters. After filtering, the measured currents are compared to the reference currents to produce error signals. The error signal from the converter side is then passed through the PI controller to produce a firing angle order.

In the same way, the DC system voltage at the inverter end is measured with the proper transducers and passes through the appropriate filters. After filtering, the measured voltage is compared to the reference voltage to produce error signals. The error signal from the converter side is then passed through the PI controller to produce a firing angle order.

Similarly, the DC system extinction angle at the inverter end is measured with the proper transducers and passes through the appropriate filters. After filtering, the measured extinction angle is compared to the reference extinction angle to produce error signals. The error signal from the converter side is then passed through the PI controller to produce a firing angle order. These three firing angle orders are compared, and the minimum is used to produce the firing pulses for the valves [20].

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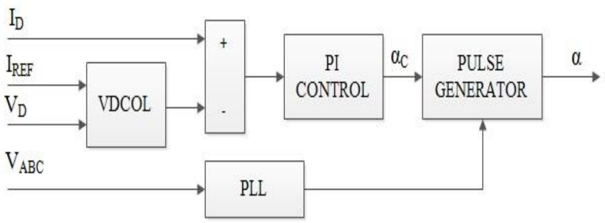

Fig 2. Logic diagram of the rectifier control system model.

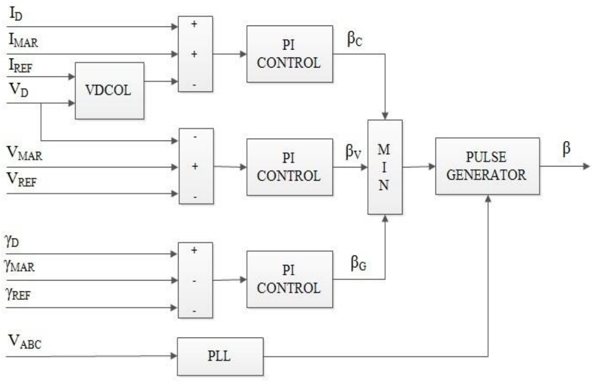

Fig 3. Logic diagram of the inverter control system model.

The reference currents for the CC controllers are obtained from the master controller outputs through the voltage-dependent current order limiter (VDCOL) [21] 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 the 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 forces 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 [22]. 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 [23] with essential modifications. For step response analysis, the system has been simulated for a duration of 2 sec. in MATLAB-Simulink environment.

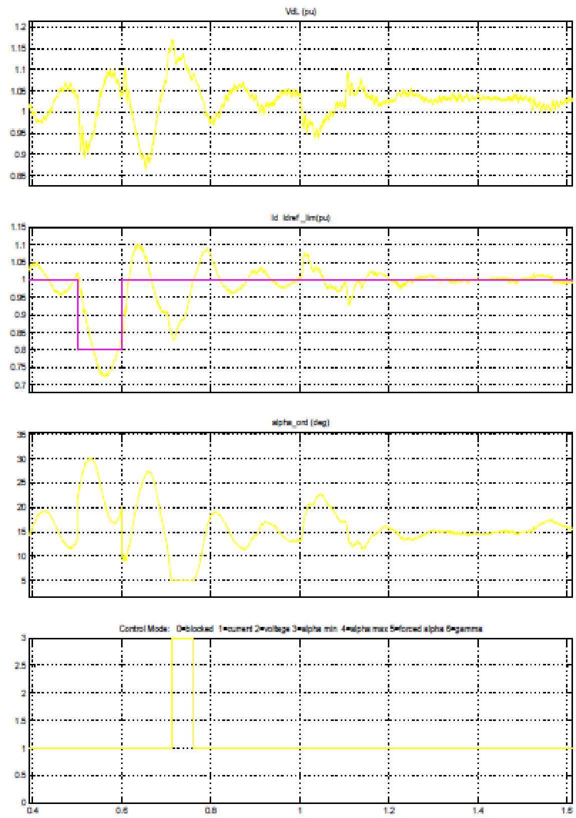

Fig 4. Rectifier DC quantities

A. Step response of current regulators

In order to observe the step response of current regulators at both rectifier and inverter side, at t = 0.5s, a -0.2 p.u. the step is applied for a duration of 0.1s to the reference current. Figures 4 and 5 show the response of the current regulators in the rectifier and inverter side respectively. The step-change is effected in less than 0.5s, and the step response is well controlled and stable.

B. Step response of voltage regulator

In order to observe the dynamic response of the voltage regulator at the inverter side, at t = 0.7s, a +0.2 p.u. the step is applied for a duration of 0.1s to the reference voltage. Figure 4 and 5 also shows the response of the inverter voltage regulator in the rectifier and inverter side respectively. The step-change is effected in less than 0.2s, and the step response is well controlled and stable. At t=1.234 the voltage controller at the inverter side comes into action.

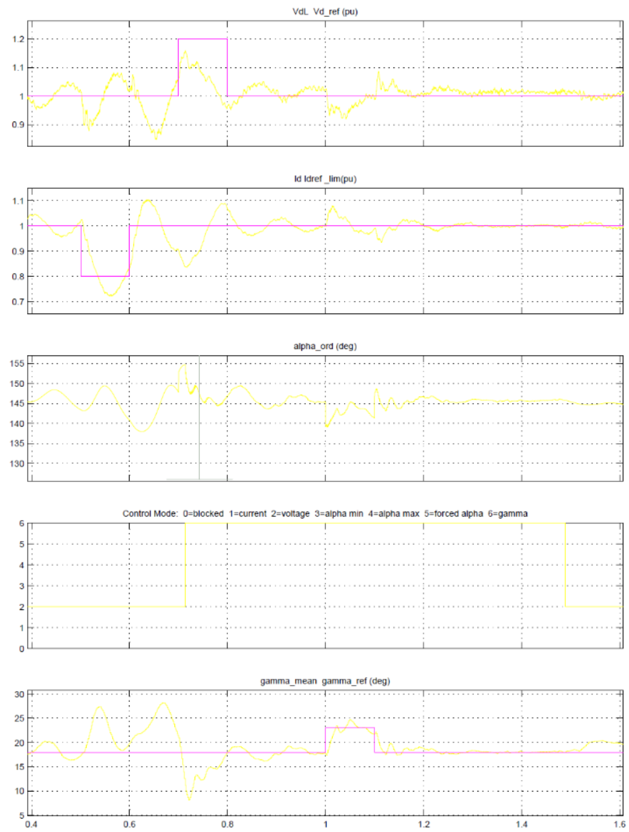

Fig 5. Inverter DC quantities

C. Step Response of Extinction Angle Regulator

In order to observe the dynamic response of extinction angle regulator at inverter side, at t = 1s, the extinction angle is raised from 18 to 23 degree for a duration of 0.1s. The figures 5 also shows the response of the inverter voltage regulator in rectifier and inverter side respectively. The step change is effected in less than 200 ms, and the step response is well controlled and stable. As it clear that the extiction angle regualtor plays a vital role in the control of inverter.

IV.CONCLUSION

The HVDC transmission system model connected to weak AC system is implemented in the Matlab/Simulink environment and the step response of the controllers in controlling the desired current, voltage and extinction angle for typical step change is investigated by observing the rectifier DC quantities and inverter DC quantities. Simulation results show that the step change is well controlled by the corresponding controllers.

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