Power limitations of the HVDC Transmission Power System

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Abstract: - The scope of the presented paper is concentrated on two terminal HVDC transmission system. The intention of the paper is to present a precise insight into the limitations of the transmitted power of a HVDC system incorporated in real AC power system. The paper demonstrates the impacts of the combined AC/DC system model parameters on the transmitted power through the DC link. Also, in this paper an efficient AC/DC load flow method is developed. This method accommodates perfectly the various types of HVDC system control modes. In addition, the switching between these control modes can be done easily in the developed AC/DC load flow method. Moreover, this method is considered a reliable computational tool used to evaluate the limitations of the HVDC transmission system power. Then, the effectiveness of the developed AC/DC load flow method and the influence of the system parameters on the capability of the HVDC transmission system are investigated on a test system composed of two parallel HVDC/AC lines incorporated in AC power system.

Key-Words: - HVDC, modelling, ac/dc load flow, dc power

1 Introduction

HVDC transmission systems are being used extensively in interconnected power systems worldwide. They are used both to transfer power, economically [1, 2], over long distances, and to transfer power between two systems do not run in synchronism. Nowadays, HVDC transmission systems become attractive complement to the AC power systems for power transmission at increasing power levels.

Most HVDC transmission systems that are in service can be modelled as two terminals having one controlled rectifier and one controlled inverter as links to the AC system. Therefore, the scope of the presented paper is concentrated on two terminal HVDC transmission system.

The existing of a DC link in the power system requires an adequate modelling for power flow analysis. The mathematical model [3, 4, 5] of the two terminal HVDC transmission model taking into account the various types of HVDC system control modes is considered in this paper.

The main purpose of the paper is to investigate the precise insight into the limitations of the HVDC transmission system power. The AC/DC system model parameters have major impacts on the power transmitted through the DC link. Therefore, the presented paper shows how the maximum available power which can be transmitted through the DC link has a limited value affected by the system model parameters.

The paper develops an efficient AC/DC load flow method which accommodates perfectly the various types of HVDC system control modes. In this method, the switching between the control modes can be easily done. The developed AC/DC load flow method is considered a reliable computational tool used to evaluate the limitations of the HVDC transmission system power. Then, in order to illustrate the effectiveness of the developed AC/DC load flow method and the influence of the combined AC/DC system model parameters on the HVDC transmission system capability are demonstrated on a test system.

2 HVDC Transmission System Model

Two parallel HVDC/AC lines incorporated in two AC power systems [6] are shown in Fig. 1. The actual values of elements of the combined AC/DC system are given in the figure. Based on the per unit system described in Appendix *A*, the mathematical model for the steady state behaviour of the two terminal DC link can be given as follows:

$$V_{dR} = (3\sqrt{2}/\pi)a_R V_{tR} \cos\alpha - (3/\pi)X_{cR} I_d \quad (1)$$

$$V_{dI} = (3\sqrt{2}/\pi)a_I V_{tI} \cos\gamma - (3/\pi)X_{cI} I_d \quad (2)$$

$$V_{dR} = V_{dI} + R_d I_d \quad (3)$$

$$P_{dR} = V_{dR} I_d \quad (4)$$

$$P_{dI} = V_{dI} I_d \quad (5)$$

$$S_{dR} = (3\sqrt{2}/\pi) k\, a_R V_{tR} I_d \quad (6)$$

$$S_{dI} = (3\sqrt{2}/\pi) k\, a_I V_{tI} I_d \quad (7)$$

$$Q_{dR} = \sqrt{S_{dR}^2 - P_{dR}^2} \quad (8)$$

$$Q_{dI} = \sqrt{S_{dI}^2 - P_{dI}^2} \quad (9)$$

where: subscripts *R* and *I* refer to the rectifier and the inverter, respectively, and k = 0.995 [5].

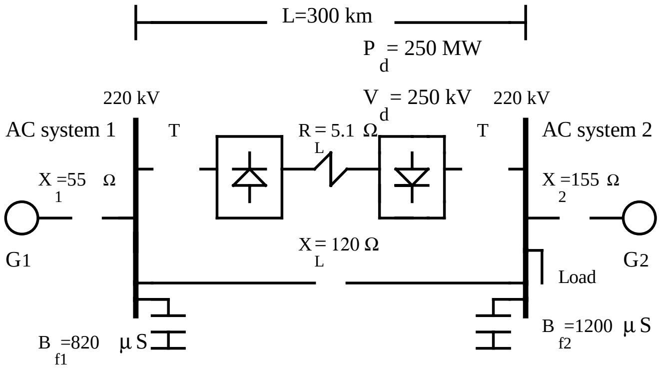

Fig. 1. The combined AC/DC system model.

3 Analytical Solution of HVDC System Equations

The two terminal HVDC system has seven DC variables to be determined. These variables can be given by the following vector:

$$[x_{dc}] = [\alpha,\ \gamma,\ a_R\ ,\ a_I\ ,\ V_{dI}\ ,\ P_{dI}\ ,\ I_d]^T \quad (10)$$

Because there are three independent DC equations, Eqs. 1 through 3, four variables associated with the HVDC system control modes have to be specified in order to define a unique solution for the DC equations.

4 The AC/DC Load Flow Method

Fig. 2 shows the flowchart of the developed AC/DC load flow method. This method is obtained by linking the DC load flow method [5, 6], illustrated in Fig. 3, with Newton-Raphson AC load flow technique.

For the combined AC/DC system model, the operating state can be defined by the following vector:

$$[x] = [V\ ,\delta\ ,x_{dc}\ ]^T \quad (11)$$

where: **V** is vector of the voltage magnitudes at all AC system buses and δ is vector of the voltage angles at all AC system buses except that at the slack bus which is assumed to be equal to zero.

The normal AC power flow equations are valid, except that the mismatch power flow equations at the converter commutation AC buses are modified. Therefore, the mismatch power flow equations may be summarized [6] as follows:

$$\begin{bmatrix} \Delta P(V,\delta) \\ \Delta P_t(V,\delta,x_{dc}) \\ \Delta Q(V,\delta) \\ \Delta Q_t(V,\delta,x_{dc}) \end{bmatrix} = 0 \quad (12)$$

As shown in Fig. 2, the solution for a complete simulation of the combined AC/DC system model can be done sequentially between the existing AC load flow technique and the developed DC load flow method till reaching the appropriate convergence.

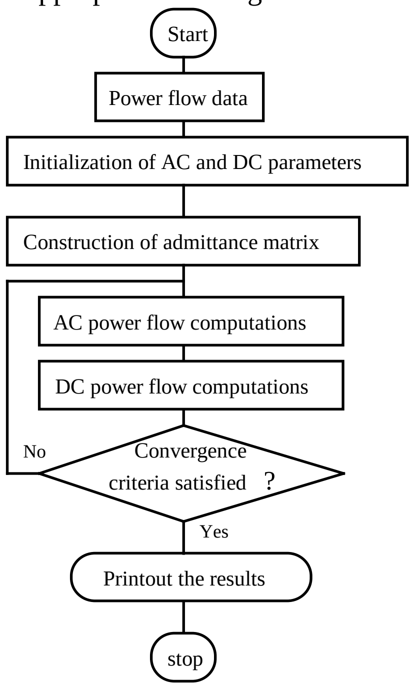

Fig. 2. Flowchart of the AC/DC load flow method

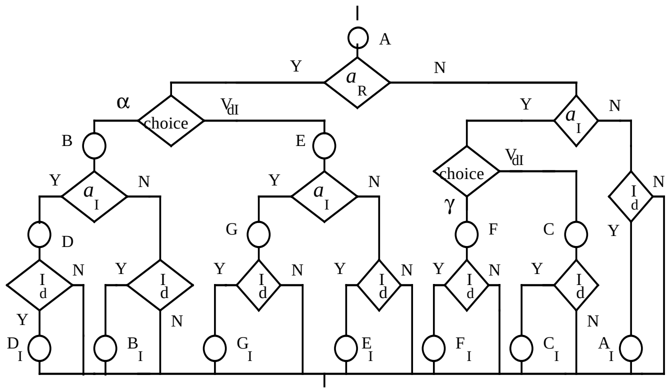

Fig. 3. Flowchart of the DC load flow method

5 Limitations of the HVDC System Power

5.1 Maximum Available DC Transmitted Power

At the inverter terminal, Fig. 4 shows the variation of the DC transmitted power, the AC bus voltage and the direct voltage with respect to the direct current when the short circuit ratio, SCR, of AC system 2 is 2.35. Appendix *B* gives the definition of the short circuit ratio which may be used as an index to measure the strength of the AC system.

Fig. 4 is obtained when the HVDC system is operating under the conditions of the rectifier firing angle α, the inverter extinction angle γ, and the inverter transformer tap ratio a_I, are maintained at $5^o, 16.5^o$, and 0.914, respectively. These conditions together with selecting values for AC filter banks at the rectifier and inverter AC sides equal to 1210 and 2410 μS, respectively are considered in order to obtain an operating point at which the DC link transmits rated DC power at rated values of both direct voltage and commutation AC bus voltage. From Fig. 4, it is noted that the increase in the direct current is accompanied by an increase in the DC transmitted power up to reaching a point at which maximum available DC power P_d^{max} can be transmitted through the DC link under the specified conditions. But, the increase in direct current is accompanied by a decrease in both of direct voltage and AC bus voltage at the inverter terminal. When the direct current increases to values greater than its value that corresponds to the point of maximum available DC transmitted power, the DC transmitted power decreases as shown in Fig. 4. The reason of this is that the AC bus voltage depression i.e., decrease or collapse, will be larger than the increase in the direct current because there is no an existing method for AC voltage control at the inverter commutation AC bus. This leads to a decrease in the DC power transmitted and a more decrease in the direct voltage as shown in Fig. 4.

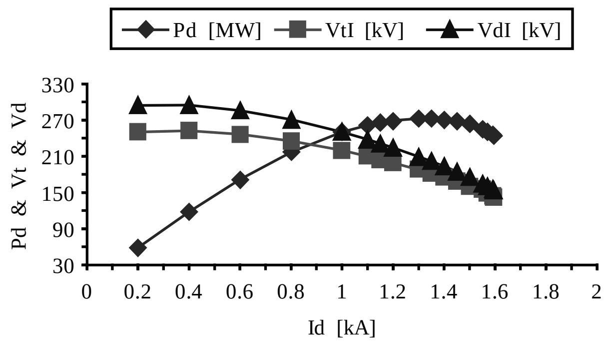

Fig. 4. At the inverter terminal, variation of DC power transmitted, AC bus voltage and direct voltage with respect to the direct current.

5.2. Impact of the AC System Strength on P_d^{max}

Fig. 5 shows the variation of the DC transmitted power with respect to the direct current at different values of SCRs of the AC system 2. From Fig. 5, it is noted that when the AC system becomes weaker, the maximum available DC transmitted power P_d^{max} decreases more. The decrease in SCR from 5.0 to 2.18 results in a decrease in the P_d^{max} from 352.02 to 266.57 MW. This is because when the AC system becomes weak, it can not be able to supply the reactive power required to compensate the reactive power demand by the DC converter without more falling in the commutation AC bus voltage as shown in Fig. 6.

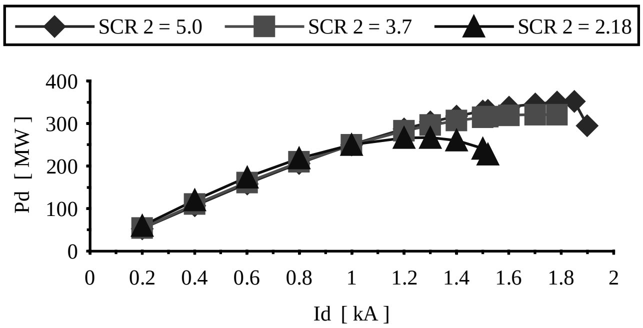

Fig. 5. Influence of AC system strength on the DC power transmitted / direct current characteristics.

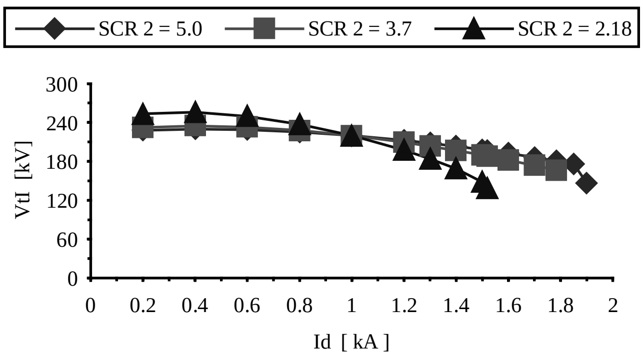

Fig. 6. Influence of the AC system strength on the AC bus voltage / direct current characteristics.

5.3. Impacts of the Control Angles on P_d^{max}

5.3.1. Impact of the Firing Angle α on P_d^{max}

When the HVDC system is operating with extinction angle γ equal to 15.07^o, rated direct voltage of 250 kV and with SCR of the AC system 2 equal to 2.35, Fig. 7 shows variation of the reactive power absorbed by the rectifier with respect to the DC transmitted power at various values of the firing angle, α. From Fig. 7, it is noted that when the rectifier firing angle increases from 5^o to 16^o the maximum available DC transmitted power decreases from 270.0 to 255.42 MW. This is mainly due to the high increase in the rectifier consumed reactive power associated with the increase in the rectifier firing angle as shown in Fig. 7.

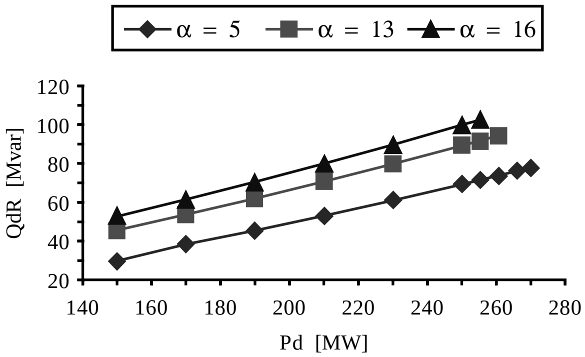

Fig. 7. The reactive power consumed by the rectifier as function of the power transmitted through the DC link at various values of the firing angle, α.

5.3.2. Impact of the Extinction Angle γ on P_d^{max}

When the HVDC system is operating with firing angle α equal to 5.0^{o}, rated direct voltage of 250 kV and with SCR of the AC system 2 equal to 2.35, Fig. 8 shows variation of the reactive power consumed by the inverter with respect to the DC transmitted power at various values of the extinction angle, γ.

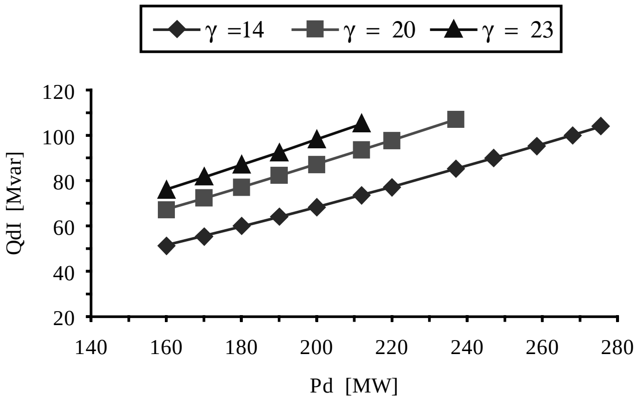

Fig. 8. Variation of the reactive power consumed by the inverter with respect to the DC power transmitted at various values of the extinction angle, γ.

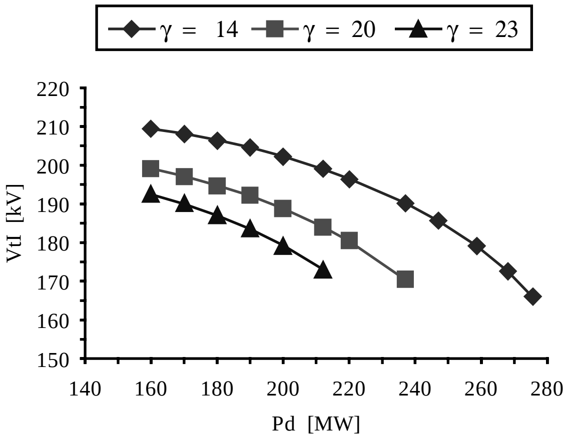

Fig. 9. Influence of the inverter extinction angle, γ varying on the inverter AC terminal voltage as function of the DC power transmitted.

From Fig. 8, it is clear that when the inverter extinction angle increases from 14^{o} to 23^{o}, the maximum available DC power decreases from 275.5 to 212.0 MW. This is basically because with increasing the extinction angle, the reactive power absorption by the inverter also increases as shown in Fig. 8. This leads to more falling in the commutation AC bus voltage, as shown in Fig. 9, which, in turn, results in a limitation to the power transmitted through the DC link.

6. Conclusion

Capability of the HVDC system to transmit DC power through the DC link is affected by the combined AC/DC system model parameters. A precise insight into the limitations of the transmitted power of HVDC system incorporated in real AC power system has been introduced. The impacts of the system parameters such as the strength of the AC power system and the converter control angles on DC power transmitted through the DC link have been investigated in this paper. Also, the influence of these parameters on the commutation AC bus voltage has been included. In addition, an efficient and reliable AC/DC load flow method has been developed. This method has proven the capability for accommodating the different types of the HVDC system control modes. Also, the switching between the control modes has been done perfectly in this method. Furthermore, the developed AC/DC load flow method has been considered a good computational tool for handling the problems of the limitations of the HVDC transmission system power and of the commutation AC bus voltage collapse.

Appendix A

Per unit system for the combined AC/DC system model

The per unit system which can be used to convert the AC power flow and the DC system equations into per unit can be described as follows:

A.1 AC system

For the AC system, the base quantities are assumed as follows:

S_b^{ac} is the three phase power base [MVA]

V_b^{ac} is the line to line voltage base [kV]

Therefore, the AC current base can be calculated from the following equation:

$$I_b^{ac} = \frac{S_b^{ac}}{\sqrt{3}\, V_b^{ac}} \quad [kA] \qquad (13)$$

and the AC impedance base is given by:

$$Z_b^{ac} = \frac{V_b^{ac}}{\sqrt{3}\, I_b^{ac}} \qquad [\Omega] \qquad (14)$$

DC System

For the DC system, the base quantities are assumed as follows:

$$P_b^{dc} = S_b^{ac} \qquad [MW] \qquad (15)$$

$$V_b^{dc} = V_b^{ac} \qquad [kV] \qquad (16)$$

Then, the direct current and the DC impedance bases can be calculated from the following two equations, respectively.

$$I_b^{dc} = \frac{P_b^{dc}}{V_b^{dc}} \qquad [kA] \qquad (17)$$

$$Z_b^{dc} = \frac{V_b^{dc}}{I_b^{dc}} \qquad [\Omega] \qquad (18)$$

For the described per unit system, it can be noted that the direct current and DC impedance bases are related to the AC current and AC impedance bases by the following two equations, respectively.

$$I_b^{dc} = \sqrt{3}\, I_b^{ac} \qquad [kA] \qquad (19)$$

$$Z_b^{dc} = Z_b^{ac} \qquad [\Omega] \qquad (20)$$

Appendix B

B.1 Short Circuit Ratio

An AC/DC system is regarded as weak when the short circuit capacity of the AC system seen from the commutation AC bus is low compared to the power level of the DC system. As a measurement of the strength of the AC system at the converter AC bus, the short circuit ratio SCR, can be used. SCR is defined as the ratio of the AC system three phase short circuit MVA at the commutation AC bus and the DC system rated capacity in MW. Therefore, SCR can be computed as follow:

$$SCR = \frac{S_{ac(pu)}^{sc}}{P_{d(pu)}^{rated}} = \frac{v_{pu}\, i_{(pu)}^{*}}{P_{d(pu)}^{rated}} = = \frac{v_{pu}\left(v_{pu}^{*} / z_{sc(pu)}^{*}\right)}{P_{d(pu)}^{rated}} = \frac{V_{pu}^{2}}{z_{sc(pu)}^{*}\, P_{d(pu)}^{rated}} \qquad (21)$$

where:

$S_{ac(pu)}^{sc}$: is the three phase short circuit capacity of the AC system seen from the converter in per unit of the power base,

$P_{d(pu)}^{rated}$: is the rated DC power in per unit of the power base,

v_{pu}: is the rated commutation AC bus voltage in per unit of the AC voltage base,

$i_{(pu)}$: is the commutation AC bus current in pu.

V_{pu} : is the magnitude of rated commutation AC bus voltage in per unit of the AC voltage base,

$z_{sc(pu)}$: is the short circuit impedance of the AC system seen from the converter in per unit of the AC voltage base and the power base, $z_{sc(pu)} = Z_{sc(pu)} \angle\Theta_z$,

When the rated DC power and the rated commutation AC bus voltage are used as the power base and the AC voltage base, respectively, Eq. (*B*.1) becomes:

$$SCR = \frac{1}{z_{sc(pu)}^{*}} = \frac{1}{Z_{sc(pu)}} \angle\Theta_z \qquad (22)$$

The AC/DC interconnecting point is often considered as weak if the magnitude of SCR is less than 3.0. With weak AC power systems, many problems are encountered due to the higher sensitivity of AC voltage at the converter AC terminal to changes in the DC transmitted power. One of the most interesting problem is the power and AC voltage instability occurred at the converter AC terminals [6].

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