

# **Voltage/Power Stability Study upon Power System with Multiple-Infeed Configuration of HVDC Links Using Quasi-static Modal Analysis Approach**

**Master's thesis**

**By**

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## **Abstract**

Quasi-Static Modal Analysis methodology is extended to a fictional system with multiple-infeed configuration of 5 HVDC links for voltage/power stability analysis study. Weak elements or area in the electrical system can be identified by using Q-V modal analysis with eigenvalues, participation factors and V-Q sensitivities. Maximum Power Curves, indicating stability margin for HVDC links, are used to analyze HVDC links that are integrated in AC system, for power stability analysis purpose.

**Keywords: HVDC, Multiple-infeed, Q-V Modal Analysis, V-Q Sensitivity, Maximum Power Curve, Power stability, Voltage stability**

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## List of acronyms

<b>ABB</b>	Asea Brown Boveri
<b>AC</b>	Alternating Current
<b>DC</b>	Direct Current
<b>HVDC</b>	High Voltage Direct Current
<b>MPC</b>	Maximum Power Curve
<b>SVC</b>	Static Var Compensator
<b>MAP</b>	Maximum Available Power
<b><math>\alpha</math></b>	Firing Angle
<b><math>\gamma</math></b>	Extinction Angle
<b>SCR</b>	Short Circuit Ratio
<b>ESCR</b>	Effective Short Circuit Ratio
<b>CSCR</b>	Critical Short Circuit Ratio
<b>AVR</b>	Automatic Voltage Regulator

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# 1 Introduction

A fictional power system which includes several 500 kV AC lines and 5 HVDC transmission links feeding power into a heavily loaded region from remote generating areas has been studied in this project.

A power system operating under this condition with so much power being injected by HVDC converters into the same region, has a basic problem that needs to be investigated: whether or not this system can maintain voltage stability with reasonable margin.

Voltage stability is a dynamic phenomenon and can be studied using extended transient/midterm stability simulation. However, such simulations do not provide sensitivity information or degree to investigate stability. They are also time consuming required for analysis of the results. Therefore, these dynamic simulations are intended to be used in specific fault situations, where it is known that results may be fast or transient voltage collapse, which would require coordination of controls to solve those specific problems.

Usually, the voltage stability analysis would require examination of an extensive range of system conditions and a large number of contingency scenarios. For such applications, the approach based on steady state analysis is attractive and, when properly used, will provide a good insight into the voltage/reactive power problems. Again, this type of study, based on the traditional static approaches, is also difficult and would require a lot of work and simulations. They also do not provide sensitivity information.

Quasi-static modal analysis approaches, including V-Q sensitivity analysis and Q-V modal analysis are more effective and efficient for AC system analysis. The advantages of these analysis approaches are that they give voltage stability-related information from a system-wide perspective. With the Quasi-static Modal Analysis approach, which has extra advantages that it provides information regarding the mechanism of instability, it is possible to evaluate the security of the transmission grid by quantifying the stability margins and power transfer limits. It is also possible to identify weak points in the system and areas of voltage instability, as well as identification of possible remedial measure actions to be taken to improve the system stability in those identified weak points.

With the Quasi-static Modal Analysis approach the computation of a number of important eigenvalues and the associated eigenvectors of the reduced Jacobian matrix is made. In the reduced Jacobian matrix, Q-V information of generators, loads, reactive power compensation devices and HVDC converters in the network are included. From this it is possible to analyze the voltage and reactive power characteristics of the system.

The eigenvalues of the Reduced Jacobian identify the different modes, and the magnitudes of the eigenvalues provide a relative measure of proximity to instability. The corresponding eigenvectors will provide information related to the mechanism of loss of voltage stability, which are useful in determining system improvements or operating strategies that could be used to prevent the detected proximity of voltage instability.

Hence, these two approaches, V-Q sensitivity analysis and Q-V modal analysis approach, were used in this study to evaluate the system stability margin, in order to identify the weak area of the system, and to explore the interaction between the AC and the DC system.

The Maximum Power Curve method, or MPC, is also a good static approach for the stability analysis of HVDC transmission system, which was introduced by J.D. Ainsworth in the earlier 80's. This method was used to a single infeed topology of HVDC converter, where the power sensitivity to small changes in the DC current from the direct current transmission was studied and power stability limits were verified. This study has extended the use of MPC to a multiple-infeed topology, where different HVDC links are connected to different buses. The investigation stability of each HVDC link was conducted by evaluating their stability margins and the interactions, among all HVDC links, were also investigated under certain system condition in this study.

## 2 Description of Theories

V-Q Sensitivity and Q-V Modal Analysis approaches are described clearly in [1], and related applications for voltage stability analysis can also be found in [2] and [3]. For DC system, MPC (Maximum Power Curve) methodology is explained in [4], and has been used in many applications [5]. Here these approaches are shortly reviewed.

### 2.1 V-Q Sensitivity Analysis

For each given moment and condition, the power system can be considered as a linear system with the relatively fixed operating state, and can be represented by the following linearized form, which is also the equation used in the Newton-Raphson power flow calculation method.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad (2.1)$$

Where,

- $\Delta P$  = incremental change in bus real power
- $\Delta Q$  = incremental change in bus reactive power
- $\Delta \theta$  = incremental change in bus voltage angle
- $\Delta V$  = incremental change in bus voltage magnitude

$J_{P\theta}$ ,  $J_{PV}$ ,  $J_{Q\theta}$ ,  $J_{QV}$  are the partial derivatives of bus incremental active and reactive power with respect to bus voltage angles and magnitudes.

When advanced devices are used in the system, such as HVDC converter and SVC, the corresponding elements of the Jacobian matrix are modified to include the steady state characteristic of these devices. The characteristic may be different based on the different control mode, such as constant DC current operation with constant inverter voltage, or constant extinction angle for HVDC converter.

System voltage stability is affected by both active power (P) and reactive power (Q). When only a small disturbance is considered, an important relationship is between the bus voltage and reactive power. At a given operating point, active power is kept constant, which means  $\Delta P = 0$ .

Thus,

$$\begin{bmatrix} \Delta Q \end{bmatrix} = \begin{bmatrix} J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \end{bmatrix} \begin{bmatrix} \Delta V \end{bmatrix} = \begin{bmatrix} J_R \end{bmatrix} \begin{bmatrix} \Delta V \end{bmatrix} \quad (2.2)$$

Or,

$$\begin{bmatrix} \Delta V \end{bmatrix} = \begin{bmatrix} J_R^{-1} \end{bmatrix} \begin{bmatrix} \Delta Q \end{bmatrix} \quad (2.3)$$

$J_R$  is called the reduced Jacobian matrix of the system;  $J_R^{-1}$  is called reduced V-Q Jacobian matrix.

In the reduced V-Q Jacobian matrix, the  $i^{\text{th}}$  diagonal element is the V-Q sensitivity at bus  $i$ , and indicates the relationship between voltage and imported reactive power on this bus. When it is positive, the increase of the reactive power induces the increase of bus voltage, which means the system is voltage stable. The smaller the  $i^{\text{th}}$  diagonal element, the more stable the system. When it is negative, the increase of the reactive power leads to decrease of bus voltage. Thus, the system is voltage unstable.

## 2.2 Q-V modal analysis

In Equation (2.2), the Reduced Jacobian matrix,  $J_R$ , can also be represented as

$$[J_R] = \xi \Lambda \eta \quad (2.4)$$

Where,

$\xi$  is the right eigenvector matrix of  $J_R$   
 $\eta$  is the left eigenvector matrix of  $J_R$   
 $\Lambda$  is the diagonal eigenvalues matrix of  $J_R$

Then,

$$[J_R^{-1}] = \xi \Lambda^{-1} \eta \quad (2.5)$$

Substituting in Equation (2.3) gives

$$\Delta V = \xi \Lambda^{-1} \eta \Delta Q \quad (2.6)$$

Or,

$$\Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q \quad (2.7)$$

$\xi_i$  is the  $i^{\text{th}}$  column right eigenvector and  $\eta_i$  is the  $i^{\text{th}}$  row left eigenvector of  $J_R$ .

Since  $\xi^{-1} = \eta$ , Equation (2.6) can also be represented as

$$\Delta v = \Lambda^{-1} \Delta q \quad (2.8)$$

Where,

$\Delta v = \eta \Delta V$  is the vector of modal voltage variations

$\Delta q = \eta \Delta Q$  is the vector of modal reactive power variations

$\Lambda^{-1}$  is a diagonal matrix. This means that a coupled representation of a system given as in the equation 2.3 has been transformed to an uncoupled representation given by equation (2.8), representing an uncoupled first order equation. Thus, for the  $i^{\text{th}}$  mode

$$\Delta v_i = \frac{1}{\lambda_i} \Delta q_i \quad (2.9)$$

The eigenvalues and the corresponding eigenvectors of  $J_R$  define different modes of the system. The magnitudes of the eigenvalues determine the degree of stability for different modes. If  $\lambda_i > 0$ , the  $i^{\text{th}}$  mode voltage and the  $i^{\text{th}}$  mode reactive power variation are in the same direction, indicating that the system is voltage stable. The smaller the  $\lambda_i$ , the more critical the mode. If  $\lambda_i < 0$ , they are in opposite directions, indicating that the system is voltage unstable.

From the concept of modal analysis, the following participation factors can also be defined.

### **Bus participation factors**

The participation factors of bus  $k$  in mode  $i$  is given as

$$P_{ki} = \xi_{ki} \eta_{ik} \quad (2.10)$$

The Bus Participation Factor determines the contribution of  $\lambda_i$  to the V-Q sensitivity at bus  $k$ . A high value of  $P_{ki}$  at bus  $k$  for mode  $i$  means this bus is close to voltage instability in this mode. Therefore, Bus Participation Factor can be used to determine the weak areas of the system. Generally, there are two types of modes, localized and non-localized. The localized mode has very few buses with large participants and others with almost zero value, while the non-localized mode has many buses with relatively small participation.

### **Branch participation factors**

The Branch Participation Factor of branch  $j$  in mode  $i$  is defined as

$$P_{ji} = \frac{\Delta Q_j}{\Delta Q_{\max}} \quad (2.11)$$

Where,

$\Delta Q_j$  is the incremental change in reactive power loss of branch  $j$

$\Delta Q_{\max}$  is the maximum incremental change in reactive power loss among all branches

Branch participations indicate, for each mode, which branches consume the most reactive power for a given incremental change in reactive load. This identifies the weak or heavily loaded branches in the system.

### **Generator participation factors**

Similar to the branch participation factors, the relative participation of generator  $m$  in mode  $i$  is given as

$$P_{mi} = \frac{\Delta Q_m}{\Delta Q_{\max}} \quad (2.12)$$

Where,

$\Delta Q_m$  is the incremental change in reactive power generation of generator  $m$



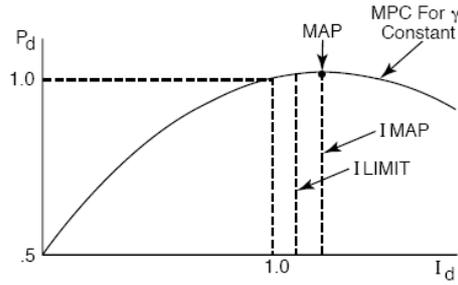


Fig. 2.2. Maximum Power Curve for  $\gamma$  minimum

If the inverter is operating at minimum constant extinction angle  $\gamma$ , the resulting curve will represent maximum obtainable power for the system parameters being considered. This curve is termed the Maximum Power Curve (MPC). Any power can be obtained below MPC by increasing  $\alpha$  and  $\gamma$ , but power higher than MPC can be obtained only if one or more system parameters are changed-e.g. by reduced system impedance, increased system emf, larger capacitor banks, etc.

A similar MPC curve can be obtained for the rectifier at minimum constant  $\alpha$ .

An MPC exhibits a maximum value, termed Maximum Available Power (MAP) as can be seen in Fig. 2.2. The increase of the current beyond MAP reduces the DC voltage to a greater extent than the corresponding DC current increase. This could be counteracted by changing the AC system conditions-e.g. by controlling the AC terminal voltage. It should be noted that  $dP_d/dI_d$  is positive for operation at DC currents smaller than  $I_{MAP}$ , the current corresponding to MAP;  $dP_d/dI_d$  is negative at DC currents larger than  $I_{MAP}$ .

To characterize system, Short Circuit Ratio (SCR), Effective Short Circuit Ratio (ESCR) and Critical Effective Short Circuit Ratio (CSCR) are defined.

SCR is often defined by:

$$SCR = \frac{S}{P_{d1}} \quad (2.13)$$

Where  $S$  is the AC system three-phase symmetrical short-circuit capacity (MVA) at the converter terminal AC bus with 1.0 p.u. AC voltage, and  $P_{d1}$  is the rated DC terminal power (MW).

ESCR is defined as:

$$ESCR = \frac{S - Q_c}{P_{d1}} \quad (2.14)$$

Where  $Q_c$  is the amount of reactive power compensation installed at inverter bus terminal.

CSCR is defined as the corresponding SCR, when the rated values of  $P_d$ ,  $I_d$ ,  $U_d$ , and  $U_L$  (all at 1.0 p.u.) correspond to the maximum point of Maximum Power Curve. It represents a borderline when operating at  $\gamma$  constant, as the ratio  $dP_d/dI_d$  changes its sign.

### 3 MPC Application to Simple Model

In order to understand and get some insights into SCR, ESCR, CSCR, MPC and their relationships, two simple systems have been studied: one is a simplified single HVDC link; the other is a simplified single HVDC link with an AC line in parallel.

#### 3.1 Single HVDC link model (configuration A)

Fig. 3.1 is the simplified diagram of single HVDC link, named configuration A.

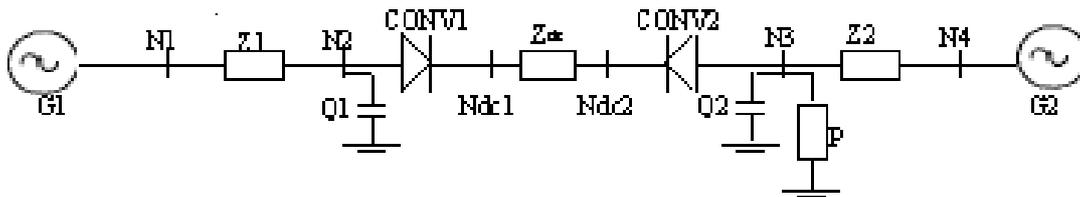


Fig. 3.1. Single HVDC Link (configuration A)

The terms, assumptions and parameters used in Fig. 3.1 are defined in Table 3.1.

TABLE 3.1  
TERMS, ASSUMPTIONS AND PARAMETERS

Terms, Assumptions, Parameters	Description
G1, G2	Thevenin generators with slack bus type
Z1, Z2	Thevenin impedances
$Z_{dc}$	DC line impedance
Q1, Q2	Shunt capacitors including filters
P	Pure resistive load: 3000MW
CONV1, CONV2	Rectifier and inverter with converter transformers
N1, N2, N3, N4	AC nodes (500 kV)
Ndc1, Ndc2	DC nodes
Damping angle	80 degree
$P_d$	Rated DC power: 3000 MW
$U_d$	Rated DC voltage: 500 kV
SCR	Short Circuit Ratio calculated on inverter side
Initial conditions	1). Voltage of N2, N3 is 525 kV 2). Voltage of Ndc1, and Ndc2 are 500 kV and 473.7 kV respectively (considering voltage drop across DC line) 3). CONV1: firing angle $\alpha=15^\circ$ ; DC Current 6 kA; Current control; Tap changer is fixed 4). CONV2: extinction angle $\gamma=17^\circ$ ; DC Current 6 kA; Voltage and angle control; Tap changer is fixed

In configuration A according to Fig. 3.1, four cases were studied; Table 3.2 below summarizes the characteristic of each case.

TABLE 3.2  
PARAMETERS FOR CONFIGURATION A

Case No.	SCR	ESCR	$Z_2$ (Ohm)	$Z_{eq}$ (Ohm) for SCR
No. 1	4	3.4	22.97	22.97
No. 2	3	2.4	30.625	30.625
No. 3	2.5	1.9	36.75	36.75
No. 4	1.6(CSCR)	1	57.42	57.42

Note: All values calculated above are based on equations in Appendix A.

The resulted Maximum Power Curves and corresponding V-I curves are shown below.

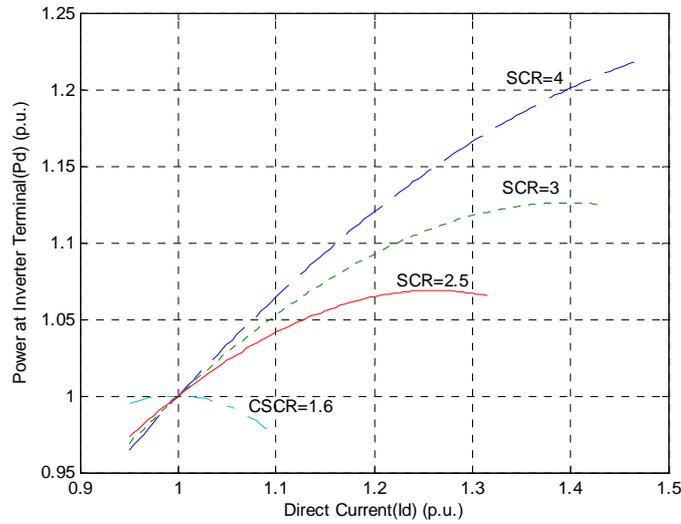


Fig. 3.2. Maximum Power Curves

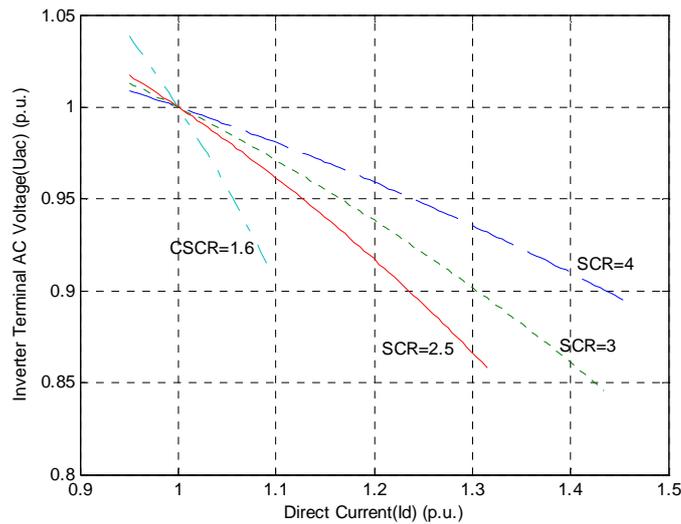


Fig. 3.3. V - I curves

The following conclusions can be obtained after analyzing the results above:

1. Before MAP in MPC, DC power increases as DC current increases;

2. From the V-I curve, it is possible to observe that the voltage decreases with the increase of DC current. This is mainly due to the increase of reactive power consumption of the converter. The lower SCR, the higher the voltage drop;
3. There is a certain power stability margin, as long as the short circuit ratio is larger than 1.6, CSCR;
4. The larger the SCR, the larger the stability margin;
5. The lower SCR, the lower MAP;
6. The HVDC link should always operate before MAP point, for stability reasons.

### 3.2 Single HVDC link with AC line in parallel (configuration B)

In configuration B, shown in Fig. 3.4, a Parallel AC line is connected to the HVDC link.

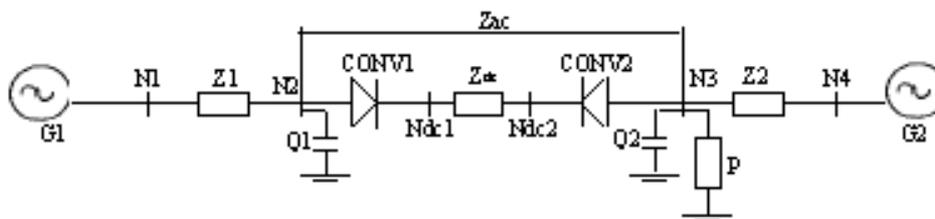


Fig. 3.4. Single HVDC Link with AC Line in Parallel (configuration B)

Four cases were also studied in the configuration B, which were described in Table 3.3.

TABLE 3.3  
PARAMETERS FOR CONFIGURATION B

Case No.	SCR	ESCR	$Z_2$ (Ohm)	$Z_{eq}$ (Ohm) for SCR
No. 1	4	3.36	34.6	22.97
No. 2	3	2.36	55.48	30.625
No. 3	2.5	1.86	79.37	36.75
No. 4	2.18(CSCR)	1.54	109.74	42.14

Note: The values are calculated assuming equations presented in Appendix A.

The resulted MPC and corresponding V-I curves are shown below.

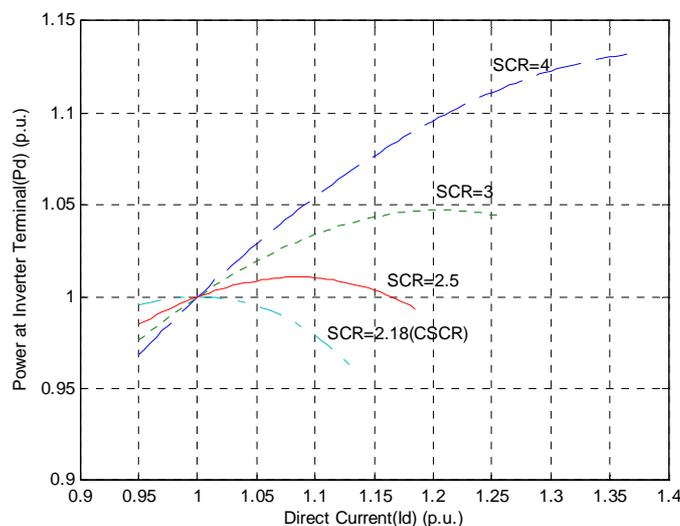


Fig. 3.5. Maximum Power Curves

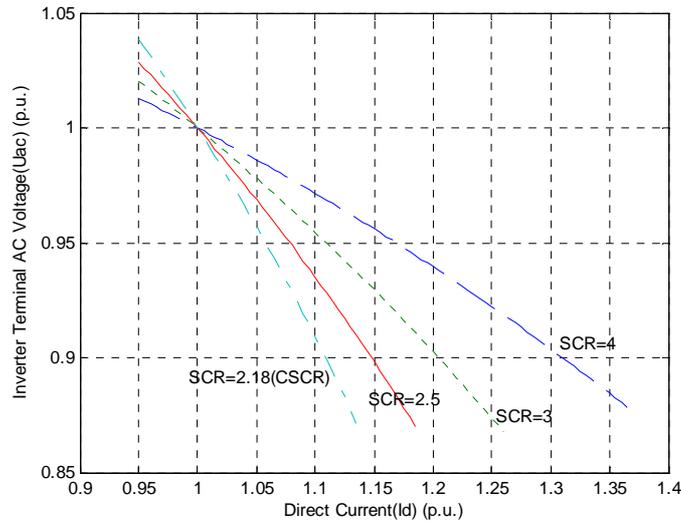


Fig. 3.6. V - I curves

Some conclusions:

1. Before MAP in MPC, DC power increases with increase of DC current;
2. In V-I curve, AC voltage decreases if DC current increases;
3. There is a certain margin, as long as short circuit ratio is larger than 2.18 (CSCR);
4. The larger the SCR, the larger the stability margin;
5. The lower SCR, the lower MAP;
6. HVDC should be operated before MAP point for stability reason of the converter.

### 3.3 Comparison between configuration A and configuration B

The results obtained in configuration B are similar to the results obtained in configuration A. However, the obtained Critical Short Circuit Ratio is 2.18 (compared to 1.6 in configuration A).

The reason is that, in configuration B, the converters at the rectifier and inverter terminals of the HVDC link are now coupled by the parallel AC line. This means that the rectifier converter slightly affects the operating condition of the inverter and lowers the Maximum Power Curve as shown in the following figures.

Case 1: SCR=4, MPC and V-I curve

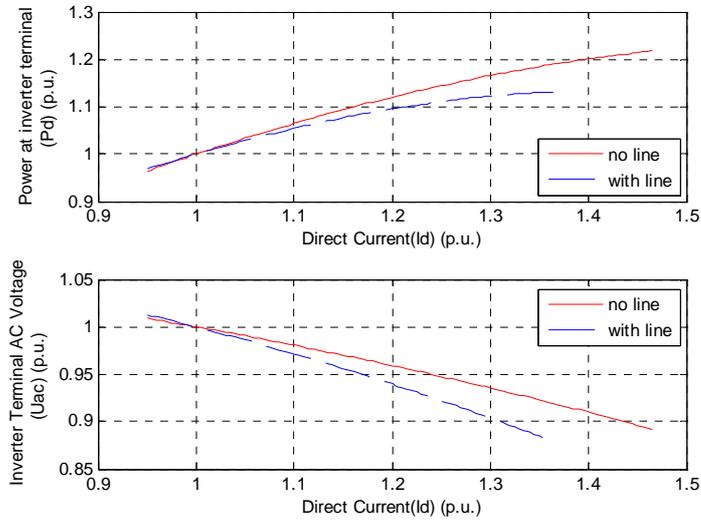


Fig.3.7. Comparison between no line and with line when SCR=4

Case 2: SCR=3, MPC and V-I curve

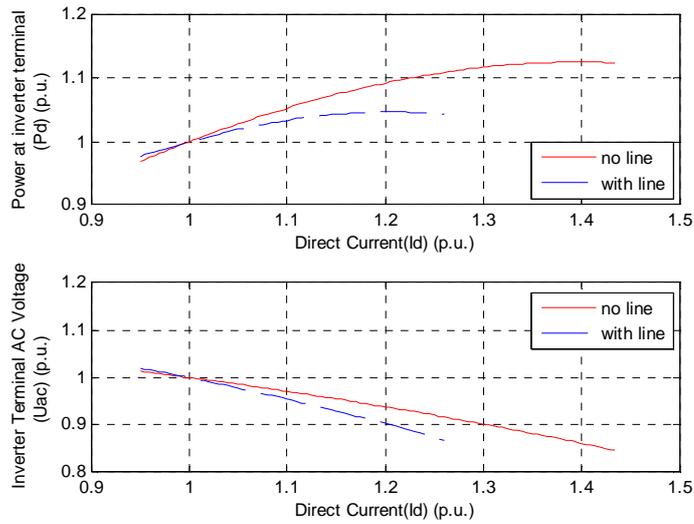


Fig. 3.8. Comparison between no line and with line when SCR=3

Case 3: SCR=2.5, MPC and V-I curve

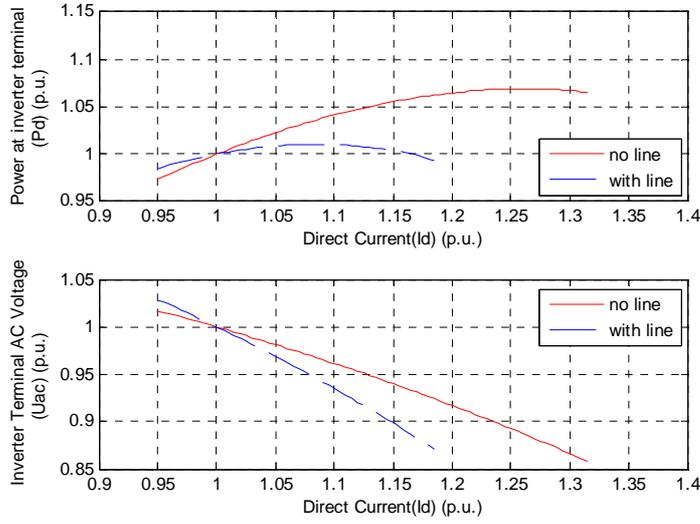


Fig. 3.9. Comparison between no line and with line when SCR=2.5

Case 4: CSCR=1.6 for configuration A and CSCR=2.18 for configuration B

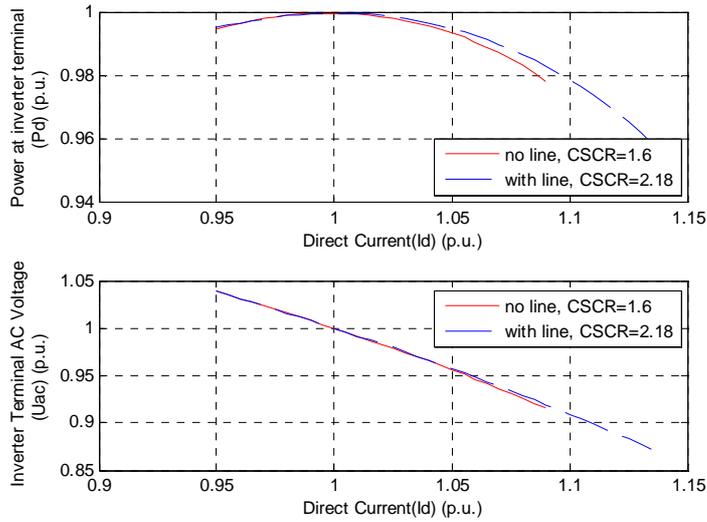


Fig. 3.10. Comparison between no line (CSCR=1.6) and with line (CSCR=2.18)

## 4 Description of the system to be studied

The system studied in this report is presented in Fig. 4.1.

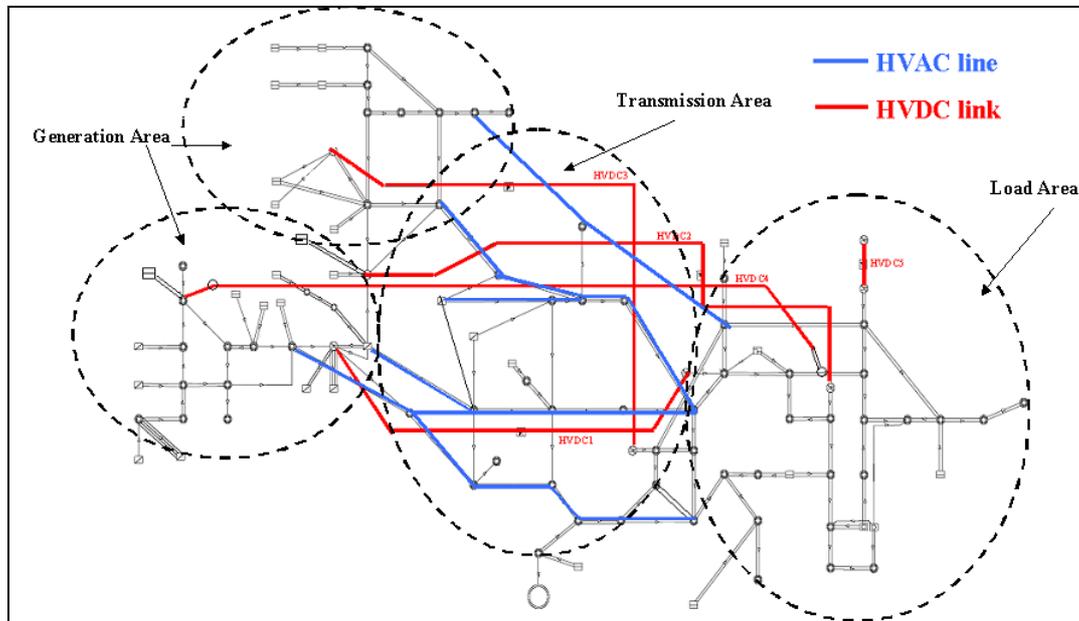


Fig. 4.1. Structure of equivalent system studied

### 4.1 AC Network

An equivalent system was built, which includes two generation areas, one load area, and a transmission area between them. Although there are some big generators in the load area, a large part of the electric power needed in that area is supplied from generation areas through four double circuit AC transmission lines and five HVDC links.

A basic assumption made in the study is that the controls of the HVDC transmission links are much faster than the control of generator units, control of the transformer tap position and reactive power compensation switching devices.

From the above assumption the model of the AC system was made considering that:

- A generator was represented as Thevenin source behind its transient impedance.
- Load was assumed to be in constant active and reactive power mode, which was independent of the bus voltage.
- Transformer had fixed turns ratio.
- Reactive power compensation like shunt capacitor was modeled as constant impedance.

Some statistic data of AC system are provided in Table 4.1 and Table 4.2.

TABLE 4.1  
NUMBER OF SYSTEM ELEMENTS

Bus Shunt	98
Line	265
Load	79
Generator	47
2 Windings Transformer	59
Node	181

TABLE 4.2  
GENERATION AND CONSUMPTION

	P Gen (MW)	P Load (MW)	Q Load (MVar)
Network	45298	49129	22803
Load area	14468	38563	13878
Transmission area	8978	4427	2233
Generation area1	12304	3501	3101
Generation area2	9548	2637	3592

## 4.2 HVDC links

There are five HVDC links feeding more than 15 GW power into load area. HVDC5 connects to a network that is not synchronized with the studied system; the other 4 links transmit power from generation areas to load area, inside the studied system.

The locations of 5 HVDC links are shown in Fig. 4.1. Table 4.3 gives some basic characteristics of each HVDC link.

TABLE 4.3  
FIVE HVDC LINKS

HVDC Link	Rating (MW)	Voltage Level (kV)	Short Circuit Current (kA)	SCR
HVDC1	1800	± 500	44	9,74
HVDC2	3000	± 500	32	9,70
HVDC3	3000	± 500	26	7,88
HVDC4	5000	± 800	41	7,46
HVDC5	3000	± 500	19	5,76

## 5 Maximum Power Curve

The Maximum Power Curve and V-I curve of different HVDC links operating in the studied system were calculated assuming that the DC current in one HVDC link was increased while DC currents in the other four HVDC links were unchanged. It was also assumed that all HVDC links were operating in Constant Current Control mode. It should be pointed out here the system conditions, in terms of Short Circuit Current and Short Circuit Ratio, measured at that converter bus, are according to Table 4.3.

Results from the calculation are presented in Fig. 5.1 and Fig. 5.2. As it can be observed from the curves, some HVDC links are operating very close to the Maximum Available Power (MAP) condition. Especially for HVDC 5, there is almost no stability margin at all. A current increase of just a few percent in this HVDC transmission link results in operating at the MAP point.

This observation does not fit quite well with the results presented in section 3.1. In section 3.1, it shows that the Maximum Power Curve of an HVDC link operating in a strong system, say SCR greater than 4, would have very high stability margin conditions (see Fig. 3.2). In Fig. 5.1, HVDC 5, which has SCR greater than 4 (SCR=5.76 according to Table 4.3), is operating with poor stability margin.

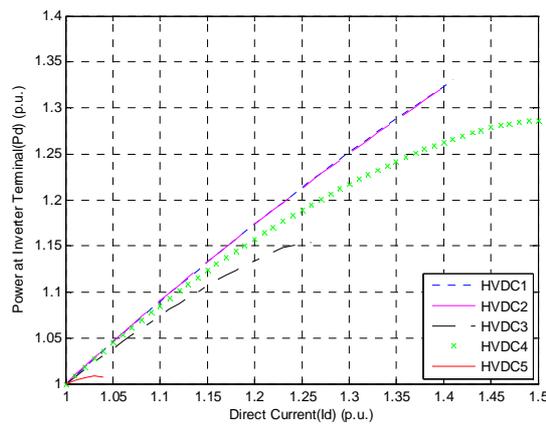


Fig. 5.1. Maximum Power Curves for five HVDC links

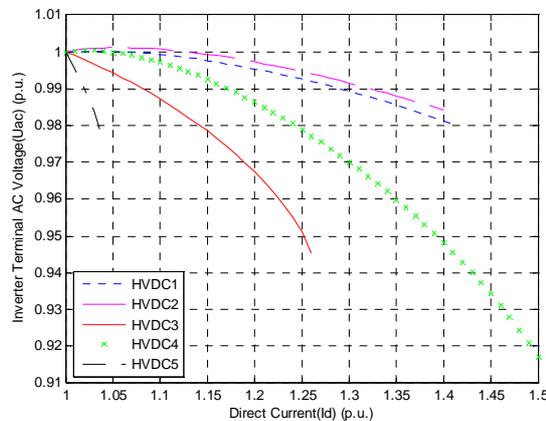


Fig. 5.2. V - I Curves of five HVDC links

## 6 Q-V Modal Analysis and V-Q Sensitivity Analysis

The Q-V modal analysis methodology was used to investigate the interaction between AC system and HVDC links. The eight smallest eigenvalues and corresponding bus, branch and generator participation factors and the self-sensitivity of each bus were calculated at some different operating conditions of the system.

### 6.1 Q-V Modal Analysis

#### Eigenvalues

Table 6.1 ~ 6.5 list the eight smallest eigenvalues at different operating conditions of 5 HVDC links.

TABLE 6.1  
VARIATION OF EIGENVALUES ( $\lambda$ ) WITH CHANGE OF HVDC1 DC CURRENT

Case 1	Idc (HVDC1)				
	1 p.u.	1.1 p.u.	1.2 p.u.	1.3 p.u.	1.4 p.u.
Mode A	4.9	2.2	2.4	2.4	2.4
Mode B	34.1	34.5	34.6	34.7	34.7
Mode C	41.5	41.4	41.4	41.2	41.0
Mode D	47.5	46.9	47.0	46.9	46.7
Mode E	52.9	52.0	52.2	52.2	52.1
Mode F	67.3	67.6	67.8	67.8	67.7
Mode G	81.1	81.1	81.2	81.2	81.1
Mode H	83.5	83.5	83.7	83.7	83.6

TABLE 6.2  
VARIATION OF EIGENVALUES ( $\lambda$ ) WITH CHANGE OF HVDC2 DC CURRENT

Case 2	Idc (HVDC2)				
	1 p.u.	1.1 p.u.	1.2 p.u.	1.3 p.u.	1.375 p.u.
Mode A	4.9	2.8	3.4	3.8	4.0
Mode B	34.1	35.0	35.5	35.9	36.0
Mode C	41.5	41.9	42.2	42.3	42.4
Mode D	47.5	47.5	47.9	48.0	48.0
Mode E	52.9	52.8	53.4	53.7	53.9
Mode F	67.3	68.3	68.9	69.2	69.4
Mode G	81.1	81.9	82.6	83.1	83.2
Mode H	83.5	84.2	84.7	85.0	85.1

TABLE 6.3  
VARIATION OF EIGENVALUES ( $\lambda$ ) WITH CHANGE OF HVDC3 DC CURRENT

Case3	Idc (HVDC3)			
	1 p.u.	1.1 p.u.	1.2 p.u.	1.24 p.u.
Mode A	4.9	1.7	1.1	0.5
Mode B	34.1	34.0	33.5	33.0
Mode C	41.5	41.1	40.6	40.2
Mode D	47.5	46.5	45.9	45.4
Mode E	52.9	51.4	50.6	49.8
Mode F	67.3	66.9	66.0	65.2
Mode G	81.1	80.4	79.4	78.5
Mode H	83.5	82.8	82.0	81.3

TABLE 6.4  
VARIATION OF EIGENVALUES ( $\lambda$ ) WITH CHANGE OF HVDC4 DC CURRENT

Case 4	Idc (HVDC4)					
	1 p.u.	1.1 p.u.	1.2 p.u.	1.3 p.u.	1.4 p.u.	1.48 p.u.
Mode A	4.9	2.5	2.6	2.5	1.9	0.5
Mode B	34.1	34.7	34.8	34.5	34.0	32.7
Mode C	41.5	41.6	41.4	41.0	40.3	39.0
Mode D	47.5	47.1	46.9	46.4	45.5	44.1
Mode E	52.9	52.2	52.1	51.5	50.5	48.5
Mode F	67.3	67.9	68.0	67.6	66.8	65.1
Mode G	81.1	81.3	81.2	80.5	79.3	76.9
Mode H	83.5	83.7	83.6	83.2	82.3	80.7

TABLE 6.5  
VARIATION OF EIGENVALUES ( $\lambda$ ) WITH CHANGE OF HVDC5 DC CURRENT

Case 5	Idc (HVDC5)					
	1 p.u.	1.01 p.u.	1.02 p.u.	1.03 p.u.	1.04 p.u.	1.05 p.u.
Mode A	4.9	1.7	1.5	1.2	0.9	0.2
Mode B	34.1	34.0	33.8	33.5	33.2	32.6
Mode C	41.5	41.3	41.1	40.9	40.7	40.3
Mode D	47.5	46.6	46.4	46.2	45.8	45.3
Mode E	52.9	51.5	51.2	50.8	50.4	49.6
Mode F	67.3	67.1	66.8	66.5	66.1	65.3
Mode G	81.1	80.4	80.1	79.7	79.2	78.3
Mode H	83.5	83.0	82.7	82.4	82.0	81.2

Based on these tables, the following conclusions can be obtained.

- Mode A has the smallest eigenvalues and is much smaller than other modes, which indicates that it is the weakest mode and is critical to the voltage stability of system, while other modes are much safer.
- With the increase of current of HVDC links, the eigenvalue of mode A gave the corresponding variation, while all the eigenvalues of other modes changed a little. This indicates that mode A reflects the influence of HVDC links on the system.

- Variation of DC current on an individual HVDC link led to different variation of eigenvalues in mode A. For example, HVDC5 gives the largest adverse effect to system stability, since the eigenvalue reduced significantly when the DC current increased. However, HVDC2 can improve the system stability when its DC current increases continually.

Since HVDC5 significantly affects the system stability, a more detailed study should be made on HVDC5, meanwhile, mode A is focused on.

### Bus Participations of Mode A

Table 6.6 provides the bus participations of mode A at operating conditions, when HVDC5 DC current was 1 p.u. and 1.05 p.u., respectively.

TABLE 6.6  
BUS PARTICIPATION FACTOR (PF) OF MODE A AT TWO MOMENTS

Idc = 1 p.u., $\lambda = 4.9$			Idc = 1.05 p.u., $\lambda = 0.2$		
Bus No.	PF	Area	Bus No.	PF	Area
1358	0.046	2	1737	0.042	2
1365	0.044	2	1358	0.038	2
1360	0.044	2	1365	0.038	2
1737	0.043	2	1360	0.038	2
1732	0.043	2	1732	0.038	2
1758	0.040	2	1749	0.036	2
1749	0.039	2	1728	0.036	2
1740	0.038	2	1758	0.035	2
1734	0.038	2	2050	0.035	3
1728	0.036	2	1740	0.035	2
2050	0.033	3	1734	0.034	2
1766	0.032	2	1104	0.032	3
1104	0.031	3	1766	0.031	2
1733	0.028	2	1733	0.031	2
1364	0.028	2	1787	0.027	2
1743	0.026	2	1778	0.025	3
1090	0.023	3	1743	0.025	2
1760	0.022	2	1796	0.025	2
1745	0.020	2	1784	0.024	2
1105	0.019	3	1090	0.023	2
1796	0.019	2	1364	0.023	2
1778	0.019	2	1760	0.021	2

It is clear that the mode A is a typical non-localized mode because it contains a large number of buses with almost same but very small participations. Generally, this kind of non-localized mode with very low eigenvalues indicates that this area has been heavily loaded and the reactive power support inside the area has been almost exhausted. This is a “interface area”, where the four main transmission corridors and some HVDC links terminate, see Fig. 6.1. With the increase of HVDC5

DC current, Bus 1737 has the highest participation in the list, while the participation of other buses did not change too much.

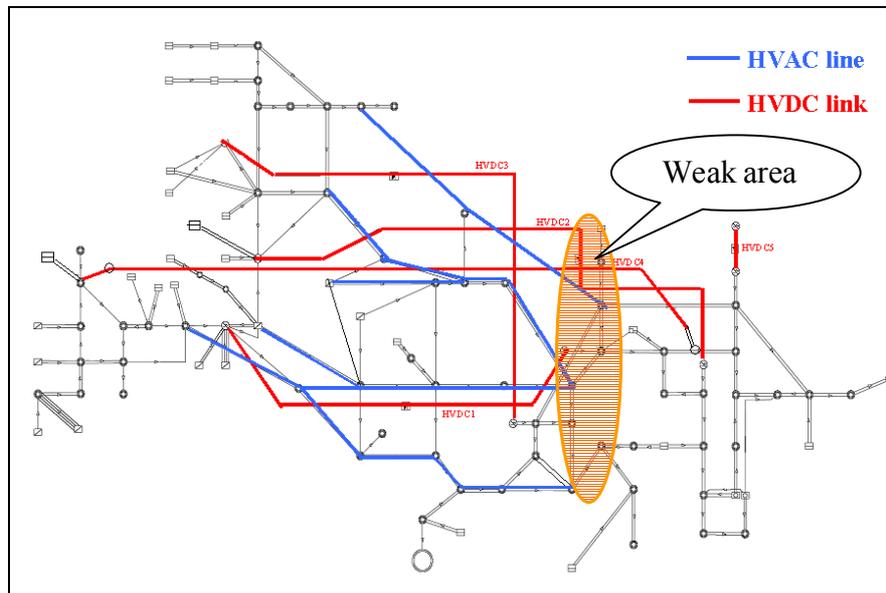


Fig. 6.1. Location of interface area

### Branch Participation Factors

Table 6.7 lists some branches with high participation factors of mode A at the two operating conditions. Two types of branches should be noticed in the table. One is the equivalent branch representing generator transient impedances during the transient procedure, such as L-1274, whose participations actually indicate the quantity of reactive power absorbed by corresponding generators. Hence, this will be investigated when studying the Generator Participation Factors. Another type is the parallel transmission line having the same value of participations marked with an asterisk. Since the branch participations give the information how much reactive power is consumed by these branches, the sum of participations of these parallel lines reflects the real reactive power quantity absorbed by them from the system. Therefore, the participations of parallel lines provided in the table are their summations.

TABLE 6.7  
BRANCH PARTICIPATION FACTOR (PF) OF MODE A AT TWO MOMENTS

Idc (HVDC5)	Branch Name	PF
1 p.u.	*L-1090 -2050	1.128
	L-1274 -11274	1.000
	*L-1094 -1097	0.866
	*L-1104 -1105	0.852
	*L-1097 -1267	0.801
	*L-1104 -1267	0.638
	L-1062 -11062	0.600
	L-1279 -11279	0.505
	L-1280 -11280	0.483
1.05 p.u.	L-1279 -11279	0.414
	*L-1090 -2050	1.015

	L-1274 -11274	1.000
	*L-1094 -1097	0.850
	*L-1104 -1105	0.807
	*L-1097 -1267	0.750
	*L-1104 -1267	0.654
	L-1062 -11062	0.537
	L-1280 -11280	0.398
	1274 -1650	0.382

Most of the long transmission lines, belonging to four main transmission corridors and transferring a large quantity of power from the western generation area to the eastern load area, have high participations. Therefore, they are critical for mode A. The system may lose voltage stability if some of these branches are tripped.

When power imported into load area by HVDC5 was increased, the ranking of branch participations did not change, which indicates that these branches were always critical for mode A.

### Generator Participation Factors

Some generators with high participations in mode A were provided in Table 6.8 when the current of HVDC5 was 1 p.u. and 1.05 p.u.. All the generators with high participations in the table are significant for maintaining the system stable operation since they supply much more reactive power when the load increases in the given mode. If these generators are lost, the system will lose stability. Most of these generators are located in load area or are connected to main transmission lines feeding this area. It should be noticed that the generator 111974 is an equivalent generator representing lots of generators in a small area. When HVDC5 current was increased to 1.05 p.u., generator 11947 had the highest participation, which indicates that it contributed the significant reactive power to maintain the system stability during transient process.

However, some equivalent branches of generator transient impedances also have high branch participations in mode A, which shows the great effect of generator transient impedance on the system by absorbing lots of reactive power during the transient process. Especially for some big generators in the load area, such as generator 11274, 11280, 11283 and 11279, their transient impedances consumed a lot of reactive power, which reduced the reactive power support in this area.

TABLE 6.8  
GENERATION PARTICIPATION FACTOR (PF) of MODE A AT TWO MOMENTS

Idc = 1 p.u. (HVDC5)			Idc = 1.05 p.u. (HVDC5)		
Generator	PF	Area	Generator	PF	Area
111974_G99	1.000	4	11947	1.000	4
11062_G1	0.901	3	111974_G99	0.770	4
11280_G1	0.856	2	11062_G1	0.725	3
11274_G1	0.851	2	11274_G1	0.664	2
11781_G99	0.734	2	11280_G1	0.630	2
11279_G1	0.717	2	11781_G99	0.571	2
11773_G99	0.666	2	11808_G99	0.508	2
11808_G99	0.654	2	11279_G1	0.488	2

12283	0.650	1	11760_G99	0.486	2
11760_G99	0.644	2	12283	0.456	1

## 6.2 V-Q Self-Sensitivities

V-Q Self-Sensitivities were also calculated for all the buses at the operating conditions (1 p.u. and 1.05 p.u. of HVDC5 DC current). Table 6.9 lists some buses with the highest sensitivities. It is clear that buses with high participations in mode A also have high sensitivities.

TABLE 6.9  
U-Q SELF-SINSITIVITY

Idc = 1 p.u., $\lambda = 4.9$		Idc = 1.05 p.u., $\lambda = 0.2$	
Bus Name	Sensitivity	Bus Name	Sensitivity
1963	0.022	1737	0.179
1758	0.018	1358	0.162
1737	0.018	1365	0.159
1358	0.017	1360	0.156
1365	0.016	1732	0.155
1749	0.015	1749	0.154
1283	0.015	1728	0.152
2050	0.014	1758	0.150
1360	0.014	2050	0.148
1728	0.014	1740	0.145
1740	0.014	1734	0.142
1104	0.013	1104	0.136
1732	0.013	1766	0.130
1364	0.013	1733	0.124
1743	0.012	1787	0.111
1090	0.012	1743	0.108

In order to show the change of bus sensitivities with the increase of HVDC5 DC current, sensitivities of 4 buses were calculated at five operating conditions of HVDC5 in terms of DC current, see Fig. 6.2. With the increase of HVDC5 DC current they became more and more sensitive. When current was close to its maximum value, the sensitivities of these buses increased rapidly and up to about 0.18, which means 5.6 MVAR incremental of reactive power results in 1 kV variation of bus voltage. At this point, the system almost reached its stability limit. If HVDC5 current kept increasing, the system would lose its voltage stability and get close to voltage collapse (the collapse is initiated in the region close to bus 1737).

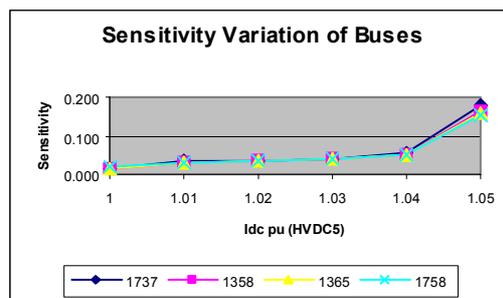


Fig. 6.2. Sensitivity Variation

## 7 System Performance After Taking Remedial Action

The previous section indicates that the “interface” area is the main factor that adversely affects operation and stability of HVDC5 as well as some other HVDC Links. Based on the system structure, a remedial action was taken by adding a certain reactive power support devices on bus 1733, because this bus is both inside the weak area and close to HVDC5. This device supports bus voltage in this area by supplying extra reactive power during transient process.

Two key points should be noticed about this reactive power support device. One is that it should have a fast response to the change of system situation caused by fast DC current variation of HVDC link; therefore, SVC or STACOM should be used. A fast switching shunt capacitor bank can also be used. The other is that this kind of remedial action, only adding one device on one bus to support the bus voltage in a big area, is impossible in practice, since the reactive power exhaustion involves a big area and huge quantity of reactive power will be needed.

### Eigenvalues

The magnitude of eigenvalue of mode A increased significantly after taking the remedial action to support the voltage in the “interface” area, which means stability related to mode A is enhanced. See Table 7.1. However, this extra reactive power support did not affect other modes because the eigenvalues of other modes almost kept constant.

TABLE 7.1  
IMPROVEMENT COMPARISON OF MODE A

	Idc = 1 p.u.		Idc = 1.05 p.u.	
	Case 1	Case 2	Case 1	Case 2
Mode A	4.9	20.7	0.2	20.7
Mode B	34.1	36.2	32.6	36.1
Mode C	41.5	41.5	40.3	41.5
Mode D	47.5	46.8	45.3	46.8
Mode E	52.9	51.8	49.6	51.7
Mode F	67.3	68.0	65.3	67.9
Mode G	81.1	81.5	78.3	81.4
Mode H	83.5	87.0	81.2	86.9

Case 1: before taking remedial action;  
Case 2: after taking remedial action.

### Maximum Power Curve

By comparing the curves with and without SVC connected to bus 1733, it can be concluded that there is a great improvement of MPCs, especially for the HVDC5 link.

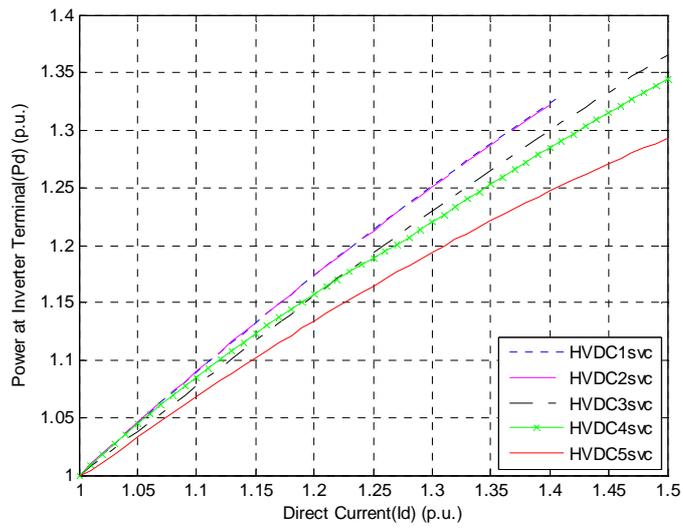


Fig. 7.1. MPC with SVC

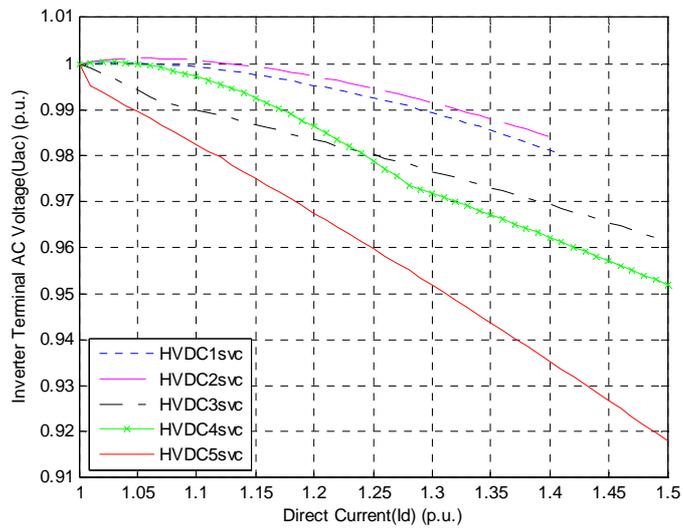


Fig. 7.2. V-I curve with SVC

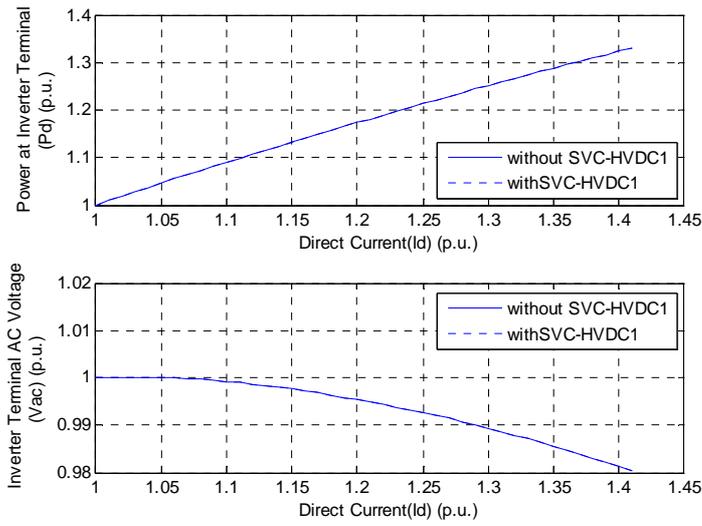


Fig. 7.3. Comparison between system without SVC and system with SVC for HVDC1

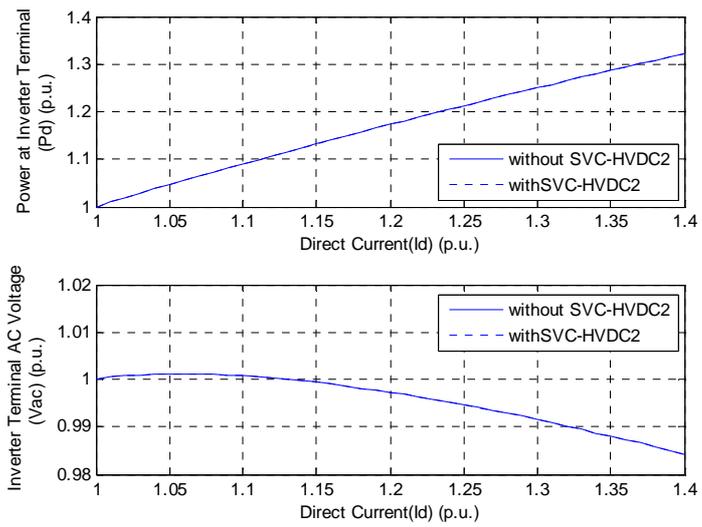


Fig. 7.4. Comparison between system without SVC and system with SVC for HVDC2

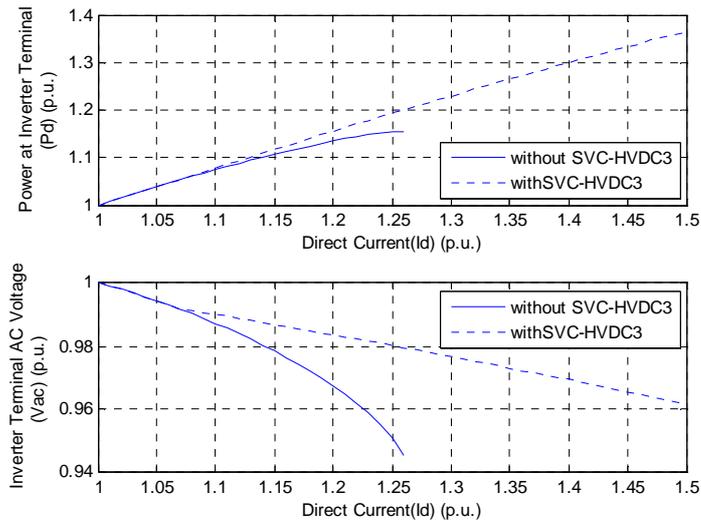


Fig. 7.5. Comparison between system without SVC and system with SVC for HVDC3

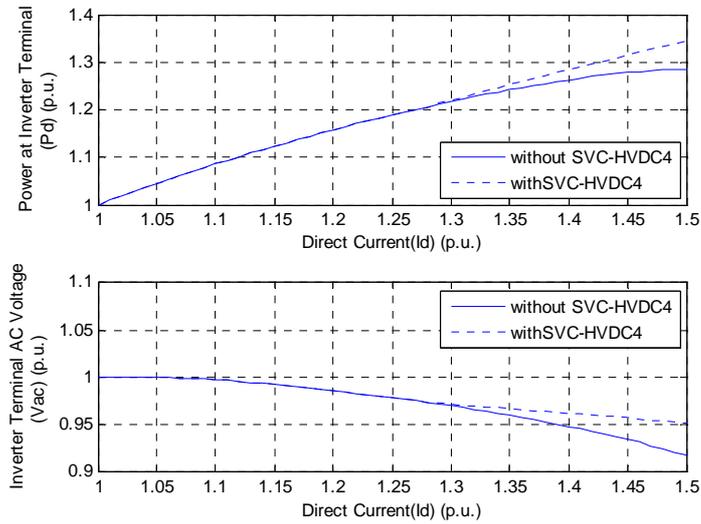


Fig. 7.6. Comparison between system without SVC and system with SVC for HVDC4

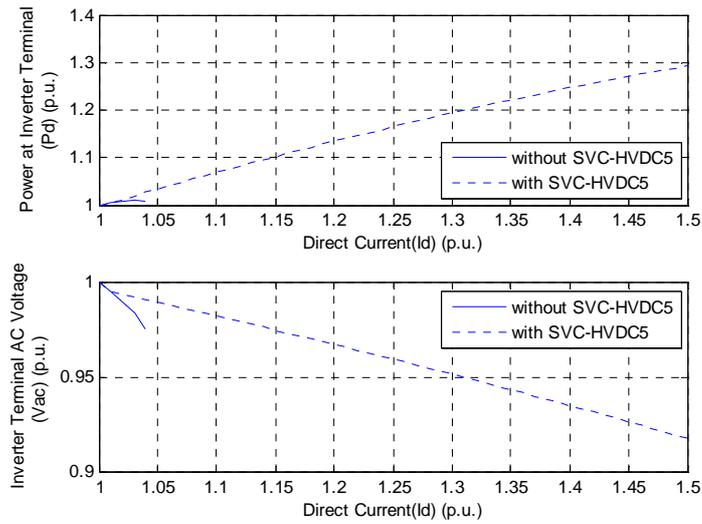


Fig. 7.7. Comparison between system without SVC and system with SVC for HVDC5

According to the simulation, the amount of SVC, which was needed to maintain the voltage on bus 1733, was recorded and drawn as curve versus DC current for every HVDC link. These curves clearly show that high reactive power requirement needs met for normal operation of HVDC5 link.

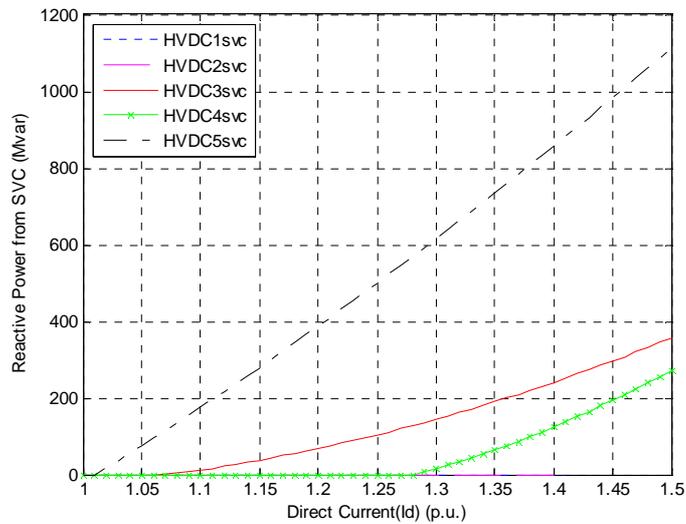


Fig. 7.8. Comparison of Reactive power needed

## 8 P-V Curves

P-V curves relate bus voltage to load within the region, which give an approximate indication to voltage collapse due to excess of load level in a given area. P-V curves of five AC buses of HVDC inverters in load area were drawn when all the converters of HVDC were replaced by the equivalent loads that were independent on the bus voltage, and scaling loads in load area and all the generators in the whole system, see Fig. 8.1. From the figure it is possible to observe that the operation point of the AC system is close to the “nose” part of the curves, which indicates that the AC system is already heavily loaded and its operation point is much close to the system stability limit.

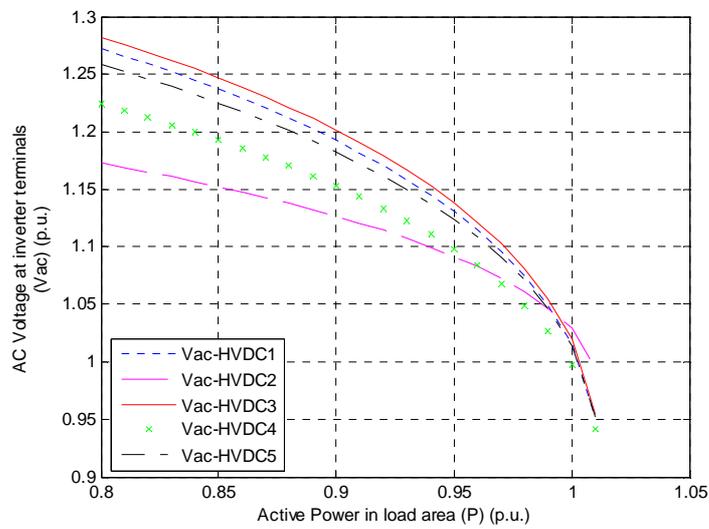


Fig. 8.1. P-V curves of AC buses of 5 HVDC inverters

## 9 Interaction Among 5 HVDC Links through AC System

As analyzed above, the change of eigenvalues of mode A with the increase of DC current of HVDC links shows two different influences of HVDC links on the AC system, because of the existence of the weak area in the system. To show the interaction among 5 HVDC links through AC system, the active power transferred through all the 5 HVDC links was recorded simultaneously when the current of only one HVDC link was increased to its own maximum value, see Fig. 9.1, Fig. 9.2, Fig. 9.3, Fig. 9.4 and Fig. 9.5.

It should be noticed that all HVDC transmission links are operating in constant current control mode, which means that the delivered power is affected by operating voltage at the inverter terminal.

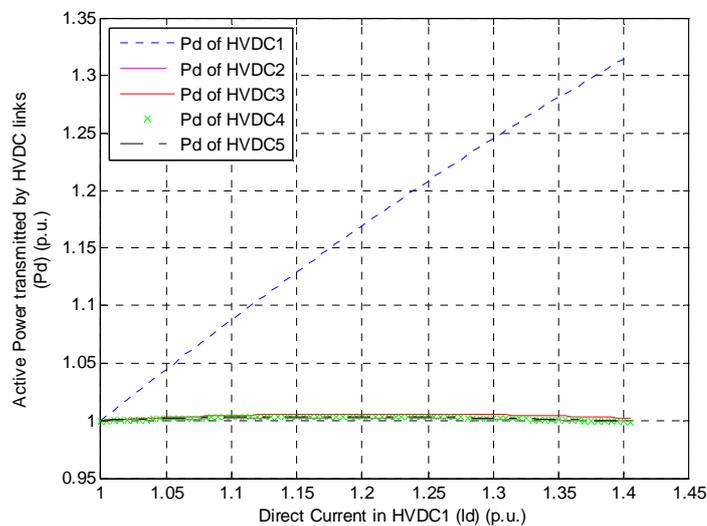


Fig. 9.1. MPCs of 5 HVDC links with the increase of HVDC1 current order

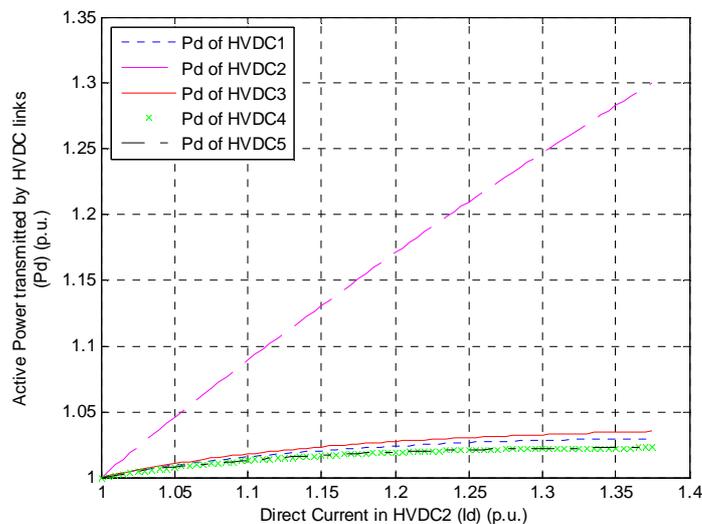


Fig. 9.2. MPCs of 5 HVDC links with the increase of HVDC2 current order

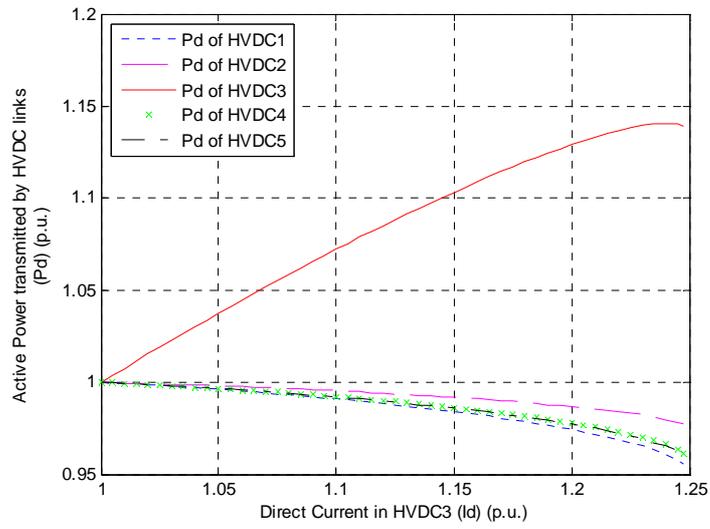


Fig. 9.3. MPCs of 5 HVDC links with the increase of HVDC3 current order

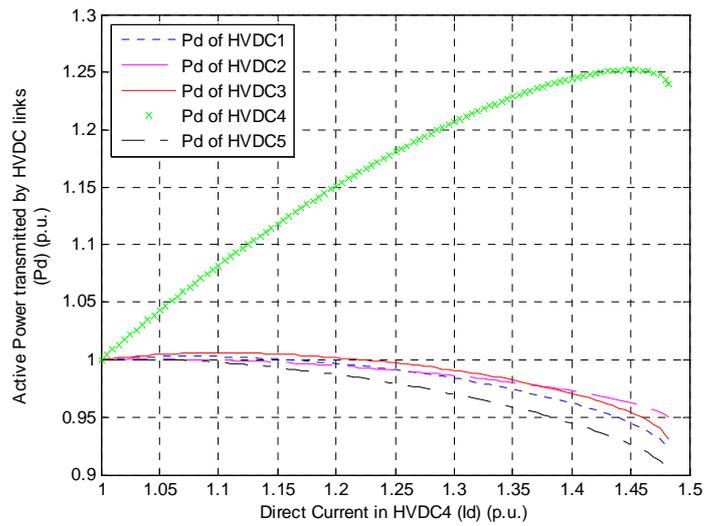


Fig. 9.4. MPCs of 5 HVDC links with the increase of HVDC4 DC current order

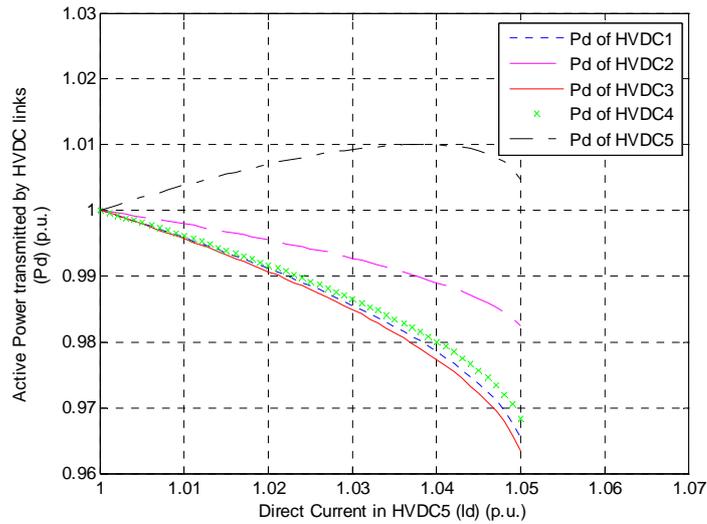


Fig. 9.5. MPCs of 5 HVDC links with the increase of HVDC5 DC current order

It is clear that when active power transferred through one HVDC link was increased by increasing DC current, other 4 links had different responses, similar with the responses of eigenvalue. The increase of active power of HVDC5 induced a much greater decrease of active power in other links, while the same change in HVDC3 and HVDC4 just led to a slight effect on the other links. Other links, such as HVDC1 and HVDC2 even benefited from the increase of active power in HVDC2 because the active power transferred by them even increased a little.

The structure of AC system and the location of HVDC links can give a preliminary explanation about these different effects among 5 HVDC links.

Among all the 5 HVDC links, HVDC5 imports power into load area from another asynchronous power system, and all the other four links, HVDC1, HVDC2, HVDC3 and HVDC4 transfer power from generation area to load area inside the same system. Therefore, there is no parallel AC transmission line along HVDC5, while four main AC transmission corridors accompany other 4 links. On the other hand, HVDC1, HVDC3 and HVDC4 are terminated in or close to the “interface” area, while the end of HVDC2 is far from it.

The increase of power through HVDC5 induced decrease of voltage in load area, which led to greater decrease of imported power through other four HVDC links. Thus, the four main AC transmission corridors were forced to transfer more power to load area and made the voltage further lower in that area, since these stressed AC transmission lines absorbed more reactive power from adjacency. This vicious circle made HVDC5 operate close to its Maximum Available Power.

For the other 4 HVDC links, more active power imported through these links will alleviate the parallel AC lines, which makes these lines consuming less reactive power. Therefore, the voltage of the weak area does not decrease too much or even increases, like HVDC2, which makes the system more stable.

HVDC2 is a more typical case to show the phenomenon of alleviating AC transmission lines by increasing power transferred through HVDC link, since the active power transferred through other 4 HVDC links even increase slightly when its DC current increases.

## 10 Conclusions

Based on this study, the following conclusions can be made:

- Quasi Static Modal Analysis methodology can be used to study Multiple-infeed configuration of HVDC links, giving an indication of possible interaction between AC and DC systems.
- From the study it is possible to identify critical areas in the system. This means that faults and outage of elements in those areas, like transmission lines, shunt compensation or generators are also the critical fault cases. These cases can now be focused on in more detailed study using time domain simulations where a better description of the system and corresponding control system of active devices are included.
- The study has been made using a rather difficult system since the major AC transmission lines are heavily loaded. The analysis of P-V curves and Q-V modal analysis methodology indicates that the system is operating close to the voltage stability limit. This could also be observed when performing analysis of Maximum Power Curves made for individual transmission link.
- Although the Short Circuit Ratio (SCR) measured at each converter bus is quite high (larger than 5), the study has shown that there is not much stability margin for some transmission links. Some HVDC transmission links are operating close to the Maximum Available Power (MAP) point, measured from the MPC curves. The low stability margin is due to the heavily loaded conditions of the major AC transmission lines that are also feeding the load area.
- A parallel AC line with an HVDC transmission link affects the stability condition of the converters at the inverter terminal. Because of the parallel AC line, the rectifier and inverter become coupled, resulting that it affects the operating conditions of the inverter terminal that normally operates at minimum extinction angle.

## **11 Suggestions for future work**

The following work can be done in the future on the basis of this study.

- Study on the original network, instead of the equivalent network
- Simulate loads in a more precise way, with constant P and Q mode, constant current mode and constant impedance mode, not only constant P and Q mode
- Introduce Multi-Infeed Short Circuit Ratio (MSCR) and Multi-Infeed Effective Short Circuit Ratio (MESCR) to study interaction between HVDC links [7]
- More detailed study of interaction between HVDC link and AC system, especially in heavily loaded region
- Consider Constant Power Control, instead of Constant Current Control for HVDC links

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## Appendix A

### Equations for chapter 3.1

$$SCR = \frac{U^2}{Z_{eq} \cdot P_d}$$

$$Z_{eq} = \frac{U^2}{SCR \cdot P_d}$$

$$ESCR = \frac{\frac{U^2}{Z_{eq}} - Q_2}{P_d}$$

where

$$U = 525kV$$

$$P_d = 3000MW$$

$$Q_1 = 1644MVar, Q_2 = 1800MVar, \frac{X}{R} = \tan(80^\circ) = 5.67$$

### Equations for chapter 3.2

$$SCR = \frac{U^2}{Z_{eq} \cdot P_d}$$

$$Z_{eq} = \frac{U^2}{SCR \cdot P_d}$$

$$Z_{eq} = \frac{(Z_1 + Z_{ac}) \cdot Z_2}{Z_1 + Z_{ac} + Z_2}$$

$$Z_2 = \frac{Z_{eq}}{1 - \frac{Z_{eq}}{Z_1 + Z_{ac}}}$$

Assume

$$Z_{Q1} = -\frac{U^2}{Q_1}, Z_{Q2} = -\frac{U^2}{Q_2}, Z'_{eq} = ((Z_1 // Z_{Q1} + Z_{ac}) // Z_{Q2}) // Z_2$$

So

$$ESCR = \frac{U^2}{Z'_{eq} \cdot P_d}$$

Where

$$U = 525kV, P = 3000MW, Z_1 = 18.375\Omega, Q_1 = 1644MVar, Q_2 = 1800MVar, \frac{X}{R} = \tan(80^\circ) = 5.67$$

## Appendix B

### Model and Parameters of HVDC Links

#### 1. HVDC Model In Simulation

All the five HVDC links that will be simulated in the study are bipolar links with 12-pulse converter configuration per pole, as shown in Fig.1. Each bipolar link is represented in simulation by an equivalent single pole, as shown in Fig.2, which means that the pole in mono-polar operation represented in Neplan is equivalent to two poles in bipolar operation in the real system. By doing that the model will be reduced but the performance is unchanged.

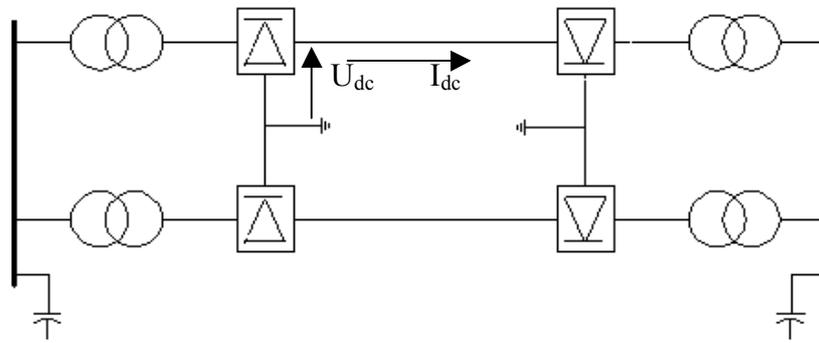


Fig. 1. Bipolar HVDC link configuration

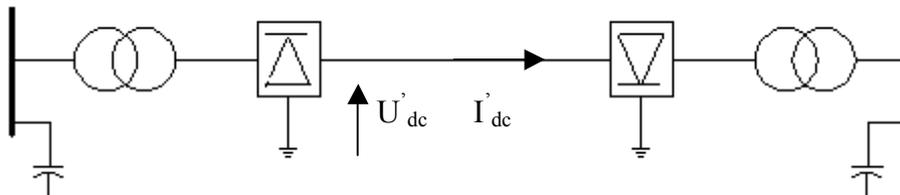


Fig. 2. Monopolar HVDC link configuration

#### 2. Parameters

Element	Parameter	HVDC1	HVDC2	HVDC3	HVDC4	HVDC5
Rectifier	Control mode	CC <sup>1</sup>	CC	CC	CC	CC
	Rated Power	1800 MW	3000 MW	3000 MW	5000 MW	3000 MW
	Rated Current	3.6 kA	6 kA	6 kA	6.25 kA	6 kA
	Nominal DC voltage	500 kV	500 kV	500 kV	800 kV	500 kV

	Nominal firing angle	15°	15°	15°	15°	15°
	Minimum firing angle	5°	5°	5°	5°	5°
	Transformer turns ratio	1.8139	0.8015	0.8267	1.2824	0.8015
	Number of Bridges	1	1	1	1	1
	Current margin	10%	10%	10%	10%	10%
	Commutating reactance	12.292 Ohm	8.134 Ohm	7.848 Ohm	12.474 Ohm	7.936 Ohm
	Shunt capacitor	920 MVar	880 MVar	840 MVar	3120 MVar	1375 MVar
Inverter	Regulation	CEA <sup>2</sup>	CEA	CEA	CEA	CEA
	Nominal DC current	3.6 kA	6 kA	6 kA	6.25 kA	6 kA
	Regulated DC voltage	468.7 kV	463.8 kV	472.7 kV	764 kV	473.7 kV
	Nominal extinction angle	17°	17°	17°	17°	17°
	Transformer turns ratio <sup>3</sup>	1.726	1.822	0.8267	1.2215	0.7642
	Number of Bridges	1	1	1	1	1
	Commutating reactance	11.692 Ohm	7.739 Ohm	7.848 Ohm	11.865 Ohm	7.943 Ohm
Shunt capacitor	930 MVar	2580 MVar	1580 MVar	1980 MVar	1598 MVar	
DC line	Length	1 kM	1 kM	1 kM	1 kM	1 kM
	Resistance	8.7 Ohm	6.03 Ohm	4.545 Ohm	5.755 Ohm	4.4 Ohm
AC node	Nominal AC voltage	230 kV	525 kV	525 kV	525 kV	525 kV
DC node	Nominal DC voltage	500 kV	500 kV	500 kV	500 kV	500 kV

Note 1: CC is Constant Current operation mode.

Note 2: CEA is Constant Extinction Angle operation mode.

Note 3: the step of converter transformer tap changer was set as a very small value to meet the voltage control requirement. In simulation, all the tap changers were locked.