MULTIPLE INFEED SHORT CIRCUIT RATIO – ASPECTS RELATED TO MULTIPLE HVDC INTO ONE AC NETWORK

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Abstract – The paper suggests an extension of the classical definition of Short Circuit Ratio and Effective Short Circuit Ratio to multiple infeed of HVDC transmission configuration. With such new indexes, which consider the interaction between converter stations, it is possible to predict low frequency resonances, dynamic overvoltages and risk for voltage and power instability at low value of the index, similar to single infeed configuration.

In this paper it is also discussed other relevant issues related to integration of multiple HVDC links when the strength of the system is relatively low compared to the amount of power delivered by the HVDC links.

Keywords: Multi Infeed of HVDC Transmission, Weak AC Systems, Multi-Iinfeed Short Circuit Ratio, Multi-Infeed Effective Short Circuit Ratio

1 INTRODUCTION

It is well recognized that there are a number of problems and phenomena related with an inverter HVDC terminal based on current source converters when connected to weak AC networks. These problems and phenomena may impact the design and operation of the HVDC system. Among the consequences of special concern the following important ones can be listed:

- High temporary overvoltages
- Low frequency resonances
- Risk for voltage and power instability
- Long restart times
- High risk for commutation failures

Traditionally, an index, which is used to assess the performance of single-feed converter at the bus, is the Short Circuit Ratio (SCR) or Effective Short Circuit Ratio (ESCR). These indexes, which will be detailed described in the paper, are basically defined as the ratio between the short circuit capacity of the AC network at the commutation bus and the nominal DC power level.

In this paper we extend the definition of SCR and ESCR to multiple infeed of the HVDC converter with a new definition of Multi-Infeed Short Circuit Ratio (MSCR) and Multi-Infeed Effective Short Circuit Ratio (MESCR). It will be shown that with such new indexes it is possible to predict low frequency resonances, dynamic overvoltage levels and possible risk for voltage and power instability in the system in case of low levels of MSCR or MESCR applied to multiple infeed of HVDC converters, in a similar way as the traditional SCR and ESCR are used for single infeed.

The paper will also cover the fundamental aspects of integration of multiple HVDC links feeding power into different points in the same ac network area. There are a number of technical aspects related to multiple infeed configurations with HVDC transmission links. When the strength of the system is relatively low as compared to the amount of power that the HVDC transmission links are feeding into the system there might be a number of adverse interaction among the HVDC transmission links and the receiving ac network and issues that need to be investigated, such as: voltage and power stability; need of coordination of recovery control based on dynamic performance during fault and during recovery of the fault; need of additional controls like power or voltage modulation, which must be coordinated between different HVDC links for stabilization of the ac network; commutation failure interaction between different HVDC converters; frequency stability; overvoltages and harmonic instability due to resonances.

2 SHORT CIRCUIT RATIO AND EFFECTIVE SHORT CIRCUIT RATIO EXTENDED TO MULTI INFEED OF HVDC SYSTEM

The performance of various components in a power system depends on the characteristic of the power system usually referred as the strength of the system. The strength of the system reflects the sensitivity of system variables to various disturbances in the operation of components connected in the system. In a strong system disturbances caused by a change in the power load does not give any significant changes in the voltages and angles of the power system, while in a weak system a small disturbance can cause large deviations in voltages and other variables in the network that the operation of the system can be jeopardized. Therefore, the short circuit level or the equivalent impedance at a bus is often a good measure of the strength of the system at that particular point.

As an HVDC converter can be seen as a load connected to the network with special characteristics such as voltage and angle dependence, controllability, commutation between valves taking place in the converter bridges and possibility to control the firing instants of the valves, all these characteristics are influenced by the strength of the connected system.

A model that is generally adopted for the study of HVDC converter connected to weak AC system is presented in Figure 1. Although is a simplified model, still, most of the important mechanism of the real system can be studied using this model. The usual measure of the strength of the system is the Short Circuit Ratio, which is defined as

$$SCR = \frac{S_{SC}}{P_{dN}} \qquad (1)$$

with S_{SC} as the short circuit capacity at the commutation bus and P_{dN} the rated power of the converter station. This quantity can be generalized to a complex quantity, to take the phase angle of the equivalent impedance into account as

$$\overline{SCR} = \frac{1}{\overline{Z}_L} \qquad (2)$$

with $\overline{Z}_L$ expressed in per unit of the rated power of the HVDC-converter station and the AC voltage at the commutation bus.

In order to take into account the effect of the reactive shunt compensation on the system impedance seen by the converters and therefore to give a better estimate of the total system strength, a more appropriate quantity for the strength of the system is the Effective Short Circuit Ratio, defined by

$$ESCR = \frac{S_{SC} - Q_c}{P_{dN}} \qquad (3)$$

or

$$\overline{ESCR} = \frac{1}{\overline{Z}_e} \qquad (4)$$

with $\overline{Z}_e$ as the effective impedance of the AC network as seen from the converter bus, that is, the system impedance $\overline{Z}_L$ in parallel with the AC filters and additional shunt compensation impedances.

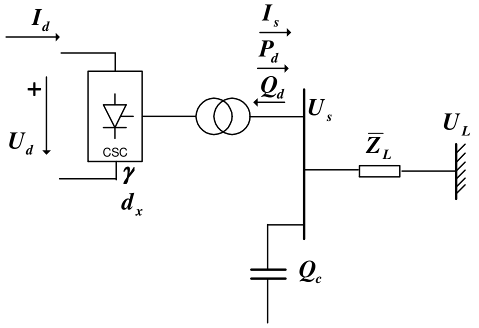


Figure 1: Simplified model of an HVDC connected to an AC network

In a multiple infeed configuration of HVDC converter stations, there will be interaction between these converters, especially if they are electrically close connected. We will now extend the accepted definition of SCR and ESCR to multiple infeed of the HVDC converter, by extracting elements of the bus-impedance matrix, $\overline{Z}_{BUS}$, calculated for the system. This matrix is used to calculate the performance of an interconnected network and whose elements are the open circuit driving points and transfer impedances. Using matrix notation, the performance equation in impedance form is

$$\overline{E}_{BUS} = \overline{Z}_{BUS} \overline{I}_{BUS} \qquad (5)$$

The study of multi infeed HVDC systems can include two or three or even more constituent point-to-point HVDC links. Following the analogy to a single infeed situation, a multiple infeed HVDC system configuration can also be studied by using a simplified system model. As in the single infeed HVDC system, in the multiple infeed configuration the system can be represented with constant Thévenin voltage source, equivalent short-circuit impedances and impedances interconnecting converter stations, reducing the non-conforming AC system topologies to that illustrated in Figures 2a and 2b, for the cases of two and three converter station terminals, respectively. With this simplified model it is also possible to study many of the important system phenomena occurring in physical AC/DC interactions. From the reduced topology the $\overline{Z}_{BUS}$ matrix is calculated retaining only the converter busses.

The following equation suggests an approximate indication of short circuit ratio at a converter bus taking into consideration the influence of operation of remote converters electrically connected to the converter bus that is under consideration

$$MSCR_n = \frac{1}{\sum_{m=1}^{k} Pdc_m \times z_{n,m}} \qquad (6)$$

where:

k: corresponds the number of HVDC terminal stations

n: is the converter bus under consideration

m: varies from converter #1 up to converter #k

Pdc_m : is the rating of the m^th^ converter in p.u.

$z_{n,m}$: is the n^th^,m^th^ element in the Z_{BUS} matrix in p.u.

We define the term

$$P_{i\,n} = Pdc_n \times z_{n,n} \quad \text{for} \quad m = n \qquad (7)$$

the participation index of the own converter connected to the bus under consideration, and the other terms,

$$P_{i\,nm} = Pdc_m \times z_{n,m} \quad \text{for} \quad m \neq n \qquad (8)$$

the participation index of the remote converter that are electrically connected to the bus under consideration.

It should be noted that the formula is also applicable for single infeed, and in this cases it will only include the terms $z_{1,1}$. It should also be noted that the smaller magnitude of the value $z_{n,m}$ the weaker will be the participation of the converter mth to the bus nth; the opposite is also true, the bigger magnitude of the $z_{n,m}$ the stronger will be the participation of the converter mth to the bus nth.

When calculating the Z_{BUS} matrix and one wish to consider the impact of the shunt compensation elements, these elements are also included in the formation of the matrix. Using the elements from this new $Z_{e\,BUS}$ we can define the Multi-Infeed Effective Short Circuit Ratio by

$$MESCR_n = \frac{1}{\sum_{m=1}^{k} Pdc_m \times z_{e\,n,m}} \qquad (9)$$

where $z_{e\,n,m}$ is the nth,mth element included in the effective $Z_{e\,BUS}$ matrix.

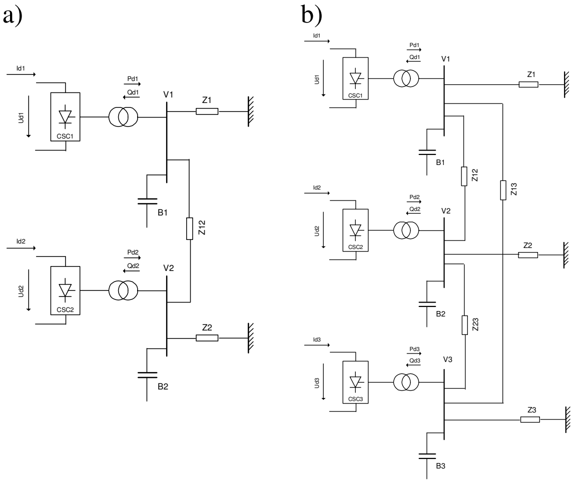


Figure 2: Simplified model of multi infeed HVDC system, a) having two HVDC-converter station and b) with three converter stations.

2.1 Estimation of temporary overvoltage at sudden load rejection

Changes in the reactive power balance of the ac network initiated by switching, fault or power flow variation, either in ac or dc systems, produces change in operating voltages. A surplus in reactive power leads to voltage increases and larger disturbances result in temporary overvoltages.

A classical HVDC substation based on line-commutated current-source converters always consumes reactive power in the order of 0.5 pu of transmitted power. For a weak system a temporary load rejection, e.g. caused by a fault in the other end of the transmission or a commutation failure, will lead to temporary overvoltages.

It is possible to estimate the overvoltages at load rejection with simple formulas. Assume the case of single infeed system according to Figure 1. The circuit diagram can also be represented according to Figure 3 that included the effective network reactance calculated by

$$\frac{1}{jX_e} = \frac{1}{jX_L} + \frac{1}{-jX_c} \qquad (10)$$

The corresponding phasor diagram of the main quantities, the terminal voltage U_s, the apparent current from the converter I_s, and the power angle φ_s are also presented in Figure 3.

The voltage drop across the effective network reactance is

$$V_{drop=}\sqrt{3}I_s X_e \qquad (11)$$

In the equation, the current and impedance can be rewritten by

$$\sqrt{3}I_s = \frac{\sqrt{P_d^2 + Q_d^2}}{U_s} = \frac{S_s}{U_s} \qquad (12)$$

$$X_e = \frac{U_s^2}{S_{SC} - Q_c} = \frac{U_{s\,N}^2}{S_{e\,N}} \qquad (13)$$

where S_s is the apparent fundamental power from the converter and $S_{e\,N}$ is effective short circuit power of the system.

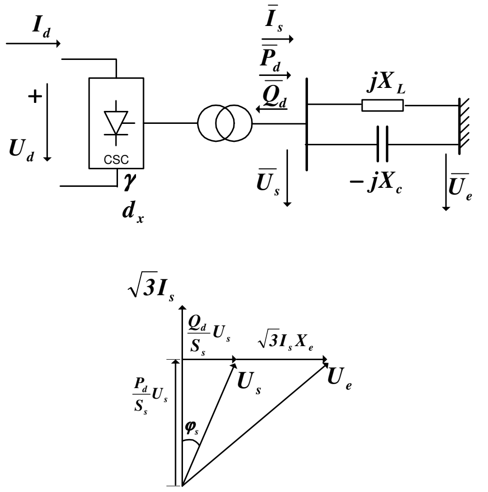


Figure 3: Circuit diagram and corresponding phasor diagram

Observing the phasor diagram in Figure 3, the voltage U_e can be calculated by

$$U_e = \sqrt{\left(\frac{S_s}{S_{e\,N}}\frac{U_{s\,N}^2}{U_s} + \frac{Q_d}{S_s}U_s\right)^2 + \left(\frac{P_d}{S_s}U_s\right)^2} \qquad (14)$$

Division of equation (14) by terminal voltage U_s, assuming the pre-conditions $U_s = U_{s\,N}$ and assuming $Q_d = 0.5 P_d$,we get

$$\frac{U_e}{U_{sN}} = \sqrt{\left(0.447 + \frac{1.118\ P_d}{S_{e\,N}}\right)^2 + 0.8} \qquad (15)$$

By making using of equation 3, results

$$\frac{U_e}{U_{sN}} = \sqrt{\left(0.447 + \frac{1.118\ P_d}{ESCR\ P_N}\right)^2 + 0.8} \qquad (16)$$

Equation (16) shows that at an instantaneous blocking of all the converters at the converter station the voltage U_s will increase to U_e. Hence, the equation gives a measure of the voltage increase at sudden load rejection as a function of the effective short circuit ratio ESCR. It should be noted the calculated overvoltage is the transient increased in the fundamental frequency component of the filter bus voltage.

If we now consider a multi infeed configuration, and for simplicity, let assume the case according to Figure 2a, which includes only two converter stations. The corresponding equivalent phasor diagram seen from bus 1 is presented in Figure 4.

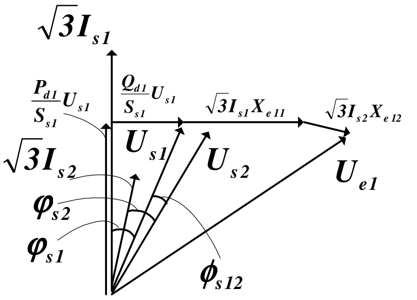


Figure 4: Phasor diagram of bus 1 corresponding to Circuit Diagram according to Figure 2a

It is assumed that converter station 1 delivers to the system an apparent power S_{s1} and converter station 2 delivers to the system apparent power S_{s2}. From the phasor diagram, it is possible to derive the following equation, corresponding to bus 1

$$U_{e1} = \sqrt{\left(\frac{Q_{d1}}{S_{s1}}U_{s1} + \sqrt{3}I_{s1}z_{e11} + \sqrt{3}I_{s2}z_{e12}\cos\phi_{12}\right)^2 + \left(\frac{P_{d1}}{S_{s1}}U_{s1} + \sqrt{3}I_{s2}z_{e12}\sin\phi_{12}\right)^2} \tag{17}$$

In the equation, the impedance elements z_{e11} and z_{e12} are obtained from the effective $Z_{e\,BUS}$ matrix and the angle ϕ_{12} is the angle difference between the converter bus voltage 1 and converter bus voltage 2.

Replacing the apparent current by corresponding apparent power we get

$$U_{e1} = \sqrt{\left(\frac{Q_{d1}}{S_{s1}}U_{s1} + \frac{S_{s1}}{U_{s1}}z_{e11} + \frac{S_{s2}}{U_{s2}}z_{e12}\cos\phi_{12}\right)^2 + \left(\frac{P_{d1}}{S_{s1}}U_{s1} + \frac{S_{s2}}{U_{s2}}z_{e12}\sin\phi_{12}\right)^2} \tag{18}$$

Assuming $U_{s1} = U_{s2} = U_{sN}$ and assuming $\phi_{12} \approx 0$

$$U_{e1} = \sqrt{\left(\frac{Q_{d1}}{S_{s1}}U_{sN} + \frac{S_{s1}}{U_{sN}}z_{e11} + \frac{S_{s2}}{U_{sN}}z_{e12}\right)^2 + \left(\frac{P_{d1}}{S_{s1}}U_{sN}\right)^2} \tag{19}$$

Dividing by U_{sN} and assuming $Q_d = 0.5P_d$

$$\frac{U_{e1}}{U_{sN}} = \sqrt{\left(0.447 + \frac{1.118P_{d1}}{U_{sN}^2}z_{e11} + \frac{1.118P_{d2}}{U_{sN}^2}z_{e12}\right)^2 + 0.8} \tag{20}$$

Converting the values into pu, and using equation (9)

$$\frac{U_{e1}}{U_{sN}} = \sqrt{\left(0.447 + \frac{1.118}{MESCR_1}\right)^2 + 0.8} \tag{21}$$

Another way to write equation (21) is by using Participation Indexes according to equations (7) and (8):

$$\frac{U_{e1}}{U_{sN}} = \sqrt{\left[0.447 + 1.118\left(P_{i1} + P_{i12}\right)\right]^2 + 0.8} \tag{22}$$

Similar equations can be derived for bus number 2.

As an example, let us consider a system according to Figure 2a and parameter values according to Table 1.

Using equations (21) or (22) we calculate the following voltage increase for the case of complete load rejection: for bus nr. 1 1.56 pu and for bus nr. 2 1.35 pu. It should be noted that these are approximated values due to the assumptions made when formulating the equations.

Table 1: Example of two-infeed system

HVDC 1	HVDC 2
$P_d = 1\ pu$	$P_d = 1\ pu$
$Q_d = 0.5\ pu$	$Q_d = 0.5\ pu$
$Q_c = 0.5\ pu$	$Q_c = 0.5\ pu$
$Z_1 = 0.666\ pu$	$Z_2 = 0.333\ pu$
tie line $Z_{12} = 1\ pu$	
$MESCR = 1.33$	$MESCR = 2$
$P_{i1} = 0.5833$	$P_{i2} = 0.3333$
$P_{i12} = 0.1667$	$P_{i21} = 0.1667$

2.2 *Estimation of resonance frequency*

In general, electrical networks have natural frequencies, and in those cases with active circuits involving control systems, these resonances may contribute to potential instabilities.

The most significant type of possible instability is the core saturation instability, which occurs if the ac side is close to a second harmonic resonance. The instability can be mitigated by suitable modification in the control system of the HVDC converters, or also the installation of low order harmonic filters.

In a single infeed configuration according to Figure 1, the resonance frequency is between the filters and shunt capacitor and the network. It can calculated by

$$\frac{\omega_0}{\omega_N} = \sqrt{\frac{S_{SC}}{Q_c}} \tag{23}$$

If we assume that $Q_c = Q_d = 0.5P_d$, then the equation is simplified to

$$\frac{\omega_0}{\omega_N} = \sqrt{2 \times SCR} \tag{24}$$

which means that a system with short circuit ratio of 2 will be resonant at second harmonic frequency.

In a multiple infeed configuration, at each converter bus, there will be a resonance frequency between the shunt elements installed at the converter bus and the network impedance seen from the converter bus. This network impedance can be extracted from the elements in the diagonal of Z_{BUS} matrix. Assume for example, the configuration according to Figure 2a, the resonance frequency for bus number 1 is obtained as follows

$$\omega_0 = \sqrt{\frac{1}{LC}} \qquad (25)$$

Taking the element $z_{11} = \omega_N L_{11}$ from the Z_{BUS} matrix, and since $\omega_N C_1 = \frac{Q_{c1}}{U_N^2}$ we get

$$\frac{\omega_0}{\omega_N} = U_N \sqrt{\frac{1}{z_{11} Q_{c1}}} \qquad (26)$$

A similar equation is obtained for bus number 2, with appropriated change in the indexes.

2.3 Voltage and Power stability

Voltage and power stability of HVDC converter are important issues when HVDC converters are connected at ac system locations having low short circuit capacity. The basic concept of voltage unstable situation is the inability of the power system to provide the reactive power needed by the load in order to maintain acceptable system voltage. This is an issue of concern for both pure ac systems and for systems that includes HVDC converters.

The Voltage and Power stability can be studied by looking at the Maximum Power Curve. The Maximum Power Curve gives an indication of the stability limit of the system, by calculating the sensitivity of a system to small changes in the controlling system quantities, like current or power reference order. A simplified model of the system according to Figures 1 and 2 can be used for studying the voltage/power stability of HVDC converters without the use of extensive simulation tools.

The Maximum Power Curve indicates the maximum amount of active power that can be transmitted when varying only the dc current from an initial operating point. The criterion for voltage/power stability at a given point is that the slope of the Maximum Power Curve, the derivate dP_d / dI_d should be positive. This indicates that an increase in dc current will result in an increase in dc power.

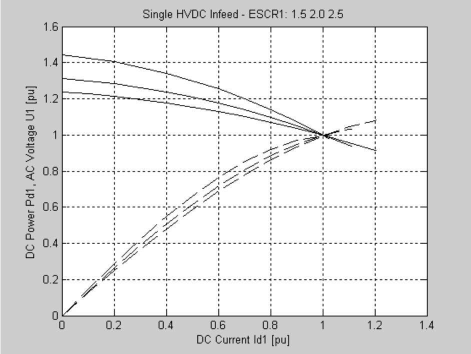
To illustrate the procedure, consider the configurations according to Figures 1, 2a and 2b, and let us calculate the Maximum Power Curve for each these configurations for Bus number 1. We will consider different values of MESCR, by varying the interconnection impedance Z12 impedance in those multi infeed configurations and Z_L for the single infeed configuration. Table 2 shows a summary of the characteristic of the studied configurations.

The study is made by computing the DC power Pd at rectifier side of the HVDC link as function of the direct current Id. Starting from nominal conditions, U, Ud, Id at 1 pu, the Thevenin voltage is held constant when Pd is computed as Id varies. When the network includes more than one HVDC, we will only consider that HVDC nr. 1 will be varying while the others are maintained operating at a fixed parameter conditions. All cases were calculated assuming current control mode at rectifier and inverter in constant extinction angle control mode. The study was made using a load flow program, and the results were plotted in Figures 5a, 5b and 5c, all referred to the HVDC nr. 1.

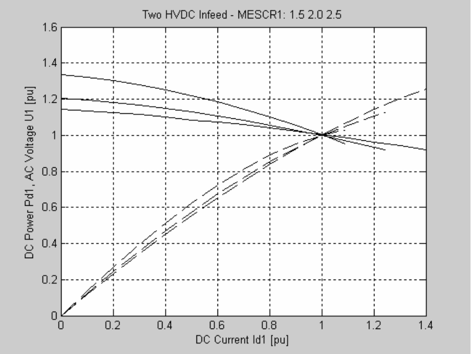
Table 2: Characteristic of studied cases

	HVDC 1		HVDC 2		HVDC 3	
Config.	MSCR	MESCR	MSCR	MESCR	MSCR	MESCR
Case A (Fig 1)	2.0	1.5				
	2.5	2.0				
	3.0	2.5				
Case B (Fig 2a)	1.94	1.5	3.36	2.7		
	2.46	2.0	3.14	2.57		
	3.0	2.5	3.0	2.5		
Case C (Fig 2b)	1.95	1.5	3.78	3.16	3.89	3.29
	2.45	2.0	3.29	2.73	3.98	3.42
	2.99	2.5	3.02	2.53	4.05	3.51

Case A:



Case B:



Case C:

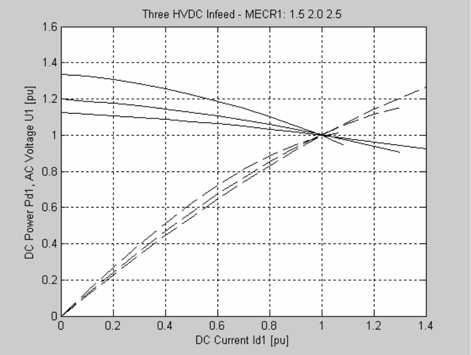


Figure 5: Maximum Power Curves for different configurations: Case A - one terminal; Case B - two terminals; Case C - three terminals

A common system base has been used to convert the quantities into pu, that is the rated DC power of HVDC link and rated AC system voltage. The rating of individual DC links in all cases is identical. This results in that a change in DC current in Case A will have stronger impact in the connected AC system as compared to Case B, and even stronger impact as compared to Case C.

The results also show that the critical network that gives the derivate $dP_d/dI_d = 0$ at nominal operating conditions is characterized by $MESCR \approx 1.5$ for any of the three studied configurations.

3 ADDITIONAL ISSUES REGARDING INTERACTION BETWEEN CONVERTER STATIONS

3.1 Commutation failures

Commutation failures occur whenever the converter valves have insufficient time to recover from conduction to withstand forward blocking voltage. Too small a commutation margin makes the inverter vulnerable to commutation failures. The commutation failures are usually initiated by some disturbances in the ac voltages, e.g., phase-to-ground faults.

In general, interaction between converter stations may occur during commutation failures, especially if they are electrically close connected. Therefore, it is desirable to prevent commutation failures. There are possible ways to reduce risk of commutation failures in a converter. For example, a disturbance that might cause an increase in the dc current or a decrease in ac voltage, and if the converter control reacts by ordering a decreased of alpha, compensating the increase of overlap angle, the commutation margin might be preserved, avoiding the commutation failure. Another example is, in case a commutation failure is detected during an ac fault, the control should transiently increase inverter gamma to avoid subsequent commutation failures during the fault. Once the fault is cleared, the angle can be slowly returned to normal.

Coordination of parameter settings between different HVDC transmissions can mitigate possible adverse interaction during recovery of sudden commutation failures.

3.2 Low inertia systems

The ability to withstand temporary losses of power infeed into a system is closely related to the total mechanical inertia of the system. Often a low inertia system is also a system with low short circuit capacity.

Commutation failures cause temporary reduction of the power infeed by the HVDC-system, which results in frequency deviation in the ac system. In low inertia systems the frequency deviation can be significant that may actuate the ac system protections. This problem becomes more severe when several HVDC converter station suffer simultaneous commutation failure if they are located in low inertia network. The duration of these disturbances is in the range of 100-300 ms for HVDC converters.

3.3 Impact of high level controls

Frequency controls and power or voltage damping controls can complement the pole power control to assist the power system following disturbances. In a multi infeed configuration it is possible to simultaneously controlling several electromechanical modes of oscillation in the power systems. The multi infeed configuration offers the opportunity to have these controls designed and operated in coordination, for example to improve inter-area stability problems. In a study case reported in [3], the control of one link was designed to supply synchronizing torque to the system while the control of another link was designed for damping low frequency oscillations. In both links the overload capability were used at different times in a coordinated manner.

4 CONCLUSIONS

The paper proposes an extension of the definition of Short Circuit Ratio and Effective Short Circuit Ratio that has been established for single infeed of an HVDC link to multiple infeed of HVDC links. With the new indexes that we designated as Multi-Infeed Short Circuit Ratio (MSCR) and Multi-Infeed Effective Short Circuit Ratio (MESCR) it is possible to predict low frequency resonances, dynamic overvoltage levels and possible risk for voltage and power instability in the system in case of low levels of MSCR or MESCR. This can be made in a similar way as the traditional SCR and ESCR used for single infeed configuration.

The paper also covered other important aspects of integration of multiple HVDC links feeding power into different points in the same ac network area: interaction between converters due to commutation failures, recovery of the converters after system disturbances and possible coordination of high level controls between HVDC links in order to stabilize the common connected AC system needs to be addressed, especially when the receiving system has low or very low short circuit capacity in relation to total power transfer by the HVDC links. With a carefully designed of the controls, multi infeed is a very reliable and powerful part in the network.

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