

A new control scheme for an HVDC transmission link with capacitor-commutated converters having the inverter operating with constant alternating voltage

P. Fischer*
ABB-HVDC
Sweden

L. Ängquist
KTH
Sweden

H.P. Nee
KTH
Sweden

SUMMARY

Experience and theoretical analysis show that the voltage and power stability becomes an important issue when high-voltage direct current (HVDC) systems using line-commutated converters (LCC) are connected to AC systems with low short-circuit capacity and that these problems become more pronounced the lower the short-circuit capacity of the connected AC system is, as compared with the rating of the HVDC converter station.

Normally some additional equipment, like static or synchronous compensators, will be installed in order to improve the performance of the HVDC transmission system, when it is connected to a weak AC system. The cost of the substation thereby will be increased.

The Capacitor-Commutated Converter (CCC), which has been developed by ABB, offers an alternative to the LCC in this kind of application. It reduces the reactive power interaction between the converter and the connected AC system. The CCC is, in principle, a classical converter provided with a series capacitor placed between the converter valves and the converter transformer.

In this paper a new control strategy that can be used together with such a CCC is presented. In the new control system the inverter emulates the operation of a Voltage Source Converter, in the sense that, beside the control of the active power flow through the converter, the reactive power exchange with the AC network can also be managed in order to adjust the alternating voltage of the converter bus.

Studies have shown that the interaction between the inverter and the connected AC system is significantly reduced, when the CCC is used together with this new control strategy. Keeping the alternating voltage constant makes it possible to control the DC-side voltage of the HVDC transmission system, allowing the rectifier converter to control the active power by means of controlling the direct current. This combination allows stable operation of the HVDC transmission system even under severe network conditions associated with low short-circuit power in the connected AC network at the inverter side.

In the paper it is shown that, with the new control scheme, it is possible to operate the inverter into an almost passive AC network (a network with very few rotating generators, resulting in almost no short circuit power). Simulation results have indicated satisfactory operation of the HVDC transmission with the inverter operating into a network having a Short-Circuit Ratio as low as 0.2 ($SCR \approx 0.2$). To the knowledge of the authors, operation of a line-commutated converter at such low SCR values has never been reported previously.

A description of the new control scheme will be presented. The calculated performance in a practically implemented installation, the Rio Madeira Back-to-Back system, will be illustrated.

KEYWORDS

HVDC, Weak system, LCC-Line Commutated Converter, CCC-Capacitor Commutated Converter, Control Principles, Rio Madeira

* paulo.fischer@se.abb.com and paulo.fischer@ee.kth.se

1.0 INTRODUCTION

The phenomena related to high-voltage direct current (HVDC) converters connected to weak AC networks have been extensively studied. The CIGRÉ and IEEE organizations have done a comprehensive research in this field and they have jointly published report guides [1] and [2], which provide a good survey of most of the associated phenomena. These phenomena have different implications on the design of an HVDC system. The following issues are of special concern:

- Risk for voltage/power instability
- High temporary over-voltages
- Low-frequency resonances
- Long restart times
- Risk for commutation failures

All these factors influence the system performance. Typically, in case of problems, they have been solved by installation of additional equipment like static or synchronous compensators [3], [4], which increases the overall cost of the substation.

The Voltage/Power stability is a basic issue of concern for HVDC systems with line-commutated converters, when they are connected to weak AC systems. The basic mechanism causing unstable behavior is the inability of the connected power system to provide the reactive power required by the converter to maintain an acceptable system voltage [5] and [6].

Traditional design of a line-commutated inverter assumes operation with constant extinction angle, γ [7]. This design allows the operation of the converters with minimum reactive power consumption, and reduced amount of reactive power shunt compensation. Alternatively, other operating properties can also be found, like e.g. constant direct voltage or constant firing angle, α . However, all these operating conditions imply similar limiting conditions in terms of the required strength of the connected AC system.

To mitigate the interaction between the converter and the connected AC system ABB has developed the Capacitor-Commutated Converter (CCC). The CCC is a classical converter provided with a series-capacitor bank placed between the converter valves and converter transformer [8], [9]. In the CCC the reactive power generation of the commutation capacitor continuously increases with increasing power. This reduces the variation of the alternating voltage conditions for varying AC power.

In [8] it is shown that the CCC has improved the performance compared to a conventional HVDC converter, especially when the converters are connected to weak AC systems. (A measure of the strength of the AC system is the unit Short Circuit Ratio, SCR, which is defined as the ratio between the short-circuit capacity of the AC network at the commutation bus and the nominal DC power level. The Effective Short Circuit Ratio, ESCR, takes into account the effect of reactive shunt compensation on the system impedance seen by the converters.) Studies demonstrated that the CCC can operate successfully when connected to AC systems with $SCR = 1$, while the conventional HVDC is limited to networks with at least $SCR \approx 2$.

The CCC concept certainly utilizes current source converter technology, in which an alternating current is created from the direct current, and injected into the AC network. However, the series capacitors influence the valve voltages such that the conduction interval can be phase-advanced making the current phase leading relative to the voltage, similar to what can be achieved by forced commutation. Accordingly, the CCC can both supply and consume reactive power to/from the network through its AC terminals. This feature is typically encountered in Voltage Source Converters (VSCs).

In a VSC its DC-side voltage is utilized to create the AC-side voltage. Its valves can conduct current in both directions so that its alternating current can lead or lag the voltage. Therefore, a VSC has a

natural capability to control the reactive power exchange with the AC network and it can be used to control the amplitude of the AC-bus voltage at the connection point in the AC network.

In the present paper a new control scheme is proposed for the CCC, which makes it possible to control the alternating voltage of the converter bus by manipulating the reactive power flow through the converter, in the same way as it can be done with a VSC. This is the first time such an approach is presented, and it is believed that this will push the limits of operation towards ever weaker grids.

Studies have shown that a CCC using this new control strategy exhibits a significantly reduced interaction with the connected AC system. When the inverter controls the AC-bus voltage it becomes possible to maintain a fixed DC-side voltage in the HVDC transmission system. Thereby, the active power transfer will be determined by the direct current, which can be controlled by the rectifier. This approach allows stable operation of the HVDC transmission system even under very severe network conditions e.g. associated with extremely low short-circuit power levels.

In principle, using this control scheme, it is possible to operate the inverter in an almost passive AC network, i.e. when only a few rotating machines are installed in the network either with low ratings or possibly located far away from the HVDC inverter station. Preliminary studies have indicated reasonable operation of the HVDC transmission with the inverter operating into a network having a Short-Circuit Ratio as low as 0.2 ($SCR \approx 0.2$). Operation at such low SCR values has never been presented before using this kind of converter. As a matter of fact, SCR values as high as 2.5 are considered to be low (i.e. representing a weak grid) for line-commutated converters in the literature [10]. This means that the suggested control scheme permits operation with grids that are more than one order of magnitude weaker than what is considered to be a weak grid.

It should be noted that the new proposed control scheme is particularly suitable with CCC considering that the CCC can operate with less reactive power consumption from the connected AC network as compared to the conventional converter. It can also allow the converter to generate reactive power, if the commutating capacitor is sized for such conditions. This allows a tight control of the alternating voltage at the connection point with the AC network, enhancing the transient performance of the combined converter and connected AC network.

It should also be noted that this control scheme can effectively be used if, and only if, the rectifier-side converter is able to control the direct current. This implies that the rectifier should be connected to a relatively strong AC network to guarantee the stability of the control loop of the direct current, resulting in a stiff direct current flowing through the inverter-side converter.

2.0 REVIEW OF THE CAPACITOR-COMMUTATED HVDC CONVERTER WITH ORDINARY CONTROLS

2.1 General

With the CCC-HVDC transmission, the control principles are in many aspects similar to the controls used in a conventional converter without series-commutated capacitors.

In a CCC, as indicated in Figure 1, the commutation voltage is composed of the AC-bus voltage and a voltage component related to the capacitor voltages. Application of the firing angle requires the knowledge of the commutation voltages for the valves. This is the major difference between the controls used in a conventional converter without series-commutated capacitors and the control used in a CCC.

Similar to a conventional HVDC transmission system, the control scheme used in a CCC-HVDC transmission will have one station continuously controlling the direct current and the other station controlling the direct voltage. The basic control functions, therefore, are the current control and the voltage control. In addition, the tap-changers of the respective converter transformer are used to maintain the normal firing angle and the direct voltage of the station in current- and voltage- control respectively.

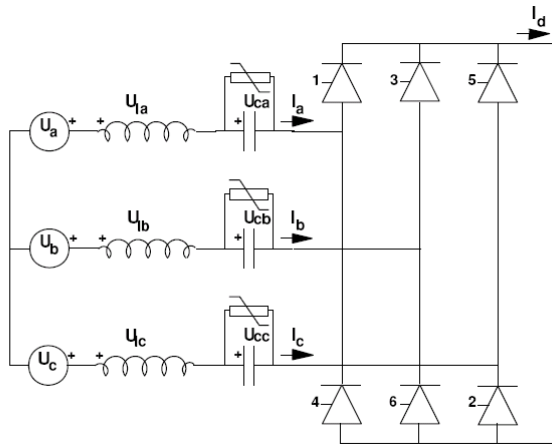


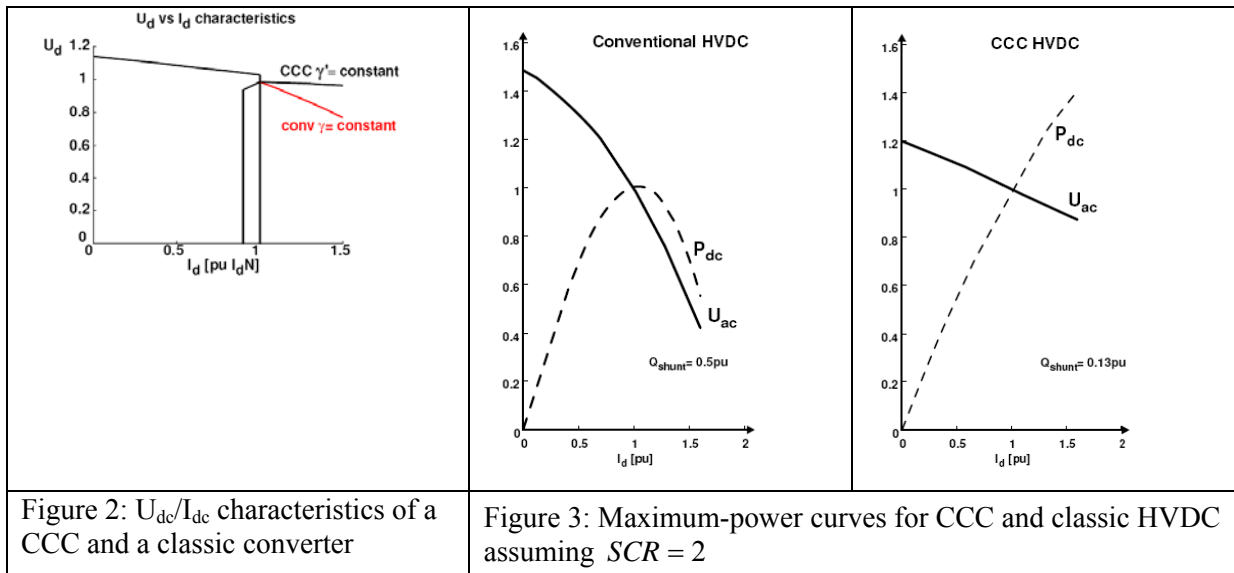
Figure 1: Commutation circuit

2.2 Reactive power

In a classic converter the reactive power consumption of the valve bridge and converter transformer is in the order of 0.45-0.55 pu based on the transmitted power. This reactive power is usually provided by shunt compensation.

In a typical CCC the required shunt is approximately 1/3 up to 1/2 of what is necessary for a classic HVDC converter. This requirement considers the reactive power consumption in the converter transformer and the reactive power generated by the commutation capacitor, which are calculated as the reactance times the square of the fundamental current.

2.3 Inverter Stability and Maximum Power Curve



Usually, a classical HVDC inverter will be operating with the smallest commutation margin, γ_0 [7]. This commutation margin is selected in such a way that the converter will operate with reduced reactive power consumption and low risk of commutation failures. However, the constant commutation margin causes negative impedance characteristics as indicated in the red curve in Figure

2. When considering the effect of the AC system impedance on the inverter impedance characteristics, a weak AC system increases the negative impedance characteristics even more.

In a CCC, the commutation margin increases at an increase of the direct current. Therefore, the corresponding U_{dc}/I_{dc} characteristics for a case of constant commutation-margin control is less sensitive to the AC system impedance as shown in Figure 2, resulting in an almost flat U_{dc}/I_{dc} slope. This gives improved stability.

The stability of an inverter connected to an AC system can be analyzed using the Maximum Power Curve (MPC). The MPC shows the active power transfer to the AC system modeled as an infinite source and short-circuit impedance. In this model the inverter is usually operating at minimum commutation-margin control. The MPC demonstrates the system response when dynamically changing the direct current, I_{dc} , from the nominal operating point. Only the initial dynamic response is modeled which implies that no action from the AC-system voltage control is included. (More details and interpretation and use of MPC can be found in [1] and [6].)

In Figure 3 the MPC curves are given for a system with an $SCR = 2$. Figure 3-A refers to a classic HVDC and Figure 3-B refers to a CCC-HVDC, respectively.

When using CCC, an increase in the direct current will result in an extension of the operating firing angle range due to the commutation voltage contribution from the commutation capacitors. This results in reduced reactive power consumption from the connected AC network. This is an opposite behavior to a classic HVDC, where an increase in the direct current requires a reduced firing angle in order to maintain a sufficient commutation margin, which causes the reactive power consumption to be increased.

From the power characteristics in a CCC the margin to the point of peak power transfer, in the MPC, is significantly improved, resulting in better stability. In fact, analysis made from the MPC for the classic converter the stability limit is reached at 1 pu current when $SCR = 2$. The corresponding critical stability point for a typical CCC can be found to be just below $SCR = 1$.

3.0 DESCRIPTION OF THE NEW CONTROL SCHEME APPLIED FOR THE RIO MADEIRA BACK-TO-BACK

3.1 Main control principle

In the previous section it was mentioned that the typical control principle used in an HVDC transmission link utilizes the direct-current control, which is handled by the rectifier. For the inverter side, it usually operates at minimum allowed γ for a safe commutation. The voltage control is made by the tap-changer control of the converter transformer, which varies the valve-side alternating voltage.

Usually, a CCC makes use of a similar principle, except that the commutation voltage contribution from the commutated capacitors is taken into account.

In some applications, an alternative operating characteristic for the inverter is to maintain a constant firing angle, α . This option gives a somewhat improved small-signal stability of the current control system in the rectifier. Another alternative for the operation of the inverter is to control the direct voltage. The commutation reference is determined based on a slow feedback control system having the direct voltage as the input to the controller. However, all these different control principles have similar limiting conditions in terms of strength of the connected AC system.

The control principles for the rectifier and inverter converter can then be visualized in Figure 4.

The new control principle to be used for the operation of the inverter-side converter of the HVDC transmission is based on the ability of the CCC to control the exchange of reactive power with the AC network from the AC terminal of the converters, and by doing that controlling the alternating voltage

of the converter bus. The new proposed control scheme for the inverter includes the following control loops:

- A main control loop that gives the inverter operation with constant alternating voltage (the controller uses the alternating voltage measured at the filter bus);
- Transiently, a direct-current controller can be selected (normally the rectifier controls the direct current, but during transients like disturbances in the connected AC network, the direct-current controller at the inverter can be selected to recover the HVDC transmission link from the fault);
- Transient operation of the inverter-side converter can also be made with constant commutation margin, when the calculated commutation margin is lower than a minimum reference, to avoid commutation failures;

It should be stressed that the new control scheme is particularly suitable with the CCC. When properly sizing the commutating capacitor it allows the converter to generate or absorb reactive power from the connected AC system, making it possible to appropriately control the alternating voltage at the commutating bus.

The main control principle for the new concept can be visualized in Figure 5.

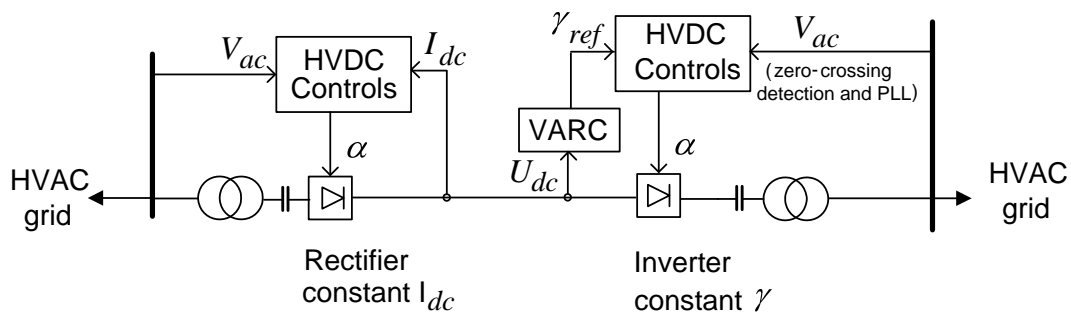


Figure 4: Typical control principle of a combined Rectifier and Inverter HVDC transmission link

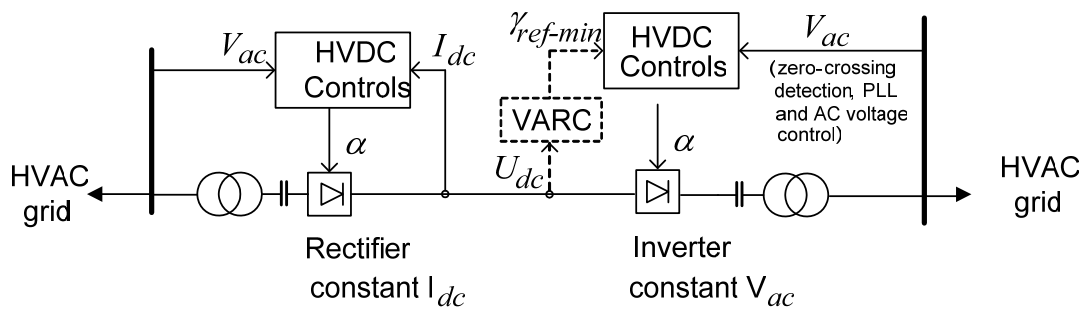


Figure 5: New control principle of a combined Rectifier and Inverter HVDC transmission link, assuming the inverter controls the alternating voltage of the connected AC system

3.2 Minimum and maximum extinction angle as a function of direct current and operating voltage

To control the alternating voltage of the connected AC system the HVDC converter uses its internal output rating capability of maximum generation and absorption of reactive power.

The maximum reactive power generation capability is determined by the operation at minimum extinction angle. To reduce the risk of frequent commutation failures this parameter is normally set not

lower than 18 degrees. The value is chosen depending on the characteristics of the connected system network.

The maximum reactive power absorption capability of the converter is a function of transmitted power and system alternating voltage level. The limitation factors are: the converter valves stresses when operating at too high angles and level of the voltage across the valves.

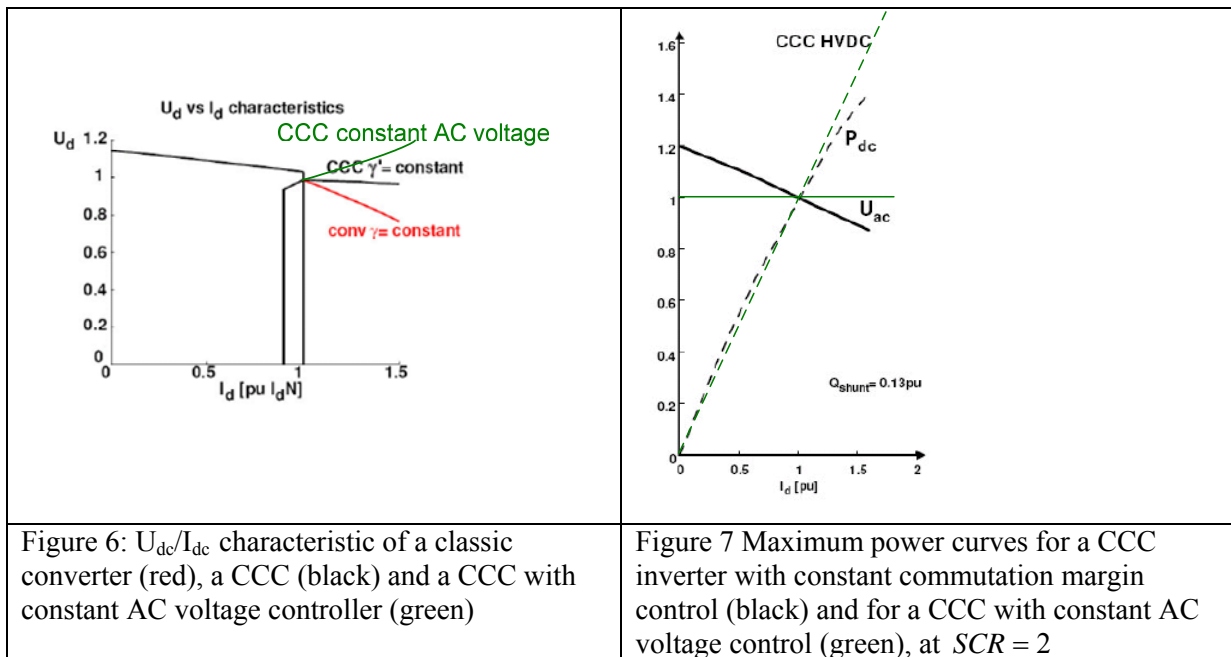
3.3 Droop function

In case more than one converter block is in operation, and assuming that these converter blocks are using identical control schemes, these blocks may be controlling the same AC-bus voltage. To prevent control instability between the converter blocks a droop in the control has to be introduced. The droop can act on the reference value in the alternating-voltage controller.

3.4 Inverter stability and Maximum Power Curve

In the previous sections it has been mentioned that a classical converter, when operating at constant commutation margin, constant γ , results in a negative impedance static characteristic (see red curve in Figure 6). In a CCC the commutation margin does increase at an increase of the direct current, and thus improves the inverter impedance characteristic even with constant commutation margin operation (see black curve in Figure 6).

Now, assuming that the inverter CCC is operating under the assumption that the alternating voltage can be controlled, this can then provide a positive inverter impedance characteristic (see green curve in Figure 6).



With a CCC, the exchange of reactive power with the connected AC network is significantly lower as compared with a conventional converter. The result of the CCC power characteristics is that the margin to the point of peak power transfer, in the MPC, is significantly improved, resulting in better stability as compared with a classical converter. A typical MPC curve for an inverter CCC connected to a system with $SCR = 2$ is shown in Figure 7 (black curve).

Assuming that the CCC inverter is now operating with constant alternating voltage, the MPC curve becomes insensitive to the connected AC system, as the alternating voltage is controlled by the

converter. The system response when dynamically changing the direct current, I_d , from the nominal operating point follows an approximately straight line as indicated in Figure 7 (green curve).

4.0 APPLICATION

4.1 The Rio Madeira HVDC transmission, focusing on the CCC Back-to-Back

The Rio Madeira HVDC transmission system consists of two bipolar transmissions rated 3150 MW each used to supply electrical power generated from the hydroelectric plants of Santo Antonio and Jirau on the Rio Madeira River close to Porto Velho to the main consuming areas in South-Eastern of Brazil (Araraquara region). To supply power to the local load centre areas in the Acre-Rondônia region two HVDC Back-to-Back blocks of 400 MW each will feed power into long 230 kV AC lines (Rio Branco – Jaurú) – see Figure 8.

For the HVDC Back-to-Back converters, there are good reasons to investigate the performance of these converters in terms of the Voltage and Power stability conditions. The reasons are that the connected 230 kV system includes very long AC lines, and that the system has almost no generation. The stability conditions of the 230 kV system are then strongly dependent on proper operation of the Back-to-Back converters.

ABB has considered Back-to-Back converters using CCC to be a means to mitigate the interaction between converter and AC system. The use of CCC eliminates the need for the synchronous condensers, improves the Voltage/Power stability, reduces the temporary overvoltage as well as the risk for resonance at low frequencies.

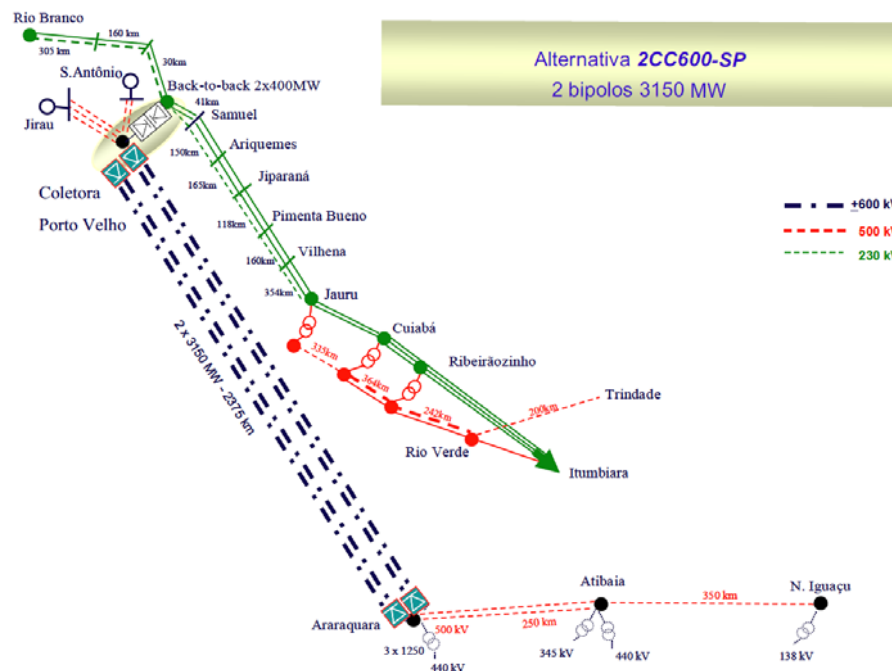


Figure 8: The Rio Madeira HVDC transmission system and the area in the Acre-Rondônia network supplied by the CCC Back-to-Back (Rio Branco – Jaurú)

The AC transmission lines in the Acre-Rondônia network are very long, resulting in that the impedance of the network seen by the converter is significantly influenced by the shunt compensation included in the network. It is also influenced by the generators connected in the Samuel power plant which is not far from the converter station.

Although the rating of each Samuel generator unit is only 50 MVA, there is a strong influence of these machines on the short-circuit power measured at the inverter-side converter bus. Having one Samuel generator machine in operation the $ESCR$ is 0.25 and assuming five machines in operation the $ESCR$ is approximately 0.75.

This $ESCR$ range is considered as the normal operating mode for Back-to-Back, which means that the system supplied by the Back-to-Back is characterized by an extremely low short-circuit level.

4.2 Test examples

In the following test examples it is assumed that the system is characterized by: an AC system connected to the rectifier having an $SCR = 2.5$ and an AC system connected to the inverter having a $SCR = 0.5$ and a corresponding $ESCR = 0.35$.

It is also assumed that the dispatch through the two Back-to-Backs is 800 MW (each block is transmitting nominal power, 400 MW).

In the Rio Madeira Back-to-Back's the inverter includes the following series capacitor and converter transformer reactance: $dx_c = 0.35$ pu and $dx_L = 0.14$ pu, respectively. Having such an arrangement under convention constant extinction angle control the Back-to-Back would be operating at a power level exceeding the critical stability point seen from the Maximum Power Curve (would be stable only for a connected AC system having $SCR = 0.75$ or higher). Three filters of 59 MVA and one shunt reactor of 63 MVA are connected at the inverter side of the Back-to-Back (excluding redundant elements).

In order to evaluate the transient stability performance of the system different types of AC faults are presented in Figure 9 A-D. Solid faults were applied close to the converter station.

The results show very good recovery from the AC system faults. There is no indication of any risk of Voltage or Power instability of the converters.

5.0 CONCLUSIONS

In this paper a new control scheme for a HVDC transmission system has been presented. This control scheme is particularly suitable with CCCs. With appropriate sizing of the commutated capacitor the converter can generate and absorb reactive power from the connected AC system, and therefore it can control the alternating voltage at the connection point to the AC network. This will substantially enhance the transient performance of the combined converter/connected AC network.

A typical CCC has a superior performance with regard to voltage and power stability and temporary overvoltage as compared to the conventional line-commutated converters without series-commutated capacitors. The performance of the CCC can be enhanced even further when using the new control scheme described in this paper.

Studies have shown that in principle, using the new control scheme, it is possible to operate the inverter-side converter into an almost passive AC network. Numerical studies and simulations have indicated satisfactory operation of the HVDC transmission with the inverter operating in a network having a Short-Circuit Ratio as low as 0.2 ($SCR \approx 0.2$).

Some examples of dynamic test simulations were presented in a system characterized by $SCR = 0.5$ and $ESCR = 0.35$. In such a system the CCC-HVDC transmission system would be naturally unstable when operating with a traditional control scheme with constant extinction angle at the inverter. When adopting the new control scheme the results have shown that the HVDC transmission exhibits very good recovery from system faults without any indication of risk for having Voltage or Power instability.

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Simulation of various faults with SCR=0.5, converters transmitting 2*400 MW

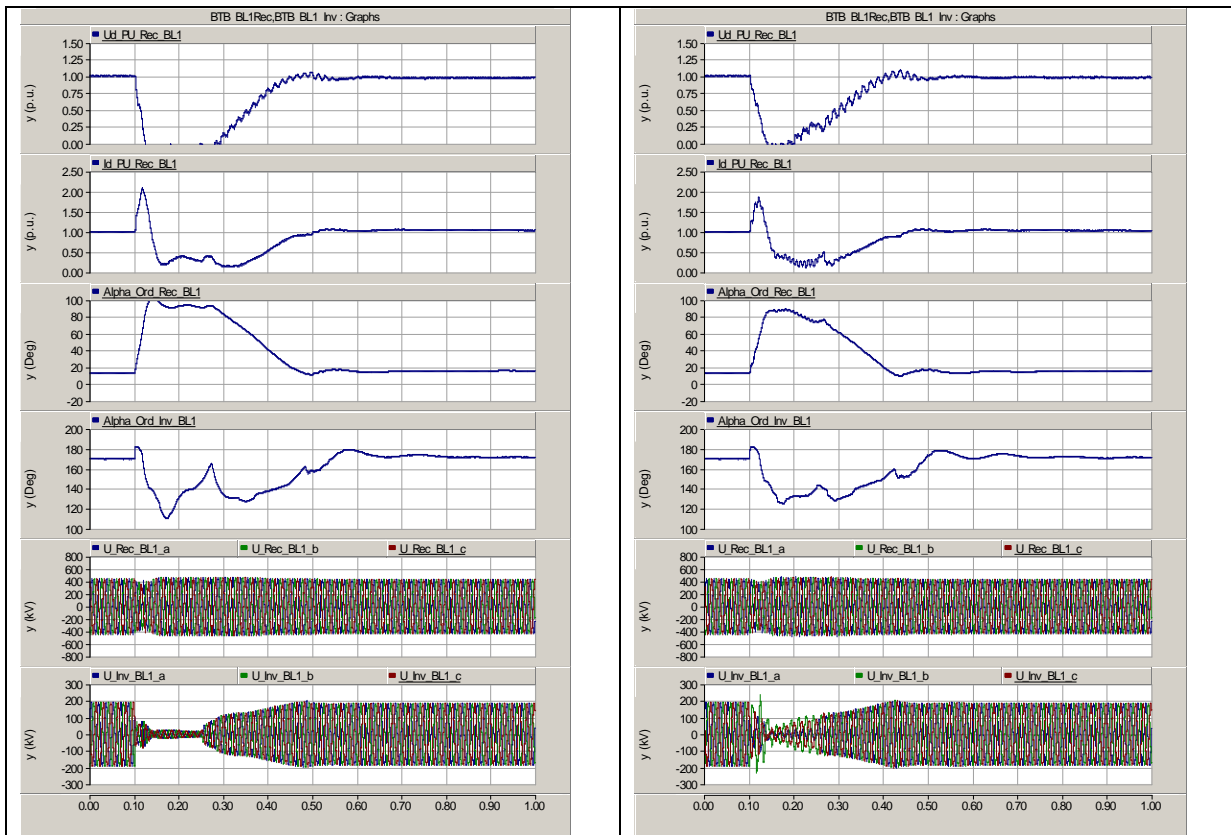


Figure 9-A: Inverter three-phase fault

Figure 9-B: Inverter single-phase fault

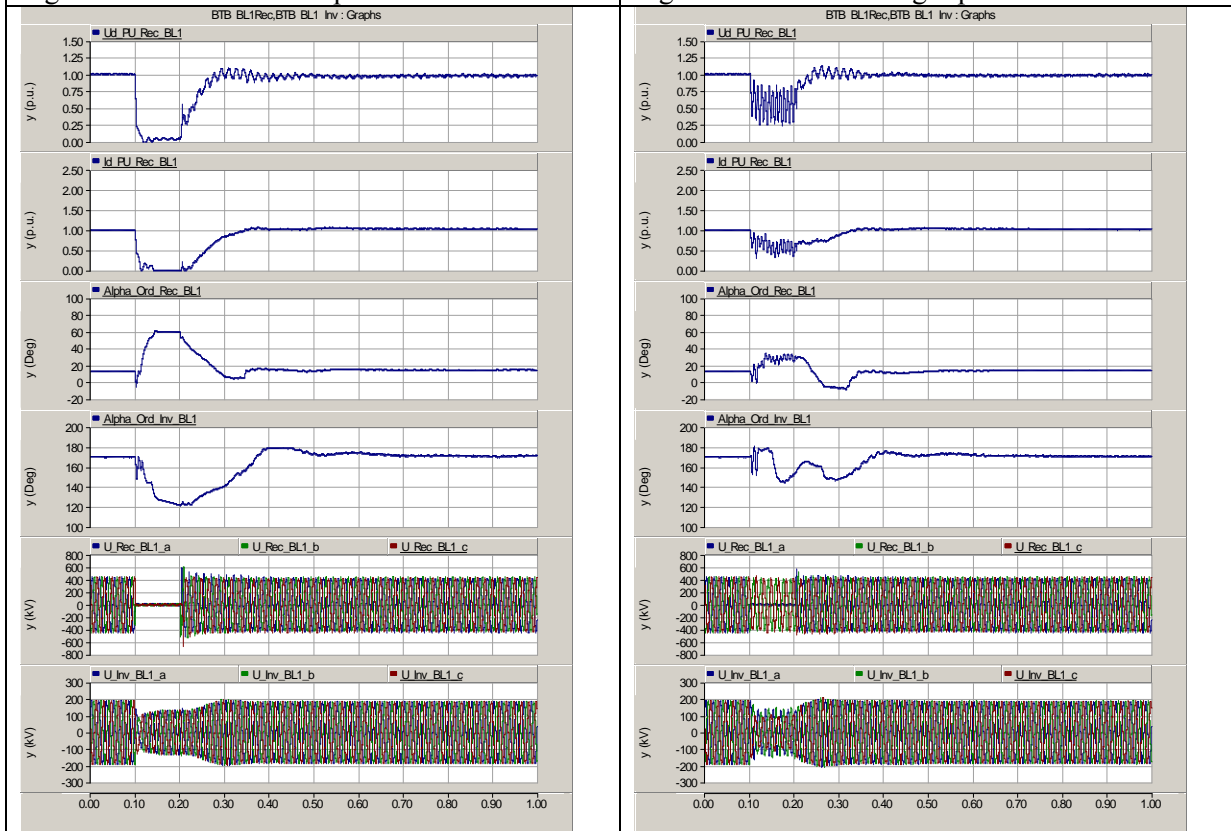


Figure 9-C: Rectifier three-phase fault

Figure 9-D: Rectifier single-phase fault