Real-Time Method to Prevent Voltage Collapse and Power Instability of HVDC Systems

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Abstract—As HVDC transmission is increasingly used in electric power grids its influence on overall voltage and power stability is under special focus. For the classic HVDC system using current sourced line-commutated converters voltage and power stability is of concern. For the light type of HVDC systems utilizing voltage sourced self-commuting converters voltage stability is in general no problem, however, transmission angle stability and, connected to this, power stability can be crucial. Essential for both types of HVDC system is the identification of unstable operating regions and their avoidance. Certain off-line analytical methods and on-line control concepts exist but they do not provide complete security. This paper demonstrates that a real-time stability analyzer and an adaptive power controller free the system from this risk of voltage and power instability. Voltage and power are stabilized at a maximum transferable power level.

Index Terms—Voltage Collapse, Voltage and Power Stability of HVDC, Control and Stability of HVDC, Weak AC Grids, Voltage Sensitivity Factor, Voltage Stability Criterion, Voltage Sourced Converter, Current Sourced Converter, Maximum Transferable Power, Proximity to Stability limit

I. INTRODUCTION

HVDC systems play an important part within the new systems of renewable power generation and AC grid interconnections. According to this their influence on grid stability has to be fully understood. Voltage collapse phenomena occurring in pure AC grids and analytical methods for stability analysis are given in [1, 2]. Quite principally this information is also useful in HVDC applications but it is not sufficient because no relation to the important voltage/power characteristics of HVDC systems is given. This is, e.g., done in [3] which summarizes existing analytical methods and discusses possibilities to improve the analysis and the prediction of stability margins in meshed AC/DC networks using classic HVDC systems. There is more material available on that subject and the author apologizes for not citing those who made their useful contributions.

The determination of stability margins in dependency on certain network conditions provides information regarding the power which can be transferred at a still acceptable AC voltage level. So at operation the power can be automatically adjusted to predetermined values which are stored in the converter power controller. This method provides stability for predictable network conditions but not for unfavorable conditions as they might evolve in the course of power system expansion or through ill coordinated operation or maintenance. An operational real-time method directly recognizing an approaching instability is needed to securely prevent voltage collapse and power instability. Before addressing this core topic of the present paper information on the system service capability of HVDC systems is given. This capability has considerable influence on voltage and power stability of HVDC systems.

II. SYSTEM SERVICE CAPABILITIES OF HVDC SYSTEMS AND THE REASONS OF INSTABILITY

Fig. 1 shows a generic configuration of a power system where HVDC transmission is used for renewable power supply from remote locations and for interconnection of AC networks. The renewable energy can come from off-shore wind farms, distant water power plants or huge solarthermal facilities as they are planned for the Sahara Desert.

The kind and extent to which an HVDC system can supply system services depend on the type of converter technology used which again depends on the transmission task. Bulk power transmission over very long distances is done with the classic HVDC system using line-commutated current sourced converters (CSC). For moderate transmission distances as well as for Back-to-Back converter stations connecting asynchronous grids the self-commutated voltage sourced converter (VSC) is preferably used. This holds also for HVDC systems making connections to distant offshore wind farms.

The classic HVDC system is restricted with regard to supplying system services. It can participate in load-frequency control but it does not provide own inertia and it needs a grid providing the commutation voltage. Contrary HVDC installations equipped with VSC can operate on AC grids with low or even no mechanically rotating generation [13].

Through specific control schemes the CSC can control reactive power and AC voltage, however, with more costly equipment and losses and not as smooth as the VSC. Also the
short circuit power of the AC grid has to be sufficiently high in relation to the DC transmission rating. A further drawback is that filtering requirements are much more demanding and expensive for the CSC than for the VSC.

The most significant difference being relevant for the present paper is that the classic HVDC system is prone to voltage and power instability if the stiffness of the AC system at the connection point of the converter (rectifier or inverter) becomes too low.

For the VSC the stiffness of the AC system has in general not an immediate bearing on voltage stability because of continuous voltage control. Low stiffness means, however, high internal grid reactance which limits the power transfer capability of the network. This can lead to transmission angle instability and a connected reduction of the transferred AC power and loss of synchronism. At full voltage control capability of the VSC, i.e., without any rating limits affecting voltage control, no hint on this stability problem is obtained before synchronism is lost.

There exist analytical methods identifying steady state stability boundaries for a given network [8] and to determine HVDC controls which avoid a transfer to outside these boundaries [7, 12]. This approach of stability analysis at design stage and implementation of corresponding stabilizing control functions is currently the state of the art to prevent voltage collapse of classic HVDC systems. It relies on complete knowledge on the relevant structure and data of the AC system comprising generation and consumption, and it is, therefore, not completely secure if this knowledge is not available or not incorporated into controls when changes occur in the course of power system expansion.

In order to reliably prevent voltage and power instability converter controls are desirable adapting automatically to changing network conditions. This paper describes a dynamic real-time method to analyze the stability state and a converter controller which uses the output of the analyzer to stabilize the HVDC system. The core idea of this approach is that not reactive power is adapted to prevent voltage and angle instability but real power is controlled on the basis of continuously available stability data. The method and the corresponding apparatus can be used in standalone or to supplement and back-up existing stabilizing controls. The viability of the proposed method is tested through transient simulations using the PSCD/EMTDC simulator. A patent application was filed.

III. PRESENT METHODS TO MAINTAIN VOLTAGE AND POWER STABILITY

The CSC of a HVDC transmission system needs a minimum ratio of short circuit power over real converter power (SCR) in order to maintain AC voltage and power stability. A minimum SCR of around 2 to 3 can be considered as a value where an acceptable performance is obtained. In [9] it was shown that this value is directly related to the dQ/dV-stability criterion [4] which is the reverse value of the voltage sensitivity factor [8]. SCR of about two relates to dQ/dV = 0 which designates the stability boundary. To be stable the system requires dQ/dV > 0. With SCR of about three there is still some stability margin. A change of the SCR and its influence on the voltage stability criterion dQ/dV is determined for the configuration of Fig. 2 where an inverter operates on a weak grid. As long as DC voltage control is active the system is solidly stable for both the SCR values (Fig. 3 and 4). When DC voltage control is given up because the extinction angle hits its minimum value system stability starts to deteriorate (Fig. 3) or is even suddenly lost (Fig. 4).

Voltage collapse can be prevented through provision of sufficient continuously controlled reactive power, which, however, requires a costly installation of a continuously operating reactive power device like the static compensator (STATCOM) [14]. Emphasis has to be put on “continuous” since with discretely switched capacitors the maximum permissible transmission angle is lower than 45 degrees [14] which is less than half of the limiting value (90 degrees) holding for continuous control.

For the option of using a thyristor controlled reactor (TCR) in parallel to capacitors careful evaluation regarding its suitability is needed because at its reactive power supply limit
the system can suddenly become unstable [14]. Another disadvantage is connected to a possible low order harmonic resonance between capacitors and the network reactance.

To save expenditures for reactive power equipment becoming only effective in rare situations voltage dependent current order limiting (VDCOL) [7, 10] and event actuated power order reduction (EAPOR) [10, 12] are applied. These functions are calibrated in accordance with actual system conditions. If in the course of power system development these conditions change unfavorably, e.g., through addition of another converter reducing the SCR value, voltage collapse could occur despite of the implemented control functions. The following demonstrates this for the configuration of Fig. 2.

If the VDCOL calibration is adapted to the voltage level of 0.9 as in Fig. 5 holding for a SCR = 3.33 then VDCOL will not be actuated for a SCR of 2.33 (Fig. 6).

Also the depressed voltage level of somewhat above 0.97 (Fig. 6) cannot be used as an indication of instability since in Fig. 5 this voltage is within the normal range still being far away from instability. The graphs of Fig. 3 to 6 were all determined with continuation power flow method [6]. The stability criterion depicted in Fig. 3 and 4 was calculated from the entries of the Jacobian Matrix: dQ/dVAC = (J21-J22*J11/J12).

It should be noted that VDCOL is in general easier to calibrate when the HVDC terminal operates on radial AC lines since then there is no influence of consumers as asynchronous machines or thermostatically controlled loads, provided the AC voltage is controlled at the remote end of the line.

The afore-mentioned installation of a STATCOM of sufficient rating would avoid voltage instability but at the same time hide transmission angle instability, i.e., the angle could exceed 90 degrees without any recognition of this fact. Such a situation could arise at an outage of one or several parallel AC line sections which would increase the equivalent reactance of the AC grid being effective at the converter terminal connection point. Trip signals could be used to identify this situation. Since a reduction of the SCR value can also appear gradually, e.g., through excitation limitation of a synchronous generator, there is not always some trip signal available which could be used to identify crucial conditions. And if the transmission angle has already passed the MTP-point then there is no way of returning to the stable region of the power/angle curve with the present controls. However, as described in the following section, further increase of the transmission angle can actually be stopped through DC current limitation.

The VSC does not have a minimum requirement on the SCR to maintain stable voltage. If, however, the reactive power supply rating is insufficient to cover the AC system's reactive power need voltage stability could also be endangered [14]. Fortunately the behavior of the VSC is much friendlier as compared with the CSC since its reactive power supply is proportional to AC voltage (at its current limit) while it is proportional to the square of AC voltage for the capacitor and filter banks providing reactive power in case of the CSC. The latter relationship is more detrimental for stability.

With large amounts of power being fed from wind farms into coastal zones and load centers being far away from the converter terminal the magnitude of the transmission angle gains an increasing importance and interest. Synchronized phase angle measurements using the Global Positioning System (GPS) could provide information on the transmission angle. However, for events increasing suddenly the inner reactance between the converter terminal and the distant AC network GPS-based information would be too slow to counteract.

To understand the mechanisms leading to instability one has to examine the dynamics of these events. This permits to find a solution for the problem. It has to be noted that for the following treatment there is no AC transmission in parallel with the DC transmission, i.e., the DC system connects asynchronous networks, respectively voltages. This is the case for many existing systems and will probably be the case for most systems to come. Nevertheless, because of its appearance in certain configurations it has to be mentioned that for parallel AC/DC systems with line-commutated converters besides the SCR value also the ratio of AC power over DC power transmitted in parallel is relevant for system stability [11].

IV. DYNAMICS OF VOLTAGE AND POWER INSTABILITY

A. Influence of the Converter Power Controller

The methods to determine the steady state stability limit via power flow computation and the voltage sensitivity factor do not show the connection to the process actually producing instability. It is a dynamic process involving the converter power controller.

For the CSC forming the terminal (rectifier or inverter) of a classic HVDC transmission system the following holds: the try of the power controller to reach the power set value at declining AC grid voltage and a correspondingly declining DC
voltage causes an increase of the DC current (Fig. 7). As long as the operating point lies on the upper branch of the voltage/power curve an increasing DC current yields higher power. If, however, the MTP-point is surpassed the power will decrease despite further increasing DC current. Current limitation as provided through VDCOL would stop further increase of the power, i.e., with limited DC current also an operating point on the lower branch of the voltage/power curve would be stable regarding AC and DC voltage. However, the efficiency would in most cases not be acceptable. Also the transmission angle remains stable despite the fact that the MTP-point is surpassed.

For an inverter besides reduced efficiency another more essential effect prevents operation on the lower branch. When surpassing the MTP-level commutation failures are likely to occur. This is due to an accelerated increase of DC current in response to decreasing AC voltage, difficulty to choose a suitable current order limit beforehand and inability of the extinction angle controller to respond fast enough to avoid commutation failures.

Fig. 8 and 9 show the voltage/power relationship and the change of the extinction angle versus time for the inverter of Fig. 2 when the DC power order is ramped up starting in “A”.

As already delineated above voltage sourced converters possess continuous voltage control capability. This ability to control the voltage conceals, however, possible transmission angle instability. Also here the power controller is actually the vehicle finally producing instability. If through some sudden or slow change of the AC network the actual power value drops below the set value the power controller will try to compensate for the power error. The graph of Fig. 11 demonstrates this situation for the configuration of Fig. 10 where for the sake of simplicity only series reactances model the AC lines.

These graphs correspond to Fig. 3 and 5. At “B” constant DC voltage control is given up and constant extinction angle control takes over. When passing the MTP-point “C” the extinction angle can no longer be kept at its minimum value of 10° due to the combined effect of accelerated AC voltage decrease and DC current increase. At “D” commutation failures occur and the system will shut down because there is no way to recover as it is normally done in stable HVDC systems at transient commutation failures occurring at, e.g., AC line faults.

Operating point “a” is stable when both AC lines are closed. When one line is switched off the power is immediately reduced to operating point “b” and subsequently increased through the power controller. Since the set value (3 p.u.) is higher than the MTP-value (2.5 p.u.) the transmission angle (delta) will run through the MTP-point “c”
of the power/angle curve of the remaining AC line. If there is no measure to recognize this and to reverse this process the power transfer becomes unstable. Here the instability is connected to increased reactive power consumption of the AC network at a rising transmission angle and decreasing real power (Fig. 12). With both lines switched on the larger one of both the grid PQ-circles intersects the (mirrored) converter PQ-circle at the stable operating point “a”.

A trip of the AC line (X2) increases the effective network reactance which in turn causes a reduction of the diameter of the grid PQ-circle. During the shift of the operating point from “a” via “b” to “c” the changes of real power P and reactive power Q go both in the same direction which means stability. After passing “c” reactive power Q continues to increase up to “d” while real power P decreases. Passing through “d” reverses the power flow direction and the operating point cycles through the grid PQ-diagram. Of course, in real operation the change from inverter to rectifier operation would be prevented by controls. But the shift of the operating point over “c” will not be recognized with presently available controls. To develop a remedial measure the diagrams of Fig. 12 are examined regarding the ratio of the PQ-changes. The ratio dP/dQ is > 0 before the MTP-level is reached and it is < 0 after the MTP-level is passed. So the sign of the ratio identifies the stability state of the system. With different voltage magnitudes of the converter terminal voltage (V1) and with reactive power delivered or consumed by an AC line working below or above its surge impedance level, the diagrams are shifted along the Q-axis. However, the principle of examining changes of real and reactive power is retained.

B. Real-Time Method for Stability Analysis

The above described and depicted relationships (Fig. 7 and 12) are used on-line to extract data providing information on the stability situation. For the CSC changes of real power and real current (Fig. 7) form a pair to be examined [5]. The sign of the quotient is obtained through forming the gradients of power (dP/dt) and current (dI/dt) with respect to time and subsequent division or multiplication of the derivatives, whereby synchronism of both the gradients is necessary, i.e., measurements have to be taken and filtered properly. For the VSC real power P and reactive power Q form a pair permitting a statement on stability (Fig. 13).

Fig. 13. Quantities versus time used to form gradients with respect to time

Also here the gradients with respect to time are determined and the stability criterion is then formed through division or multiplication of the gradients. The dynamic aspect of the voltage stability phenomenon shows here its particular relevance. Since the time derivates are determined continuously stability analysis is synchronous with time. Without taking into account the dynamics no on-line detection of the stability state would be possible. Actually the analyzer detects the transfer between the branches of the power/voltage curve, resp. power angle curve. The speed of the power controller is decisive in forming the derivatives with respect to time. It is interesting to note that the power controller which was described under IV-A as the producer of voltage collapse is now the device helping to analyze the stability situation. It should be noted that limited reactive power supply capability causes voltage depression and connected to this power instability already before the transmission angle reaches 90 degrees [14].

C. Stabilizing Controller

The voltage/power characteristic of a CSC being the terminal of a classic HVDC transmission system shows stable behavior on the upper branch if the power controller increases the DC current to obtain higher power. To accomplish this the sign of the power controller loop has to be chosen such that a power error generates a control signal increasing the DC current. When the MTP-point is surpassed further increase of DC current will yield less power. The stability analyzer will provide a signal indicating this situation to the stabilizing controller. In response to this the stabilizing controller will switch the sign of the power control loop, thereby decreasing the DC current. In this way the operating point will be shifted back to the upper curve. The analyzer detects this change and the sign of the power control loop will be switched again. By repeating this process the operating point will revolve around the MTP-point. This will be indicated to the operator who can then reduce the power set value manually.

The applicability and effectiveness of the described method depend on the mode of converter operation. As rectifier there is no problem to operate at the stability limit. Fig. 14-a and
14-b demonstrate this for $\text{SCR} = 3.33$. The power is ramped up beyond rated power of 200 MW to make use of a temporary overload capability. Shortly above 230 MW when the minimum rectifier firing angle is reached the voltage shows a steep decline and the transmission angle a correspondingly higher rate of change. At the MTP-level the system is automatically stabilized.

For inverter operation there is the necessity to detect the transfer from the upper to the lower branch of the voltage/power curve and to immediately shift the operating point back to the upper curve with an immediate automatic reduction of the power set value. This process is required to prevent commutation failures as they occur in Fig. 8 and 9.

Swings at the MTP-level can also be suppressed through an automatic MTP-dependent reduction of the power order. I.e., if the first swing or a certain countable number of such swings occur the power order is automatically reduced by an adjustable percentage, e.g. 5 %, of the actual power level which, since operating at the stability limit, is equal to the MTP-level. In this way the transmission system operates with a predetermined stability margin.

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The same control mechanism as for the CSC-rectifier holds for the VSC either operating as rectifier or as inverter. Also here the stability analyzer provides the information for the power controller to switch cyclically the sign of the control loop. Fig. 18 shows that contrary to Fig. 11 the power is kept at the maximum transferrable power level of about 2.5 p.u.
when the switch “S” is opened. Power transfer (P) is stabilized around the transmission angle “delta” of 90 degrees (Fig. 18 and 19). The difference between the phase angle “phase_Vq1” of the internal voltage Vq1 and the transmission angle “delta” is the power angle of the converter (Fig. 19).

The AC terminal V_{AC} is controlled via the internal converter voltage Vq1 (Fig. 20) the magnitude of which depends on the modulation degree of pulse width modulation. The phase angle of Vq1 is synchronized via a phase locked loop circuit with the terminal voltage.

According to the grid PQ-diagram (Fig. 12) the reactive power Q (Fig. 20) moves from the initial value in operating point “a” via “b” to the periodically changing value at “c”.

Fig. 20 shows also the adaption of the actual power P to the maximum transferrable power level being about 0.5 p.u. lower than the power order P*. DC current and the proportional real converter current (both are not shown here) decrease linearly with actual power since the DC voltage is constant. Therefore, the apparent AC terminal current I_{AC} (Fig. 20) remains within limits despite the high increase of reactive power. That is, for the here given network conditions and converter rating no overcurrent limitation restrains the voltage control function of the converter. Also, what is important, the amplitude of the power swings on the crest of the power/angle curve (Fig. 18) is rather modest. If despite of this the swings are not acceptable MTP-dependent power order tracking can be applied.

If the HVDC system is the only medium receiving power from a generation facility (e.g., hydro power plant or offshore wind farm) the automatic reduction of HVDC power in accordance with the MTP-level of the AC transmission system will cause a surplus of generated power over consumed power.

The generating facility has to cope with the requirement of adapting its generation to the actual power transmitted and consumed. This requirement is, however, in general more moderate than in case of voltage collapse and transmission angle instability where the complete load is suddenly lost. Also, since voltage collapse is avoided, an energy storage plant being installed at the converter terminal can draw the surplus energy, thereby providing sufficient time for the generating facility to adapt its generation smoothly to the actually transferred power. A relatively small storage capacity would be sufficient for this purpose.

V. CONCLUSIONS

Classic HVDC systems operating on weak AC grids need careful evaluation of the various options to ensure voltage and power stability. There are analytical methods available to determine which of the options are technically sound and robust. Determination of maximum transferrable power and the stability margin through continuation power flow analysis or sensitivity analysis belong to these methods. The results are
used for controller design and parameter calibration of, e.g., voltage dependent current order limiting or event triggered reduction of the power order. Because of a continuously changing AC grid environment there will probably come up situations when the available controls and parameters are no longer suitable. And it will be difficult, if not impossible, to keep track of all relevant network changes and to revise accordingly the controls and parameters.

For the new type of HVDC system using self-commutated voltage sourced converters the voltage stability issue is of less concern due to the reactive power supply capability. But also here voltage instability could occur if the reactive power rating would be insufficient. A more dramatic problem presents an unstable transmission angle which can happen when the transmission capacity of the AC grid is too low to transport the ordered DC power. Since at full voltage control the voltage magnitude does not indicate a destabilizing process only per GPS synchronized phase angle measurements could provide information on this situation. However, at sudden events this information comes to late to be used for stabilization. Also in a meshed network is would be difficult to determine those nodes which consistently provide the necessary data.

In view of the above described situations and the restrictions of present stabilizing measures it appears to be necessary that a new method takes into account the dynamics of the destabilizing process in real-time and that it makes use of local measurements only. This holds for classic HVDC as well as for the light type of HVDC.

This paper presents a real-time stabilizer which can either supplement and back-up or replace existing stabilizing controls. Contrary to the established voltage sensitivity factor which is determined off-line the here presented method performs dynamic on-line identification of steady state stability limits and uses directly the results for stabilization. The proposed device consists of an analyzer processing time derivatives of stability relevant quantities and a controller using the analyzer output to control real power such that the system is stabilized at a safe transferrable power level. Simulations on the PSCAD/EMTDV simulator demonstrate that voltage collapse is prevented and stable power transfer ensured with a self-calibrating stability margin. The new method has the capability to improve considerably HVDC system integrity and performance at crucial network conditions.

An international patent application (PCT/EP2010/055076) was filed.

VI. REFERENCES


VII. BIOGRAPHY

Walter Kühn was born in Autenried, Germany. He graduated from the FH Dortmund - University of Applied Sciences, Germany, with a B.Eng. degree and from the RWTH Aachen University, Germany, where he received the Dipl.-Ing. degree in 1974 and the Dr.-Ing. degree in 1980, both in Electrical Engineering. From 1974 to 1975 he pursued special studies in control engineering at Stanford University, USA, using a fellowship awarded by the German National Fellowship Foundation. In 1975 he became assistant professor at the Institute of Electrical Engineering and Automation at the RWTH Aachen University where his research work concentrated on the feasibility of hybrid AC/DC transmission systems, particularly on operational optimization and control and stability of such systems. His following industrial employment was with ABB working in the HVDC Divisions in Germany and Switzerland. He was HVDC systems engineer, head of station engineering and the technical manager of the Blackwater Back-to-Back Converter Station and the Pacific Intertie HVDC Expansion. In 1989 he joined the PTD division of AREVA in Frankfurt, Germany, where he was responsible for the network and line construction business.

In 1994 he was appointed professor at the FH Frankfurt - University of Applied Sciences, Germany. He teaches Power Systems Engineering with emphasis on HVDC transmission systems and International Project Management.