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HVDC System Stability – Analysis, Monitoring and Control in Wide Area Power Systems

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SUMMARY

To a great extent future electric power systems will use HVDC technologies, based on either current sourced or voltage sourced converters (CSC, resp. VSC). Both technologies have their merits and range of applications being connected to technical capabilities, costs and operational properties and performance. Voltage stability is an important issue in classical CSC-based HVDC systems, while voltage stability and angle stability (both transmission angle and rotor angle) are of concern in VSC-HVDC systems. The systems are vulnerable against static instability when the AC connection point at either transmission end becomes weak in a very slow and unobserved manner. These systems may also be subject to transient instability at sudden major changes of grid structure and power flow. The present work intends to provide pertinent information for the development of diagnostic tools for stability assessment and of stabilizing controls relating to HVDC systems.

The proposed approach is to implement online stability assessment (OSA) based on
1. Synchrophasors obtained from WAMS for measurement based assessment,
2. Off-line predictive static and dynamic stability computations from D-2 to near real-time considering uncertainties and the inclusion of detailed HVDC dynamics
3. Online static and dynamic stability computations utilizing continuous power flow (CPF) and fast dynamic simulations using detailed HVDC models

This article proposes developments in necessary concepts and methodologies to support different tasks in point 3 above, focusing on angle and voltage stability where VSC-HVDCs are considered. Such methods can enhance operator tools such as those currently being developed in different European projects ([1], [2]). This paper deals primarily with the computation of the voltage sensitivity factor (VSF) of VSC-HVDC systems and the impact of converter controls and controls limitation on VSF curves and stability margins. Sensitivity curves holding for normal undisturbed operation and for credible (n-1)-contingencies are calculated and from these curves thresholds are determined. The study shows the effect of VSC current limitation on the stability margin. The limitation can be imposed either on the reactive current or on the real current. In both cases the limitation reduces the stability margin.

Transient simulations on the PSCAD/EMTDC simulator are performed with static voltage sources feeding the HVDC converter converters. Comparison of the power dependent voltage and angle curves obtained from these simulations with the static curves obtained from load-flow computations show differences due to control lags. This, however, does not impair the validity of the static curves for normal power ramps and their applicability for undisturbed operation.

By replacing the static voltage sources with rotating synchronous generators it can be shown that suddenly occurring negative steady state margins must not necessarily lead to instability. Immediate DC power reduction can prevent instability. Required are a sufficiently fast response and an adaptive reduction value. It needs to be further investigated whether and how pre-calculated VSF curves from contingency computations can be used for this task.
KEYWORDS

HVDC System stability
Wide Area Power Systems
PMU
WAMS
WACS
Weak AC Grids
Stability Analysis
Voltage Sensitivity Factor
Angle Sensitivity Factor
Stability Margin
Steady State Stability
Transient Stability
Stabilizing Control
I. INTRODUCTION

With the advent of PMUs and their arrangement in WAMS it is natural to look at their applicability in networks containing HVDC and to use voltage and current phasors for the determination of suitable criteria permitting statements on steady state as well as dynamic operation conditions. To provide viable information for the scope of probable failures the mechanisms of transient power balancing and the influence of various HVDC schemes and HVDC control functions have to be fully understood.

The Classic B2B-Blackwater HVDC scheme was the first system in which the voltage sensitivity factor (VSF) was computed and applied in operation [3]. With the VSF approaching infinity the static stability boundary was defined and it was possible to determine from HVDC systems studies the necessary power reduction value when a three phase fault on the 345-kV line with subsequent line opening and only a tap of relative low short circuit power remained connected to the HVDC station. Today the VSF criterion is considered as a candidate for receiving early information on an approaching critical stability through wide area measurements [4, 5, 6]. The present focus of corresponding investigations lies on the IT and communication aspects, and real-time laboratory set-ups are directed towards finding the most suitable algorithm for determining the VSF. There are several approaches for determination of actual VSF-values; however, regarding VSF-thresholds there are different questions open:

- Can a single or only few thresholds cover the entire realm of possible contingencies?
- Can steady state thresholds be defined which provide sufficient transient stability margin for transient electromechanical swings?
- Can immediate DC power reduction provide transient stability if the stability margin becomes negative in case of a contingency?

II. STATIC SYSTEM MODEL AND STABILITY CRITERIA

The graphs of Fig. 2, 3, 4 and 5 were determined for the configuration of Fig. 1 by using a MATLAB code developed for the computation of steady state control characteristics of the HVDC inverter operating on a weak AC grid. The system model comprises Thevenin’s Equivalent and connected to this a controlled VSC converter operating as inverter (INV).

Capacitor banks provide part of the reactive power need of the AC grid to relieve the inverter partly from this duty. From a pure measurement of the AC voltage (Fig. 2) no conclusion can be drawn regarding stability conditions. For different SCR = 1/Xs and different additional AC power injection the voltage curves show different behavior. The solid lines hold for pure HVDC power injection. The dashed lines for HVDC power plus 0.3 p.u. power from another source. Xs = 0.4 p.u. corresponds to SCR = 2.5. For SCR = 2.5 the power can be increased relatively far beyond rated value before instability occurs. Of course, the decline of the AC voltage would prohibit this. Nevertheless, this illustrates the essential difference between classic HVDC and VSC type HVDC. With SCR = 2.5 classic HVDC is already very close to the static stability limit when operating with rated power. From Fig. 2 and 3 the connection between voltage and angle instability can be recognized. Since AC voltage can no longer be controlled via the converter when its reactive current is limited the maximum stable angle is lower than 90 degrees. For the given configuration the VSF is shown in Fig. 4. The horizontal line designates a VSF threshold which when surpassed results in fast declining AC voltage. That is, if the VSF curve could be determined at operation and a model computation would yield the VSF curves, then
there exists a method to prevent steady state voltage instability. It has to be noted that the horizontal differences between the solid curves (CASE 1) and the dashed curves (CASE 2) are less than 0.3 p.u. MW. The reason is that the inverter in order to control the AC terminal voltage has to provide additional reactive power for the grid reactance since the additional real power supplier keeps it reactive power constant – here at zero. This means that in CASE 2 the inverter current limit is reached at lower DC power than in CASE 1. Here the current limit is first imposed on the reactive current part (Fig. 5) and then on the total current.

With sharply decreasing reactive current the AC voltage can no longer be controlled. This example demonstrates that real power increase beyond rated value utilizing the overcurrent capability of 1.05 p.u. kA can only be exerted under consideration of its influence on voltage stability. Conclusion: If overload capability is required this can only safely be accomplished via proper VSC overload rating.

IV. WAMS IN AC GRIDS CONTAINING HVDC SYSTEMS

WAMS Example for Sensitivity Determination

Operational VSF values can be derived from synchrophasors. In [5, 6] a 5-bus system (Fig. 6) was set up on a real-time simulator. The simulator is also used as the computational tool generating the model VSF-curve (Fig. 7) at bus 5, filtered and with the application of a moving average to remove the distortion of the sensitivity by transformer tap-changer action. I.e., the curve of Fig. 7 is one of the curves of Fig. 4. It should be noted that this VSF type differs from \( \frac{dV}{dQ} \) as used in Fig. 4. However, both VSF bear the same information, they indicate that the operating point approaches the stability limit when they are heading towards infinity.

Determination of Key Indicator Voltage Deviation

There are basically two different methods to use PMUs. Method “1” utilizes PMUs to measure voltage and current phasors and computes real and reactive bus powers which in turn are used to determine voltage sensitivities by forming the ratio of voltage samples over the calculated corresponding power values [5, 6]. As long as the power system is in steady state or the changes are sufficiently small the last established VSF value will be kept. Method “2” utilizes PMUs to measure voltage phasors so that the Jacobian matrix can be determined and sensitivities calculated at the current system operating point. Here network topology and equipment data are needed [4, 7].
V. TRANSIENT SIMULATION AND STABILITY CRITERIA

To demonstrate the validity and applicability of the voltage and sensitivity curves as determined with the above static system model a point-to-point VSC type HVDC transmission system (Fig. 8) was set up on the PSCAD/EMTDC simulator. To simulate a weak grid on the inverter side the inductivity is adjusted to 0.8 H. The DC power ramp starts for the stability test at 0.8 p.u.MW (Fig. 9). The power shall ramp up to 1.2 p.u. but at somewhat above 1.1 p.u.MW, shortly after t = 6 s, the maximum available power level is reached. The transmission angle δ is about 32 degrees at the start of the ramp (Fig. 10). This corresponds to the value of about 32 degrees for Xs = 0.6 in Fig. 3.

Fig. 8. HVDC for Transient Simulation

The static AC voltage curves holding for Xs = 0.6 in Fig. 2 are identical to the dynamic voltage curve of Fig. 11 up to about t = 3.75 s when the power ramp starts. After this the transient simulation shows a voltage deviation despite the immediate increase of the PWM control voltage (Fig. 12). This is due to control lags, and it demonstrates here the difference between static and dynamic voltage curves. When the PWM control voltage hits its ceiling of 10 V at about 5.25 s (Fig. 12) then the AC voltage starts to decline due to deteriorating steady state conditions. The further voltage decay up to 6.5 s corresponds to the static decline seen in Fig. 2 for Xs = 0.6. The maximum power at t = 6 s (Fig. 2) corresponds the power limit of about 1.1 p.u. for Xs = 0.6 (Fig. 2). Comparing the transmission angle curves of Fig. 3 and Fig. 10 over the displayed power proves that the system data, particularly the short circuit power ratios, are equal. The VSF, in our case VSF = 0.062, can be quantified as a threshold. If exceeded the DC power should immediately be adapted to the new stable power level.

Fig. 9. Power
Fig. 10. Transmission Angle

For converters forming the receiving or sending end of radial AC lines the DC power reduction has an immediate stabilizing effect since the AC power flowing over the AC lines is instantaneously reduced. This picture changes when rotating synchronous machinery, resp. converters equipped with virtual inertia, are included. This is done in the next chapter.

VI. TRANSIENT SIMULATION UNDER INCLUSION OF INERTIA

In Fig. 13 the converter operates as inverter. The actual HVDC power remains constant at line opening (t = 4 s) because the DC power is controlled (Fig. 14). But both the local generator power (Fig. 15) and the AC power transfer (Fig. 16) step down. Through continuing DC power increase the total AC line power moves along the line’s PQ-circle. When the transmission angle reaches 90 degrees (marked in Fig. 17) DC power reduction is triggered in an attempt to prevent instability. But this
reduction is immediately compensated by the local mechanical synchronous generator (MSG) through its kinetic energy, so that the transmission angle cannot be stabilized. The power transferred to the onshore AC grid (Fig. 16) will accordingly decline and the DC power will increasingly flow to the local synchronous machines while the system’s operating point moves along the unstable part of the AC line’s PQ-circle towards the angle of 180 degrees with subsequent inter-area oscillations (Fig. 15 and 16). It should be noted that in future systems containing HVDC systems equipped with virtual inertia behave like MSG.

The question now is: what is the latest moment that DC power reduction would stabilize the system? By computing the angle sensitivity curves (ASF) (Fig. 19) for the normal case “A” (Xs = 0.6) and for the contingency case “B” (Xs = 1 at open AC line “a”) it can be concluded that a threshold of 0.75 provides a certain distance to the stability limit yielding some time to determine the signal for DC power reduction. The time needed depends certainly on the size of the rotating masses. Here the ASF is taken as stability criterion holding also for continuous voltage control through the generator. At continuous voltage control the VSF is zero. If the power is already, e.g. 1 p.u. MW, then dropping off the AC line seems to create immediate instability because 1 p.u.MW lies above the boundary of CASE “B”. But this steady state contemplation does not consider the fact that in reality initially the transmission angle (Fig. 17 at t = 4 s) cannot change because of the angle stiffness of the receiving and sending end AC voltages. The actual initial response to the line trip is that the real power flowing over the AC line is reduced (Fig. 16). This provides the chance to reduce the DC power early enough before the transmission angle exceeds the 90 degrees boundary. That is, if the DC power would be reduced just when the breaker opens – this could be done when a breaker trip signal would be available – then no dynamics would be excited. It remains to be investigated whether information for sufficiently fast DC power order reduction can be obtained from security computations.

VII. NETWORK CONTROL SYSTEM

Today network control systems have higher optimization and decision software (HOD) implemented to support the operator. Security computations are an important part of HOD. Expanding the power grid with HVDC transmission systems requires their inclusion in contingency analysis, monitoring and operator support. HVDC can be included in the existing system executing static and dynamic security computations. Two basic approaches can be thought of: concept (1) and concept (2) (Fig. 20).
Concept (2) means a) to exchange grid topology, switching state, parameters and actual values of voltages magnitudes and phase angles or alternatively b) to provide static equivalents (e.g. Thevenin’s Equivalent) and dynamic equivalents (including other aggregated controls behavior). Both methods shall generate output permitting to monitor the effect of contingencies. With a) a more complete picture on the effect of contingencies can be obtained than with b). Then not only the DC power but also loads at other busses and generator related limits can be investigated regarding their influence on system stability.

VIII. CONCLUSIONS AND FURTHER WORK

VSF and ASF thresholds can be determined from sensitivity curves obtained from the continuation power flow method under inclusion of controls, control limits, current limits and voltage control ceilings. Synchrophasors permit online determination of actual sensitivities. For sensitivities exceeding thresholds alarms can be issued and annunciated. For static conditions thresholds can be defined by contemplation of the VSF and ASF curves. The thresholds need to be put just at the point where the VSF and ASF curves show sharp changes versus real power. Results obtained so far hold for static conditions. From already performed dynamic computations it is concluded that transient stability can possibly be ensured when DC power reduction is executed early enough after the occurrence of a contingency. Further studies are needed to confirm this and to determine the latest permissible time when the DC power should be reduced. The implementation of virtual inertia for the reason of frequency stability delays the response for DC power steps. This aspect has also to be considered for the allocation of virtual inertia. The present investigations were performed for point-to-point HVDC systems without parallel AC paths. While also for embedded systems sensitivities and thresholds can be determined it remains open whether an increase or decrease of DC power would be necessary to stabilize the system [8]. Next steps in the ongoing study will also take up this issue.

REFERENCES