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

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***Abstract*—Power system stability is under special focus when using HVDC systems for bulk power transmission in the European Electric Power Network. This work concentrates on the important issue of voltage and transmission angle stability when using VSC based HVDC systems. The particular PQ-characteristics of VSC converters with limited overcurrent capability are included in a continuous load flow algorithm developed for a steady state model of the HVDC system. The model computations furnish sensitivity to be compared with actual sensitivities determined from synchrophasors. Transient simulations using the PSCAD/EMTDC simulator demonstrate the intricate task to keep the system stable at larger disturbances. Concepts are discussed to develop and implement the necessary tools for stability analysis and monitoring in a network control system.**

I. Introduction

The transformation of electric power systems towards a carbon-free system depending and relying on offshore wind power (North Sea), and also increasingly on hydro power from remote water reservoirs (Norway) [1], requires the addition of new High-Voltage transmission systems to the existing AC grid [2]. To a great extent these will use High-Voltage-Direct-Current Technologies, based on either current sourced converters (CSC) or voltage sourced converters (VSC). These installations add design and operational requirements to the hitherto exiting systems. Important requirements refer to stability and reliability. Both are connected to each other. Only a stable system can be reliable. These requirements can be quantified in terms of outage rates and maximum permissible interruption and down time. To meet these requirements both reliable main power equipment and IT-systems for supervising, operational analysis, monitoring and control are needed.

The technology for these tasks is in principle available, but the new main equipment technologies, in particular power electronic plants for energy transmission systems, have to be fully understood regarding their interaction with conventional AC equipment and AC transmission systems. Before dealing with the network control technology first the stability relevant characteristics of HVDC systems need to be looked at. Important points to be clarified are: By which methods and means can steady state and transient stability be quantified, analyzed, monitored and used for stabilization?

II. Background

An important area in network control systems are security computations. Besides taking into account AC equipment and subsystem outages now HVDC and FACTS controls need to be included in the power system models used for such computations. This is somewhat different from computations for power systems containing only conventional equipment where, e.g., turbine controls need not be considered for the given time frame of transient swings. The reason for this is the fast controllability of static power infeed as compared to the large inertia of synchronous machines. The inertia prevents a fast rescheduling or shut down of power injection or power consumption at power unbalances. In contrast HVDC power flow can be manipulated in accordance with transient stability requirements. E.g., at short circuits and subsequent breaker opening yielding a remaining power system of less transmission capacity the HVDC power can immediately be reduced to adapt to these new conditions.

The power values providing stability for specific fault cases can be obtained from system studies in the detailed engineering phase. Results will provide information on relevant breakers to be observed and corresponding power reduction levels. This approach of computing viable power levels for possible system faults can be applied in advance for available grid structures. Later grid changes have to be reconsidered in new fault studies leading to new power levels and breaker observation schemes. In light of the total forthcoming grid restructuring scope this appears to be a very hopeless approach. 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 wells as transient stability conditions. To provide viable information for the entire 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. This is a quite intricate task the complexity of which is increased through the fact that there exist two different types of HVDC systems having different properties being relevant for the transient performance of AC/DC systems.

The Classic B2B-Blackwater HVDC scheme was the first system in which the voltage sensitivity factor (VSF) was used for the determination of maximum power levels in dependency on the strength of an AC system. 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 (from 200 MW down to 60 MW) when a three phase fault on the 345-kV line with subsequent line opening occurred at BA switching station in Albuquerque, N.M., and only a tap of relative low short circuit power remained connected to the HVDC station.

Today the VSF criterion is considered as a suitable candidate for receiving early information on an approaching critical stability situation by continuously determining online values. The present focus of corresponding investigations lies on IT and communication aspects, and real-time laboratory set-ups are directed towards finding the most suitable algorithm for the determination of the VSF criterion [ ] and of thresholds which indicate closeness of instability if surpassed. This approach appears to be clear regarding the determination of actual VSF-values, however, regarding VSF-thresholds there are different questions open:

- Can a single or only a few thresholds cover the entire realm of possible contingencies?
- Can steady state threshold be defined which provide sufficient transient stability margin for transient electromechanical swings?

Before starting the work a commencing remark regarding steady state and transient stability appears appropriate: steady state stability refers to the property of the power system to assume an operating point and to maintain it at small disturbances. Temporarily the controlled quantities like real power and voltage will deviate from their set points, but return to this point when PI-controllers are used, even when the disturbance is still existent. With P-controllers only or slow I-parts there will be deviations, however the control loop is stable, that is, oscillations will have died out when controller phase and gain are properly calibrated. The time it takes that the stable final value is attained and the degree of damping depend on the location of the dominant poles in the root-locus map. Which poles can be shifted at all can be investigated through application of state space descriptions and determination of the controllability of the dynamic system [ ].

Transient stability refers to electromechanical stability with real rotating masses or virtual rotating masses involved in the transition from one initial steady state to the next steady state operating point. Load-frequency controls need a certain amount of inertia. Converters can participate fully in load-frequency controls including the provision of instantaneous power when this feature is implemented in controls. When, however, doing this, they lose at the same time the property to follow instantaneously a power order step which can also be relevant for realizing stabilizing controls. VSC HVDC can provide both inertia and primary load-frequency controls while Classic CSC HVDC can participate in load-frequency controls but not provide own inertia.

III. Static System Model and Stability Criteria

For VSC type HVDC systems with limited voltage control capability there exist power-voltage-curves and power-angle-curves with maximum available power at the nose of these curves. This is similar to Classic HVDC sytsems. 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. Per unit calculations generalize the applicability of the resulting diagrams since they hold for any power rating.

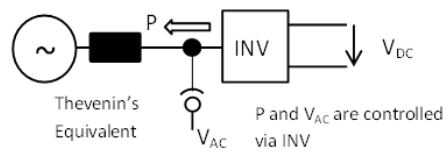

Fig. 1. Basic Configuration Studied

The system model comprises Thevenin's Equivalent and connected to this a VSC converter controlling real power flow to the grid as well as AC terminal voltage. The Jacobian of the NR algorithm used for the continuation power flow method is augmented by the differentials dP/dV_{AC}, $dP/d\delta$, dQ/dV_{AC} and $dQ/d\delta$ for the controlled inverter where δ is the transmission angle. 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 the stability situation.

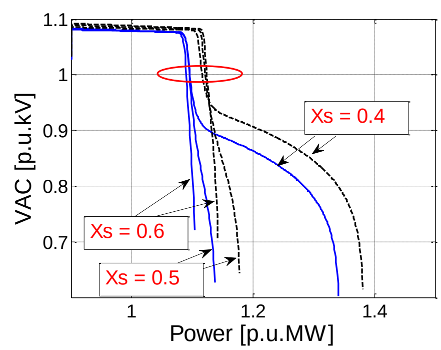

Fig. 2. AC Voltage

For different SCR (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.

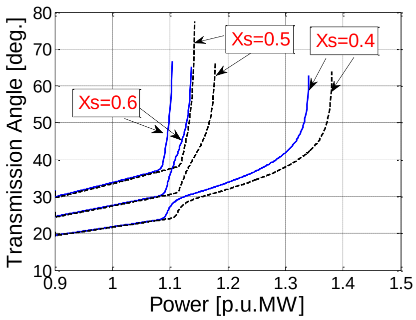

Fig. 3. Transmission Angle

The change of the AC voltage in dependency on the real power change provides information on the relative system stability. In the continuation power flow method the entries of the Jacobian are used to form the VSF:

$$\mathrm{VSF} = \frac{dV_{AC}}{dQ} = \frac{1}{J_{21} - J_{22} \times J_{11} / J_{12}}$$

For the given configuration the VSF is shown in Fig. 4. The red 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 would exist a method to prevent steady state voltage instability.

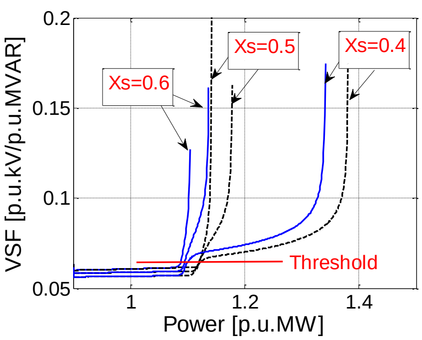

Fig. 4. Voltage Sensitivity Factor

The reactive power of the additional generator is controlled to zero. If the additional generation would inject or draw reactive power in dependency on its own real power supply as well as on the AC voltage level then the voltage sensitivity factor would be impacted.

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. Thus in CASE 2 the AC terminal voltage starts to decline at lower DC power than in CASE 1.

The voltage control capability depends on the size of the capacitor banks and the inverter's reactive power supply capability. This supply capability is exhausted when the VSC inverter reaches its current limit which is here assumed to be 1.05 p.u. of nominal current. It is interesting to note that despite declining AC voltage real power increase is still possible. Here the current limit is imposed on the reactive current part (Fig. 5) so that real current can still grow.

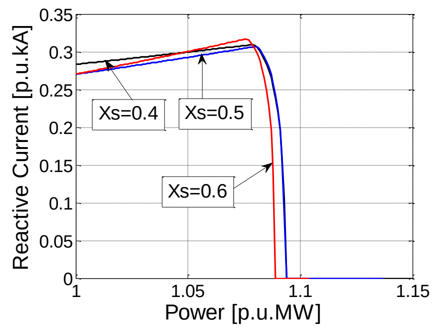

Fig. 5. Reactive Current

With sharply decreasing reactive current the AC voltage can no longer be controlled to acceptable values. However in practice, before voltage collapse occurs, undervoltage protection would have sensed low voltage conditions and the power increase would be stopped. For a short circuit power ratio of 2.5 p.u. this method would certainly work since the static stability boundary is still sufficiently far away, but for SCR = 2 and especially SCR = 1.66 this is not acceptable because small system changes would suffice to shift the operating point over the crest of the corresponding PV-curve. This example demonstrates that real power increase beyond rated value utilizing the overcurrent capability of 1.05 p.u. 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 Sensitvity Determination

Operational VSF values can be derived from synchrophasors. Comparing them with thresholds determined from a system model permits to annunciate alarms and even to control automatically the power to safe values. In [ ] a 5-bus system (Fig. 6) was set up on a real-time simulator. The simulator can be thought of as a replica of the real power system providing the measured VSF for an actually adopted operating point.

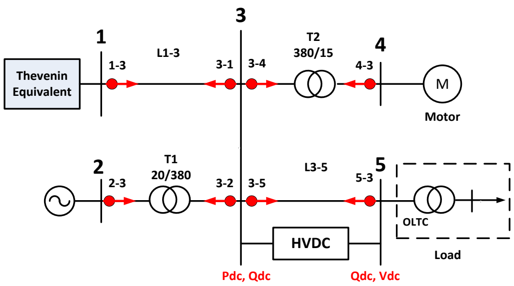

Fig. 6. Test Circuit

Here 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.

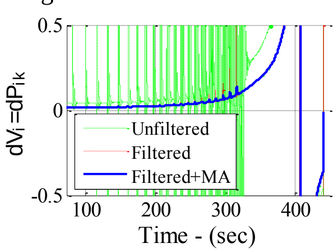

Fig. 7. VSF at Bus 5

I.e., the curve of Fig. 7 is one of the curves of Fig. 3. It should be noted that this VSF type differs from $VSF|_{P=const} = dV/dQ$ as used in Fig. 3. However, both VSF bear the same information, they indicate that the operating point approaches the stability limit when they are heading towards infinity. To compare sensitivities with thresholds by magnitude as before requires, of course, the same type, i.e. either dV/dQ or dV/dP.

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 at a current system operating point [ ]. No network topology and data and no time consuming iterations as in the NR-algorithm are needed. 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 [ ].

Method "1" needs changes of P and Q to obtain voltage sensitivities at the latest time sample "i", over a rolling window of pre-processed and filtered data:

$$VSF(i) = \frac{\Delta V(i)}{\Delta P(i)} = \frac{V(i) - V(i-1)}{P(i) - P(i-1)}$$

As long as the power system is in steady state or the changes are sufficiently small the last established VSF value will be kept.

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.

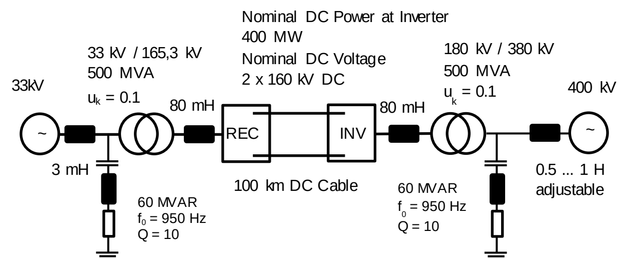

Fig. 8. Transient Simulation of HVDC Cable Transmission

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 deg. at the start of the ramp (Fig. 10).

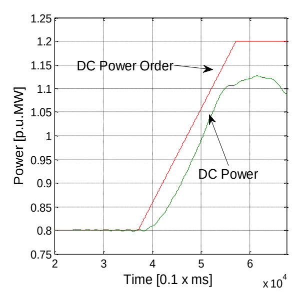

Fig. 9. Power

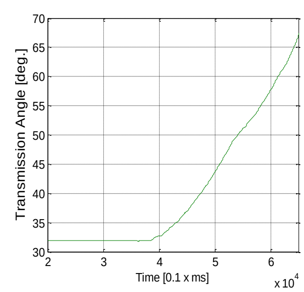

Fig. 10. Transmission Angle

This value can also be calculated:

$$\delta = \arcsin \frac{320MW \times 0.8H \times 314s^{-1}}{380kV \times 400kV} = 32 \text{ deg}.$$

The short circuit power at 0.8 H is:

$$\frac{400kV \times 380kV}{0.8H \times 314s^{-1}} = 637MVA$$

Hence, the SCR at nominal power of 400 MW is:

$$SCR = \frac{637MVA}{400MW} = 1.59$$

This corresponds to the SCR = 1.67 (= 1/Xs = 1/0.6 p.u.) used in the static computations of chapter III. The static 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).

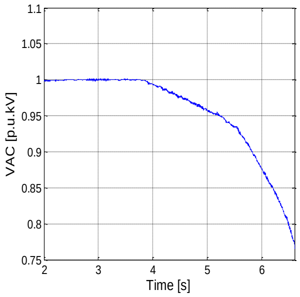

Fig. 11. AC Voltage

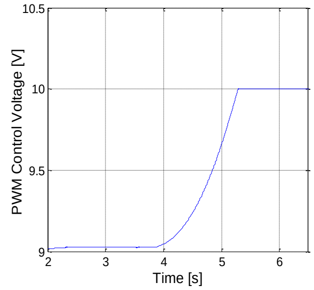

Fig. 12. PWM Control Voltage

This is due to control lags, and it demonstrates here the difference between static and dynamic voltage curves. This is not yet a collapsing voltage attributable to steady state instability. Only when the PWM control voltage hits its ceiling of 10 V at about 5.25 s (Fig. 12) then the voltage starts to decline due to deteriorating steady state conditions. The further voltage decline occurring here over time up to 6.5 s corresponds to the static decline seen in Fig. 2 for Xs = 0.6. The power crest is somewhat above 1.1 p.u.MW (Fig. 9). This result is comparable to that of Fig. 2 where the power limit is also about 1.1 p.u. for Xs = 0.6. And 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.

An essential result is that surpassing a VSF threshold determined from static computations can indicate an approaching instability without performing the transient simulation although there are differences in the voltage curve. The VSF, in our case VSF = 0.062, can be quantified as a threshold which should not be exceeded in operation. If exceeded the DC power should immediately be adapted to the new stable power level.

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

With synchronous machines being connected at the point of common connection (PCC) - bus B in Fig. 13 – fast DC power reduction will be compensated by power drawn from the rotating masses or power delivered to the rotating masses depending on whether the converter at the PCC operates as rectifier or as inverter.

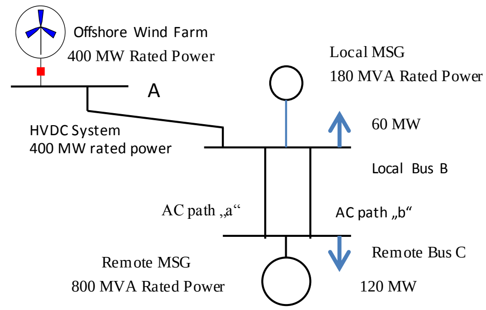

Fig. 13. Configuration for Transient Simulation

In Fig. 13 the converter operates as inverter feeding power over both the AC lines to the remote system. Both the local and the remote mechanical synchronous generator (MSG) are equipped with primary load-frequency control. The inertia constant is 3.2 s and the generator regulation is 4 % for each generator. The remote generator executes also integral frequency control.

The actual HVDC power remains constant at line opening (t = 4 s) because the DC power is controlled (Fig. 14).

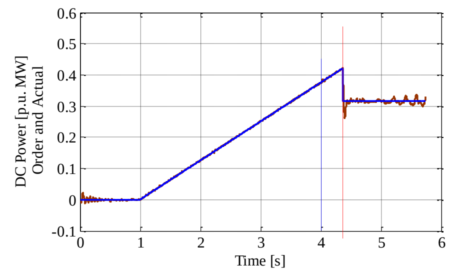

Fig. 14. DC Power

The local MSG power (Fig. 15) and, connected to this, the total AC line power (Fig. 16) step down at t = 4 s.

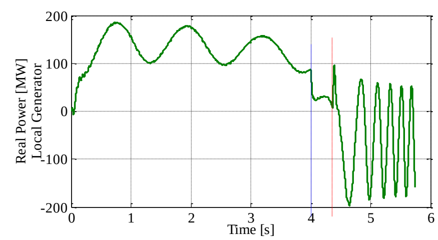

Fig. 15. Local Generator Power

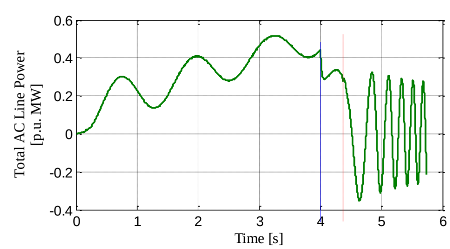

Fig. 16. Power Transfer over AC Line

Subsequent to this, the output of the local MSG will increase driven by its mechanical torque, and the DC power is still ramped up (Fig. 14) since it is assumed that no information on line opening is available at the converter station.

Through continuing DC power increase the total AC line power moves along the PQ-circle towards the crest of the transmission angle-versus-power curve. When the angle reaches 90 degrees (marked in Fig. 17) DC power reduction is triggered by a special signal derived from PQ-measurements to prevent de-synchronization.

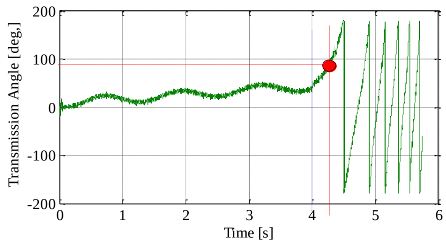

Fig. 17. Transmission Angle

But this reduction is immediately compensated by the MSG providing power from its kinetic energy so that the transmission angle, which in the mean-time has surpassed the maximum stable value of 90 degrees, will not be stabilized, i.e. there is no return to below 90 degrees. 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^o with subsequent inter-area oscillations as can be seen in Fig. 16.

Apparently the DC power reduction was too late to stabilize the system. The question then is: what is the latest moment that reduction of the DC power would stabilize the system and how can this moment be determined? Can continuous tracking of a sensitivity factor – either VSF or ASF - and its comparison with thresholds serve this purpose?

To find an answer again the steady characteristics are computed. The short circuit power with both lines in service is 307 MVA = (380 kV)² / 470 Ohm. At DC power of 152 MW (at t = 4 s: 0.38 p.u.MW x 400 MW = 152 MW) the SCR is 1.67. The transmission angle δ is then δ = sin^{-1}((1/SCR). For the static p.u. calculations the power of 1 p.u.MW is the short circuit power divided by the SCR. That is, the short circuit power is then 1.67. Also this yields, of course, 36.78 degree for the transmission angle (Fig. 18). When one AC line is switched off at t = 4 s no steady state equilibrium is possible at the already established obtained power level of 1 p.u.MW (Fig. 18). By computing the ASF curves (Fig. 19) for the normal case "A" and for the contingency case "B" (open AC line "a") it can be concluded that a threshold of 0.75 provides a certain distance to the stability limit provided the power is below the value where the threshold intercepts the ASF curves.

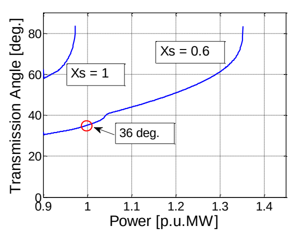

Fig. 18. Transmission Angle

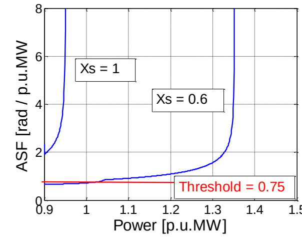

Fig. 19. ASF

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 receiving and sending end AC voltages.

The maximum stable transmission angle for continuously controlled voltage is 90 degrees which is also shown in Fig. 18. Here the ASF (Fig. 19) is taken as stability criterion since at continuous integral voltage control the VSF is zero. For proportional control there exist a VSF the magnitude of which depends on the actual configuration, data and control gain. Further work is needed to find out which type of sensitivity is most appropriate for stability analysis. This is certainly a question of which sensitivity type is more robust at changes of configuration and operating state.

The actual initial response to the line trip is that the real power flowing over the AC line changes (Fig. 16). This provides the chance to reduce the DC power early enough before the transmission angle exceeds the 90 deg. 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. Here the DC power was reduced too late and the transmission angle surpasses the maximum stable angle of 90 degrees. Both the transient (Fig. 16) and the steady state computations (Fig. 18) show the change from the starting angle value of about 35 degrees at nominal conditions towards the stability boundary of 90 degrees when the AC line "a" is switched off. Present work investigates the use of actual VSF and ASF determined in an ongoing manner from PSCAD transient simulation data. This is similar to the real-time simulation providing Fig. 7. DC power reduction would then be triggered as soon as thresholds obtained from static computations are surpassed.

VII. Network Control System

Inclusion of HVDC Model for Contingency Computations

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) as depicted in Fig. 20.

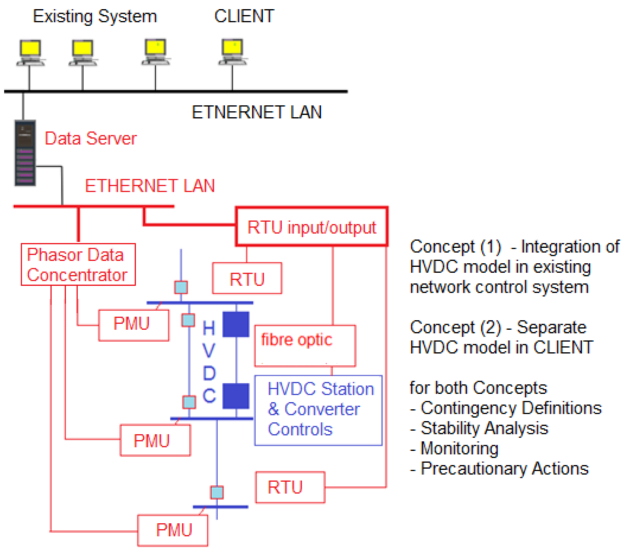

Fig. 20. Concepts for Allocation of Stability Assessment Functions

Concept (1) means to integrate HVDC system equations and control characteristics as well as stability analysis code into the existing load flow program and dynamic simulation tools. 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.

Resilient Power Control of HVDC System

If despite of all smart tools implemented the obtained situational awareness is insufficient or cannot be regarded as failsafe or if the (n-1) criterion cannot be maintained under all circumstances resilient power control should be considered for implementation in converter controls [ ].

It prevents that the HVDC operating point will move to the unstable branch of the PV-curve. In addition the system operator will be informed on the occurrence of an operation at the stability limit by receiving an alarm signal.

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 increases 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 at an unforeseen contingency. Further studies are needed to confirm this and to determine the latest permissible time when the DC power should be reduced.

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. Next steps in the ongoing study will also take up this issue.

Referring to both the questions asked in chapter III

- Can a single or only a few thresholds cover the entire realm of possible contingencies? VSF and ASF thresholds vary with configurations and operating states. Therefore, they have to be determined individually.
- Can steady state threshold be defined which provide sufficient transient stability margin for contingencies? From the present studies this is not yet clear. Further work is needed.

In addition following questions came up in the course of the study which could partly be answered but opened also new fields for further investigations:

- Can the fast controllability of an HVDC system serve the purpose to operate in steady state closer to the steady state stability limit than an AC transmission system while meeting transient stability requirements? Study results show that immediate power order reduction at an AC line trip would prevent transient swings. This suggests that the stability margin can be reduced as compared to AC infeed.
- And if so, in this respect, are there differences between CSC and VSC type HVDC? Yes, for inverter operation. Then CSC HVDC can possibly surpass the stability limit and commutation failures will occur leading to power collapse. For rectifier

operating on a weak AC grid both converter types permit to reduce the DC power instantaneously

- Must the (n-1) power system design criterion also be applied for HVDC systems or does the fast power control property permit to deviate from this generally specified requirement? Fast rescheduling capability of both types of HVDC and overload capability of Classic HVDC systems suggest that this requirement has to be rethought.
- Does a point-to-point DC transmission system differ from an embedded DC transmission system with respect to steady state margins ensuring transient stability? How does power sharing between parallel AC/DC paths influence stability margins? Are there preferences for putting more load on AC than on DC in the steady state and how do these preferences change when large disturbances occur? Shall DC be increased or decreased depending on either rectifier or inverter operation? This needs further investigations.
- Can energy storage devices increase the continuous transmission capacity by minimizing necessary stability margins for probable contingencies? Preliminary results provide a positive answer. However, further studies are needed.
- Which means for damping inter-area swings do the classic and the VSC type HVDC systems provide? How can the most efficient stabilizing signal be determined? Both types provide the capability to damp electromechanical swings. Basically the stabilizing signal can be derived from frequency or power. Whether an eigenvalue can be influenced and to what degree can be studied by determining the controllability vector for the state space description of the parallel power transmission paths. Already available results show the viability of this approach.
- What is the influence of different converter control methods – non-synchronizing versus synchronizing for VSC type HVDC? While Classic HVDC systems cannot provide synchronizing power without already existing rotating masses of synchronous generators VSC type HVDC can provide such synchronizing power on their own. VSC type HVDC can operate completely without such rotating masses. If, however, virtual inertia is implemented, the response to a power order step will be delayed. This needs to be further investigated for systems where such fast response is necessary or desired.

IX. References

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X. Biographies

Walter Kuehn (M'1997) studied Electrical Engineering at FH Dortmund (1965-1968), RWTH Aachen University (1969-1974) and Stanford University/CA (1974-1975). He was assistant professor at RWTH Aachen from 1975 to 1980. From FH Dortmund he received the B.Eng. degree (1969), from RWTH Aachen the Dipl.-Ing. (1974) and the Dr.-Ing. degrees (1980). His industrial employment was with ABB in the HVDC Systems Division. He was overall technical project manager for several executed projects, amongst them Blackwater Back-to-Back Converter Station and Pacific Intertie HVDC Expansion. His last industrial position was with AREVA managing the network and line construction business. Presently he is professor at the FH FFM University of Applied Sciences in Frankfurt, Germany, teaching Systems Engineering and Project Management of Electric Power Systems with emphasis on HVDC transmission technologies.

Luigi Vanfretti (Student Member '03, M'10) became an Assistant Professor at the Electric Power Systems Department at KTH Royal Institute of Technology, Sweden, in 2010 and was conferred the Swedish title of "Docent" in 2012. He received the EE Degree from *Universidad de San Carlos de Guatemala* in June 2005, and was a visiting researcher at The University of Glasgow, Scotland, also in 2005. He received his M.Sc. and Ph.D. in 2007 and 2009, respectively, both in Electric Power Engineering from Rensselaer Polytechnic Institute, Troy, NY, USA. For his research and teaching work towards his Ph.D. he was awarded the *Charles M. Close Award* from Rensselaer Polytechnic Institute. His main research interest is on the development of PMU data-based applications. He has served, since 2009, in the IEEE PES PSDP Working Group on Power System Dynamic Measurements, where he is now Vice-Chair. In addition, since 2009, he has served as Vice-Chair of the IEEE PES CAMS Task Force on Open Source. He is an evangelist of Free/*Libre* and Open Source Software.

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