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Test and onsite experience with System Recovery Ancillary Service functions implemented in a VSC-HVDC converter

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SUMMARY

HVDC systems based on the Voltage Sourced Converter (VSC) technology using Forced Commutated Converters (FCC) can provide a variety of network stabilizing functions. A unique functionality of VSC-HVDC systems is the ability to feed an islanded network in which the VSC-HVDC is the only power source or is in charge for the network voltage and frequency control.

A VSC prepared to provide System Recovery Ancillary Services (SRAS) features the control functions described in this document. Care has to be taken that the system will be able not only to operate into a passive network but also to allow operation in parallel with other generation units and/or into the integrated network.

During the recent commissioning of a HVDC PLUS system various on-site tests under network restoration conditions have been successfully performed. It was proven that the HVDC was able to provide sufficient support of network voltage and frequency. Operation in SRAS-Mode when connected to the integrated network as well as change-over to normal "P/Q-Mode" has been performed.

On-site observations have been compared with factory acceptance test (FAT) results. The concept of generic network modelling [1] for FAT was verified by the good correlation between on-site and FAT results.

KEYWORDS

Black Start, Black Out, SRAS, VSC, FCC, HVDC

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1 SRAS Control Functions

1.1 Black Start Capability

Prerequisite for the capability of an HVDC system to provide SRAS is the ability to "black start" the HVDC system. In this case the term "black start" is used to describe the energisation of a converter station from its d.c. side. The whole converter station is put into operation without closing its a.c. side circuit breaker. Any auxiliary power must be drawn from internal sources (e.g. diesel generators). A detailed description of a black start sequence can be found in [1].

1.2 U/f-Mode versus P/Q-Mode

There are two principal control modes for a VSC converter which differ with respect to the hierarchy of the nested closed loop controls. This results in different dynamic characteristics of voltage and frequency versus active and reactive power.

The P/Q-mode is typically used when the VSC converter is operating into an active network. In this case the converter voltage is controlled by the inner control loop to establish desired active and reactive currents into the network. Reference values for these currents are calculated by the next level control loop to achieve the desired active and reactive power. Finally, an optional outer control loop can be used to stabilize network voltage and frequency by modulating the power reference values accordingly. This control mode has superior characteristics in terms of fault ride through (FRT) capability and power dispatch as a converter controlled in P/Q-Mode allows fast control of its a.c. currents.

In contrast thereto the U/f-Mode has to be used when the VSC converter is operating into a passive network. As no other sources are present in the network, the converter has to impose voltage and frequency on the network. Currents will be a result of this voltage and the network impedance. The reference value for the imposed voltage and frequency are determined by the output of slope based control loops creating the classic relation between the active power and frequency as well as between reactive power and voltage. A converter in U/f-Mode is therefore also able to operate into a network which comprises other voltage and/or frequency controlling devices including the connection to the integrated network.

1.3 Voltage Control

In U/f-Mode a VSC could be ordered to provide a constant terminal voltage regardless of the reactive power load. However, this is in contrast to regular network voltage control which utilizes slope controls for each reactive source to coordinate and dispatch reactive power supply. The VSC is therefore equipped with a corresponding "primary" voltage control which creates a voltage deviation from a given reference voltage as a function of the actual reactive converter load and the given slope. The dynamics of this primary control are not related to the converter characteristics but emulate the typical voltage regulation time of the network. The slope can be chosen to match the dispatch requirements. By changing the reactive power set point, the operator has the ability to bring back network voltage to the desired value (manual secondary voltage control).

1.4 Frequency Control

Network frequency is used to coordinate the active power contribution of all connected sources especially in the case of a source being subject to a power limitation. Moreover, system protection schemes (e.g. load shedding, network splitting, etc.) are often based on the monitored network frequency. The VSC is therefore equipped with a "primary" frequency control which creates a frequency deviation from a given reference value as a function of the actual active converter load and a given slope. The dynamics of this primary control are not related to the converter characteristics but emulate the typical frequency regulation time of the network. The slope can be chosen to match the dispatch needs. By changing the active power set point, the operator has the ability to bring back network frequency to the desired value (manual secondary frequency control).

2 Off-Site Tests

During off-site testing for a 1000 MW HVDC PLUS system various topologies for SRAS conditions have been successfully tested using a generic test environment as described in [1]. These tests included:

- energisation of unloaded transformers up to 1100 MVA
- energisation of unloaded lines up to an individual length of 350 km
- sequential energisation of a passive network (incl. transformers and lines)
- collective energisation of a passive network (incl. transformers and lines)
- restoration of residential loads (up to 200MW block size)
- restoration of industrial loads (motor loads up to 30 MW)
- synchronizing additional generator units to the islanded network
- re-synchronizing of the islanded network to the integrated network
- single and multi-phase faults in the islanded network

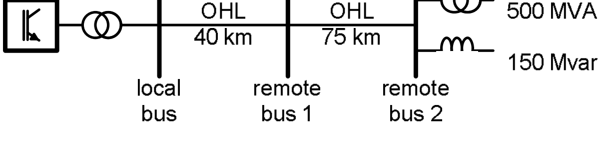
Limits for temporary voltage and frequency excursions as well as general stability requirements have been used as acceptance criteria for the simulated test results.

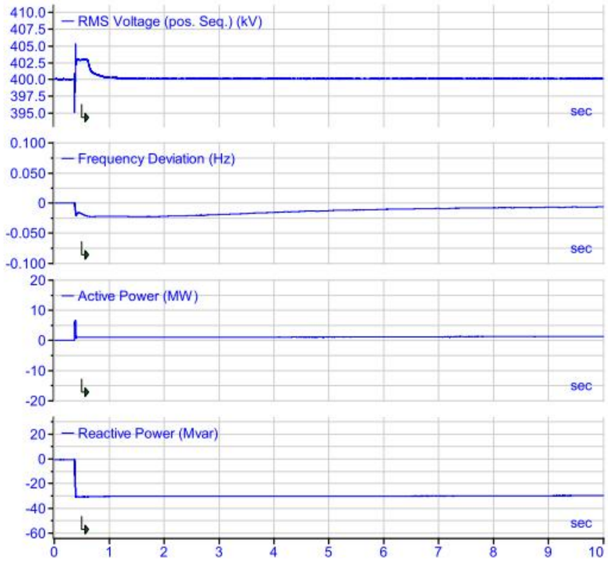
3 On-Site Test Results

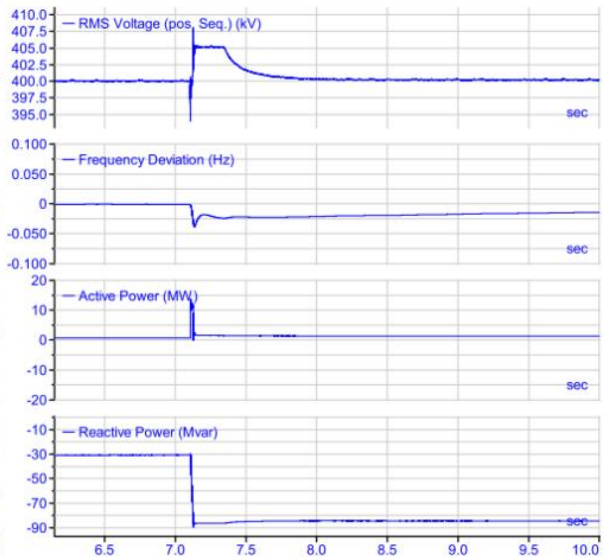
During the recent commissioning of a HVDC PLUS system the opportunity was offered to perform extensive SRAS tests. Transmission lines, transformers and a shunt reactor could be isolated from the integrated 400kV network to be reconfigured as a passive test network. Tests on network restoration have been performed separately at both ends of the HVDC link. Various aspects of possible network restoration features could be investigated.

3.1 Sequential Network Energisation

As described in [1] the sequential network restauration is a "top down" process starting from an energized bus bar by sequentially energizing lines, transformers, etc. Starting from the local bus fed by the HVDC, a first 40km overhead line section was energized providing voltage to a remote bus. In a second step a 75km line was connected thus energizing a second bus. At this second bus a 150 Mvar shunt reactor was additionally put into operation. Finally an unloaded 500MVA transformer was energized at the second remote bus. The test sequence was performed with the primary voltage control set to a 400 kV target value with a slope of 300 Mvar/kV. Primary frequency control was set to a target value of 50 Hz and a slope of 250 MW/Hz. Between switching events the operator adapted the set-point values for active and reactive power to establish desired values for voltage and frequency (manually secondary control).



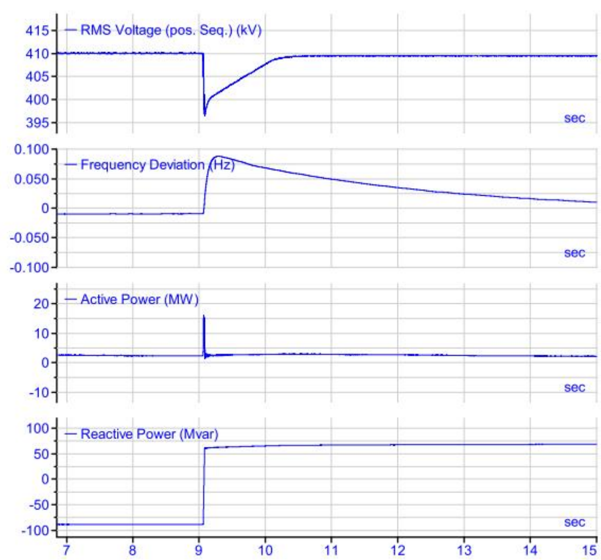


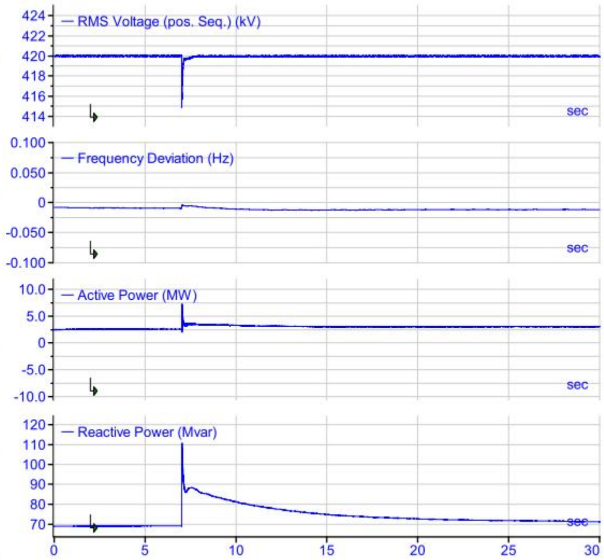


Line Energisation (40km)

Line Energisation (75km)

When line sections were energized, the capacitive loading of the converter changed instantaneously according to the line capacitance. The corresponding voltage drop was primarily caused by the voltage drop across the HVDC transformer. Primary control brought the instantaneous voltage deviation back to the steady state deviation according the 300Mvar/kV slope. A small temporary frequency deviation, caused by the converter controls reacting upon the disturbance, was compensated by primary frequency controls.





Shunt Reactor Energisation (150Mvar)

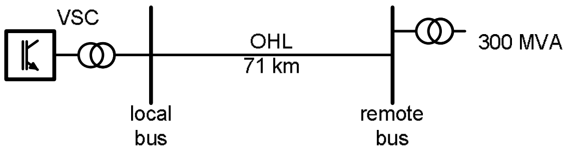
Transformer Energisation (500MVA)

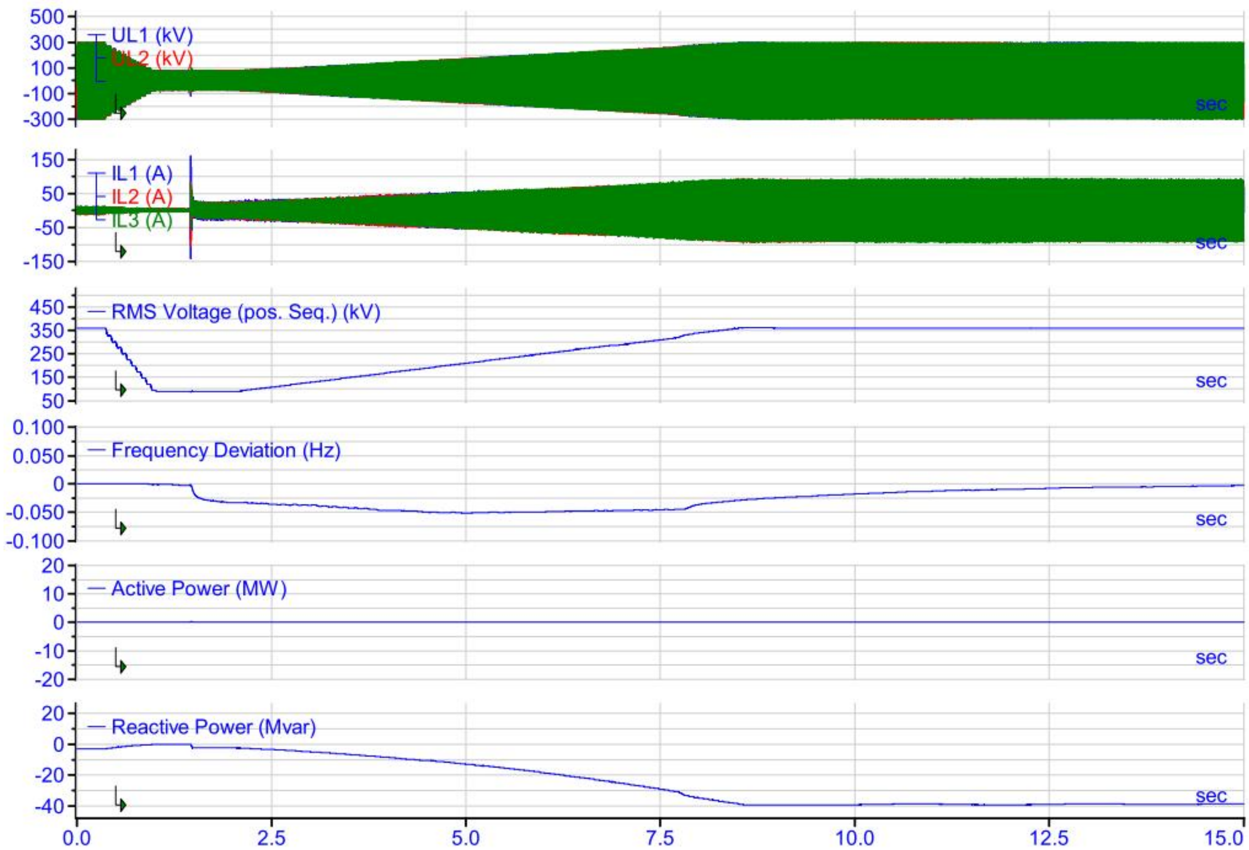
When the shunt reactor was energized it over-compensates the two a.c. lines and consequentially the converter loading changed from approximately -80 Mvar (ind.) to +70 Mvar (cap.). Again, the corresponding instantaneous voltage and frequency deviations were compensated by primary controls. Lastly the energisation of the unloaded transformer resulted in inrush effect creating a temporary reactive load.

All switching events where supported by the HVDC without excessive transient voltage or frequency deviations and the new steady state load flow was achieved in a well damped and controlled manner.

3.2 Collective Network Energisation

If network restoration is started from an isolated generation unit ("bottom up") the first group of network elements (excluding loads) can be energized collectively. In this case the network is configured off-line and subsequently the generation unit is connected to the network energizing it with a defined voltage ramp [1]. This so called "soft start" was tested by interconnecting the HVDC bus bar via a 71 km long 400 kV transmission line with a remote bus. To this bus an unloaded 300 MVA transformer was connected. The test was performed with the primary voltage control set to a 360 kV target value with a slope of 240 Mvar/kV. Primary frequency control was set to a target value of 50 Hz and a slope of 750 MW/Hz. The set-point values for active and reactive power (i.e. for manual secondary voltage control) were set to 0 MW and 0 Mvar respectively.



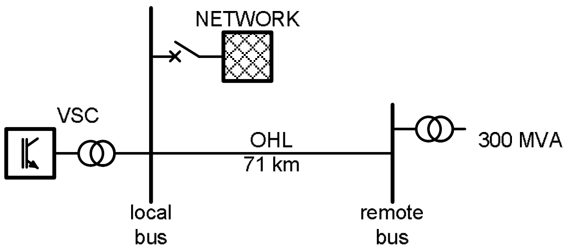


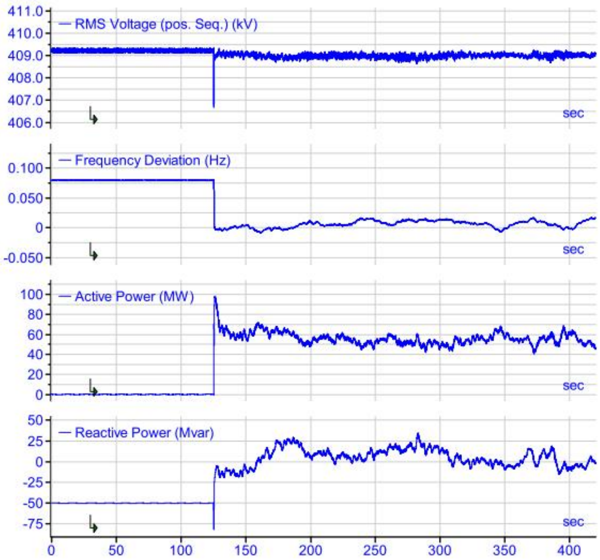
Energisation of a 300MVA Transformer via 71 km of transmission Line

Before initiating the soft start sequence, the HVDC was operating behind its open breaker generating the desired reduced network voltage of 360 kV (UL). Upon receiving the command for manual closure of the breaker, as a first step the HVDC reduced its output voltage to approximately 75 kV. Once the breaker was then physically closed, it thus resulted in limited inrush currents. Immediately after closing the breaker the HVDC started ramping up network voltage. No disturbances or oscillations where monitored during the "soft start" process.

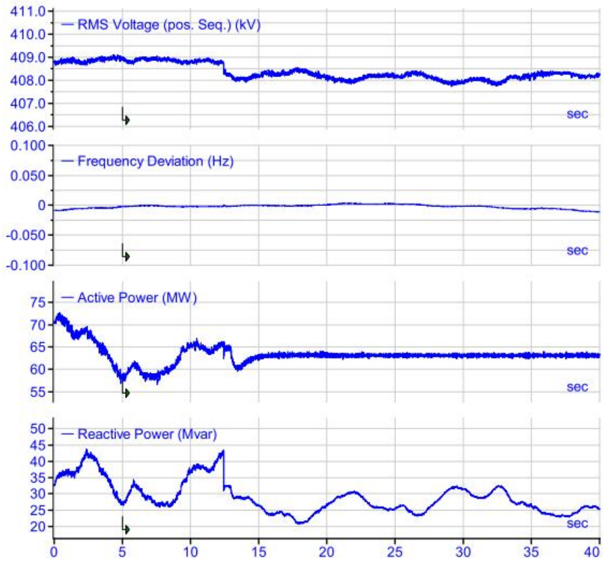
3.3 Re-Synchronization to Integrated Network

As a final step in network restoration, the islanded network fed by the HVDC has to be re-connected to the integrated network. This "re-synchronization" requires an interconnecting breaker position equipped with the necessary synch-check functionality. Dispatch in the islanded network has to establish sufficient deviations in voltage and frequency across this breaker to enable operation of the synch-check relay. A first re-synchronization test was performed as a continuation of the above described soft-start test. The HVDC was feeding one of the two local bus bars while the other bus bar was still part of the integrated network. The bus coupling breaker was used to re-synchronize the isolated network. Primary voltage control was set to a 409 kV target value with a slope of 240 Mvar/kV, primary frequency control to a target value of 50.08 Hz and a slope of 750 MW/Hz. The set-point values for active and reactive power (i.e. for manually secondary control) were set to 0 MW and 0 Mvar respectively. After successful re-synchronization with the integrated network, the HVDC was purposely kept in U/f-Mode for an additional 45 minutes. During this time several switching events in the vicinity of the local bus were performed (e.g. line energisation and load switching on the interconnected 225 kV level). Finally the HVDC was manually switched back to P/Q-Mode with voltage stabilization control (U-Mode) enabled.





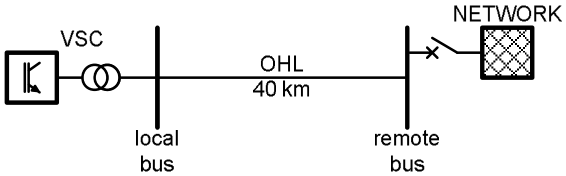
Re-Synchronization with Network
(Δf = +80mHz)

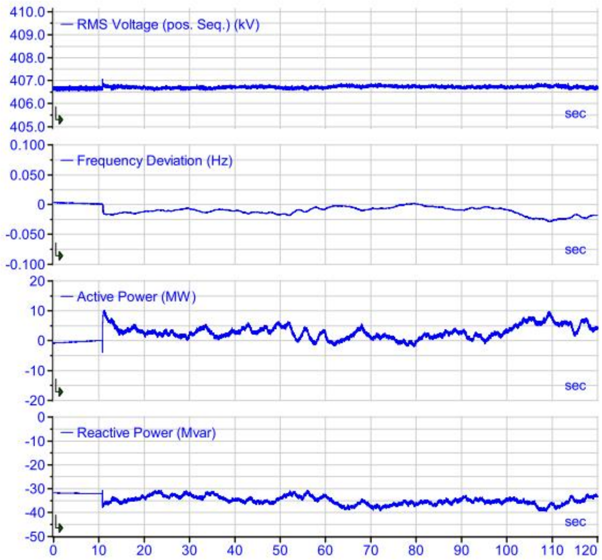


Switching to P/Q-Mode (disabled SRAS)
(RPC = U-Mode)

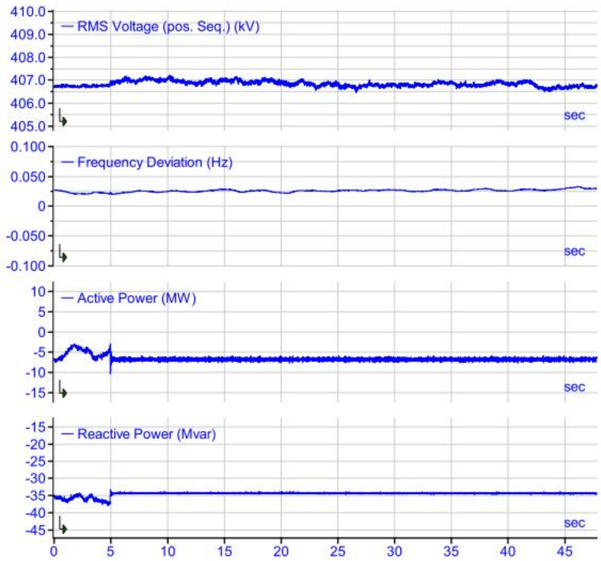
For re-synchronization a frequency deviation across the open synchronizing breaker of approximately 80 mHz was achieved by HVDC dispatch. When the breaker was closed the HVDC immediately took part in the primary voltage and frequency control of the integrated network. When SRAS mode was disabled for change back to P/Q-Mode, the actual active power output of the HVDC at that point was adopted as (constant) active power set-point. For the reactive output it can be observed that the change-over to the somewhat slower stabilization control (U-Mode) is performed without mentionable disturbances. U-Mode control was initialized - via the actual reactive power output of the converter - to a target voltage approximately 409.5 kV. However, due to a smaller slope (20Mvar/kV) a marginal drop in the average network voltage was observed.

A second re-synchronization test was performed at the other end of the link. For this test the synchronizing breaker was located at a remote bus 40 km from the HVDC. The VSC was feeding the interconnecting line with primary voltage control set to a 406 kV target value and a slope of 50 Mvar/kV. The target value of primary frequency control was 50 Hz with a slope of 250 MW/Hz. The reference values for active and reactive power (for manual secondary control) were set to 0 MW and 0 Mvar respectively. After re-synchronization the HVDC was operated in U/f-Mode for approximately an additional 40 minutes. During this time the power dispatch in the integrated network changed in a way that the power direction via the HVDC link was reversed. Finally the HVDC was switched back manually to P/Q-Mode with constant reactive power control (Q-Mode).





Re-Synchronization with Network
(Δf = -20mHz)



Switching to P/Q-Mode (disabled SRAS)
(RPC = Q-Mode)

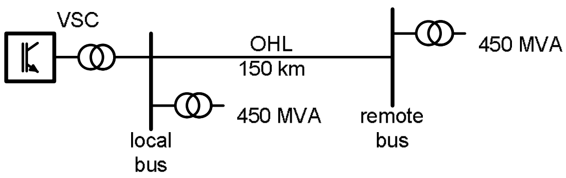
Before closing of the synchronizing breaker the integrated network showed a small under-frequency condition of approximately -20 mHz. This deviation was used for synch-check relaying. After 40 minutes of SRAS operation into the integrated network this mode was disabled and the active and reactive output of the VSC was adopted as respective set-points (in P/Q-Mode) as expected. No disturbances or oscillation were observed during the whole test.

4 Comparison with Real Time Simulation Results

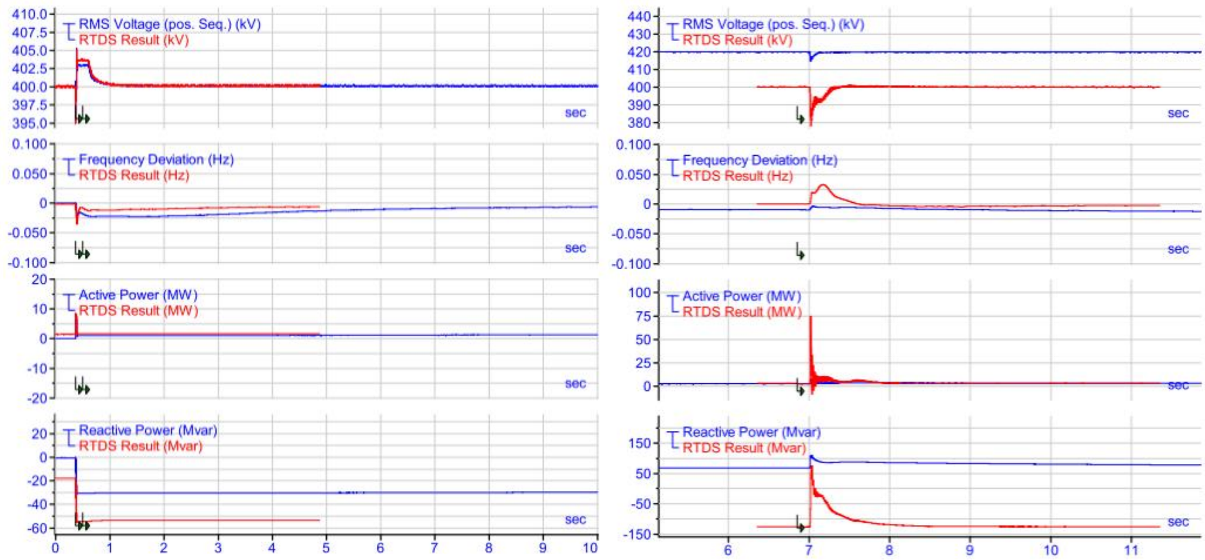
As described in [1], a generic network model was used for real time digital simulations (RTDS) performed as part of factory acceptance testing (FAT). Test cases for FAT have not been selected as to achieve best equivalency with on-site conditions, but to determine the capability of the HVDC under worst case SRAS conditions. To show correlation as well as intended deviations between FAT results and the on-site recordings, the following selected cases are presented.

During commissioning a 40 km transmission line was connected to the local bus. A similar switching event was simulated during the FAT when a 50 km transmission line was energized from the local HVDC bus. In both cases identical settings for primary and secondary controls had been selected.

For the case of the energisation of a remote transformer the FAT result has been selected which shows energisation of a 450 MVA transformer at a bus 150 km from the VSC bus.



Moreover, there was a second 450 MVA transformer already connected to the local bus before the switching event and the transmission line was not compensated by a shunt reactor at the remote bus. Consequently the load flow conditions prior and after the energisation are not identical. For FAT the transformer was modelled with maximum residual flux and energisation took place at the worst point-on-wave related to this residual flux.



Line Energisation Transformer Energisation

Line energisation recordings show very good correlation to each other although there was a reactive pre-loading of approximately 20 Mvar (ind.) in case of the FAT.

In regards to the transformer energisation two deviations between the on-site recording and the FAT result can be observed. Besides the fact that different target values for the primary voltage control had been selected, the main difference can be observed in the magnitude and duration of the temporary reactive load presented by the energized FAT transformer. The magnitude of the load and consequently the degree of voltage and frequency disturbance is caused by the transformer inrush currents that have been maximized by selecting worst case remnant flux and point-on-wave conditions for FAT. In addition, the second transformer connected to the local bus is extending the de-saturation time by "transferred saturation", an effect also known as "sympathetic inrush". The possibility to select these worst case conditions for FAT is one of the benefits of off-site testing.

5 Conclusion

On-site testing for various topologies during network restoration have been performed. With the exception of connecting loads and/or generating units, the two strategies of sequential and collective network energisation have been successfully tested. Re-synchronization with the integrated network, U/f-Mode operation into the integrated network as well as switch-over to P/Q-Mode could be verified. In no case the HVDC caused adverse disturbances or oscillation. On-site observations have been compared with factory acceptance test results. The concept of generic network modelling [1] for FAT is thus verified by the good correlation between on-site and FAT results.

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