Dynamic Performance of VSC and LCC HVDC Converters in Parallel Operation

R. Hibberts-Caswell, L. Oprea

Abstract- **This paper considers an existing Back-to-Back HVDC system with two LCC converter modules which is planned to be extended to increase the power transfer capability. The third converter module will operate in parallel with the two existing modules. The weakness of the AC networks indicated that a solution using VSC technology may be favorable. The main purpose of the paper is to investigate the performance of the VSC technology in parallel operation with LCC technology. A comprehensive EMT model of the system has been developed using the PSCAD simulation tool. This model includes all three HVDC Back-to-Back converters and the HVAC network on both sides. The system response during and following AC faults is presented. The results indicate a benefit by dynamic voltage support through application of the VSC technolog**y.

***Keywords*: Voltage Source Converter, Line Commutated Converter, PSCAD model, three-phase faults, voltage recovery.**

I. INTRODUCTION

THE development of the transmission systems is subject to manifold uncertainties. Therefore, in certain cases existing installations should be extended after some years of operation. This is the case under investigation, where the capacity of an existing HVDC Back-to-Back station with two LCC converter modules [1] should be extended. The simplified single line diagram of the configuration under study is indicated in Fig. 1. The HVDC Back-to-Back station connects two different synchronous areas, with one side at 500 kV voltage level and 400 kV voltage level at the other side. The short circuit level especially at 400 kV side is relatively low and to achieve good operational performance of the LCC HVDC Back-to-Back modules, three synchronous converters were installed at the same time as the LCC HVDC Back-to-Back modules.

II. SHORT CIRCUIT LEVELS AND ESCR EVALUATION

A common parameter used to indicate the electrical strength or weakness of an AC/DC interconnection is known as the Effective Short Circuit Ratio (ESCR). It is defined as the ratio of the fault MVA at the converter AC bus and the nominal dc power rating of the HVDC link, taking into account the effect of the shunt reactive compensation at the converter AC bus. Mathematically, the ESCR is defined as:

$$ESCR = \frac{S_F - Q_C}{P_d} \qquad (1)$$

where S_F is the fault MVA at the converter AC bus, Qc is the shunt capacitive compensation (MVAr) at the converter AC bus, and P_d is the nominal DC power (MW) of the HVDC link.

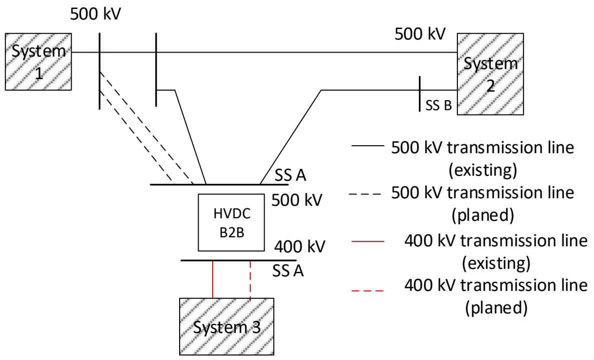

Fig. 1. Simplified diagram of the HVDC Back-to-Back converter station and the adjacent 500 kV and 400 kV systems (existing and proposed developments)

The international standards [2], [3] have made a classification of the requirements for the AC system in respect to the value of ESCR. If the reactive power consumption of the HVDC converter is assumed to be about 50% of the nominal dc power of the HVDC link and the HVDC converter is fully compensated, then the systems can be described as:

-	High ESCR system:	ESCR > 2.5
-	Low ESCR system:	1.5 < ESCR < 2.5
-	Very low ESCR system:	ESCR < 1.5

On System 3 side, the system had a very low ESCR. Without any reinforcement of the receiving AC network at the inverter side of the back-to-back connection, the weakness of the system would lead to high dynamic overvoltages and to high voltage change in case of switching the AC filter banks. Therefore, the decision has been taken that for the LCC HVDC Back-to-Back connection to operate properly in various system configurations, 3 x 60 MVAr synchronous

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condensers to be installed at the inverter side.

Based on the configuration in Fig. 1 the ESCR has been calculated, considering that the 3rd module of the HVDC Back-to-Back would be of LCC type. The calculations indicate a value for ECSR of 1.9, revealing that the structural weakness of the AC System 3 is still present. In order to cater to this aspect an additional synchronous condenser would be required to enable stable operation of a third LCC module. As an alternative technical solution, the installation of a third HVDC module using VSC technology has been selected [4]. In the 500 kV network, the System 2 part especially, there is a lack of reactive power and non-optimal voltage recovery after certain faults. Using VSC technology it is not expected that additional synchronous condensers would be required.

III. MODEL DESCRIPTION

There is limited operational experience of HVDC installations which include both LCC and VSC converters [5]. For performance investigations of the new HVDC module using VSC technology and the operation in parallel with the existing modules in LCC technology, a comprehensive model has been developed using PSCAD software. Fig. 2 presents the overall single line diagram of the HVDC Back-to-Back station.

The models of the AC systems on both sides were developed using existing load flow and transient stability (rms) models in PSS®E software. The translation from PSS®E into PSCAD was done using E-Tran software. Substation SS A was retained as a detailed model along with outgoing transmission lines to Systems 1, 2 and 3.

The high voltage (500 kV) transmission network within System 1 was modelled in detail up to a large generator station which is electrically close to SS A. For this nearby generator, the dynamic models of the machines and their controllers were imported into the PSCAD model. Network equivalents were automatically calculated for the remainder of the network not included in the detailed representation.

System 3 was modelled in detail up to 2 busses back from the converter station with the remaining parts of the network replaced by network equivalents. The HVDC modules were substituted by E-Tran during the import with LCC and VSC models contained in PSCAD substitution library files.

For the existing HVDC modules, a very detailed model of the control systems was used, representing accurately the relevant functionality and dynamic performance of the existing control systems. The detailed LCC HVDC Back-to-Back model includes the following equipment:

- 2 x 350 MW LCC HVDC converters
- converter transformers
- DC side smoothing reactors
- AC Filters
- detailed control and protection (representative of the installed control and protection system in terms of functionality and parameters, tuned for weak system operation)
- synchronous condensers
- Power Oscillation Damping (POD) control designed to modify power order with parameters tuned to original network at time of installation

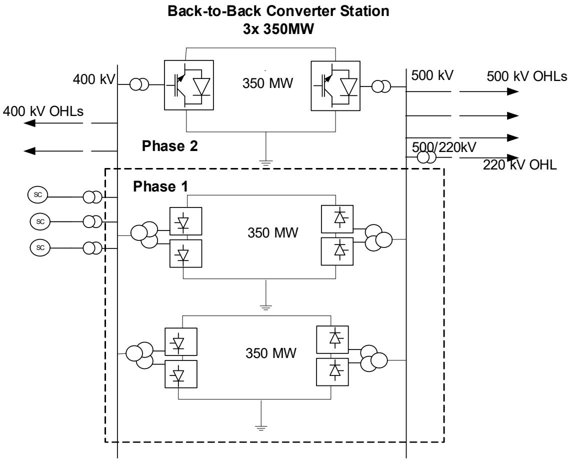

Fig. 2. Overall single line diagram of the existing and planed HVDC modules in the HVDC Back-to-Back station

For the new VSC module [6], a generic model for the converter and its controls was implemented (see Fig. 3 for an overview of one 'side' of the converter) including:

- 1 x 350 MW VSC HVDC converter (modular multilevel converter, 75 levels per valve)
- converter transformer, including saturation
- DC side smoothing reactor
- generic controls, based on decoupled d-q current control with MMC balancing/switching control

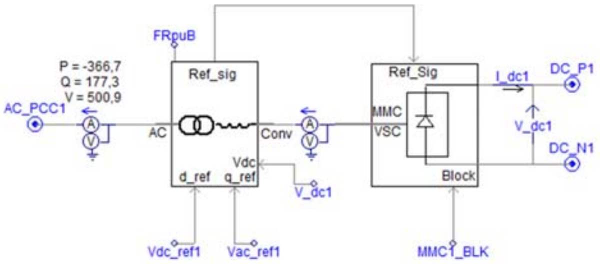

Fig. 3. Overview of VSC converter PSCAD model

The simulations documented in this paper were carried out for one load flow case only, with all three modules operating at full active power export from Systems 1/2 to System 3. This corresponds to a total active power export of approximately 1050 MW from the 500 kV side of SS A towards the 400 kV side of SS A. In total, 410 MVAr of capacitive harmonic filter banks were in service on the rectifier side and 340 MVAr on the inverter side. At the inverter side, two synchronous condensers were in service.

IV. OBSERVATIONS DURING MODEL DEVELOPMENT WITH IMPACT ON ENGINEERING DESIGN

During development of the model, design considerations were identified which will be carried forward into the engineering design phase. The selection of parameters such as DC voltage, transformer winding voltages and transformer ratings for the VSC generic model were initially verified for steady-state and dynamic performance with a stand-alone model of the VSC and Thevenin voltage source representations of the AC network with no LCC model included. After integration of the generic VSC model with the detailed LCC model and AC network representation it became apparent that although the steady-state operating points could be reached, the fault ride through performance was unsatisfactory. The root cause was a loss of controllability due to the phase arm voltage orders exceeding the voltage that could be realized by switching of sub-modules. In addition to adjustment of some control parameters, it was necessary to modify the basic design of the VSC by adjusting the transformer ratio and some other main component data. It is therefore recommended to verify the dynamic performance of the VSC together with the LCC by EMT simulation at the start of the engineering design phase, prior to procurement of the main components.

A relatively high level of AC voltage distortion was observed which must be quantified and considered in the design of the VSC. It was necessary to adjust the control system of the generic VSC model for robust operation with distorted AC voltages and currents. It is recommended that in the upcoming engineering design phase, harmonic interactions between the VSC and LCC should be investigated to ensure there is no overloading of components, that performance criteria (e.g. total harmonic distortion) can be fulfilled and that there are no high-frequency interactions which could lead to control instability.

V. CASE STUDIES

The following cases were selected to investigate the impact of dynamic voltage support using VSC technology for severe (i.e. 0% residual voltage) and remote fault cases:

- **Case 1:** 3 Phase, 100 ms solid Fault at 500 kV (rectifier) side of SS A
- **Case 2:** 3 Phase, 250 ms solid Fault in 220 kV network connected close to SS A
- **Case 3:** 3 Phase, 100 ms solid Fault at 400 kV (inverter) side of SS A

Dynamic simulations were carried out using PSCAD V4.2.1 since the model of the existing LCC system includes user definitions and pre-compiled libraries which could not be converted to newer versions of PSCAD without substantial modelling effort. Each case was carried out without (a) and with (b) the dynamic voltage support of the VSC enabled by setting the limit of q-axis (i.e. reactive) current to 0.75pu and 0 respectively.

The signals Qrec/Qinv relate to the net reactive power at the AC Point of Common Coupling (PCC) at the rectifier and inverter station respectively, including reactive power consumed by the converters, compensation provided by harmonic filters and, at the inverter side only, the synchronous condensers. In all plots, a positive value of P represents active power flowing into the HVDC system, a positive value of Q represents inductive operation.

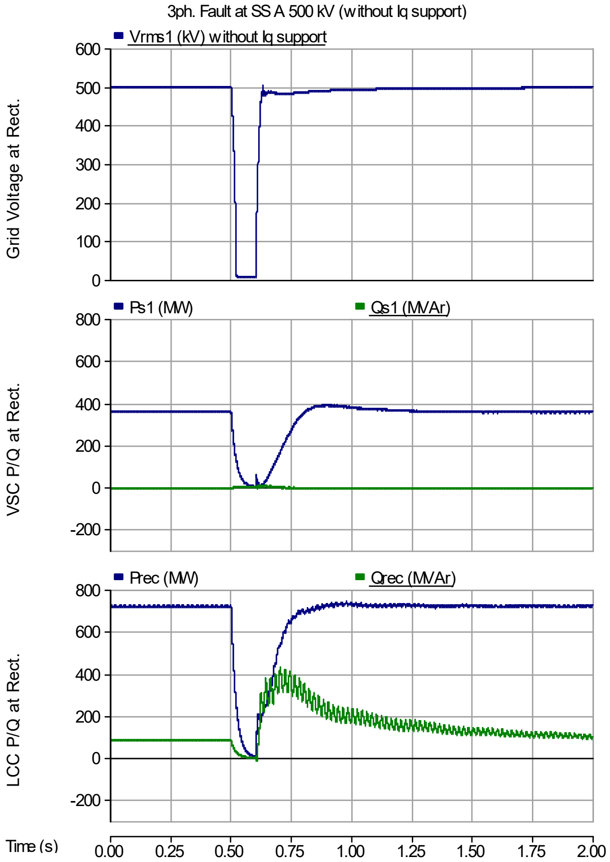

Fig. 4. Case 1a: 3 Phase, 100 ms solid Fault at 500 kV (rectifier) side of SS A without VSC dynamic voltage support

For Case 1a (without dynamic voltage support), the AC network voltages and active/reactive power flows at the interface between the Back-to-Back (rectifier side) and the rectifier side AC network are shown in Fig. 4. The LCC draws a significant amount of net reactive power during fault recovery which results in a relatively slow AC voltage recovery. Although the filters remained connected during and after the fault, they are effectively a fixed impedance and therefore the reactive power provided by the filters is dependent on the square of the AC voltage which results in a further depression of the AC voltage in this relatively weak network.

The simulation results for the same event (Case 1b) with dynamic voltage support by the VSC are shown in Fig. 5. The VSC control strategy used in the generic model is to reduce the d- and q-axis current references to zero during severe disturbances. After fault clearance, the current limits are ramped up, in this case conservatively, such that a recovery to 90% of the pre-fault active power (rectifier) occurs within around 180 ms.

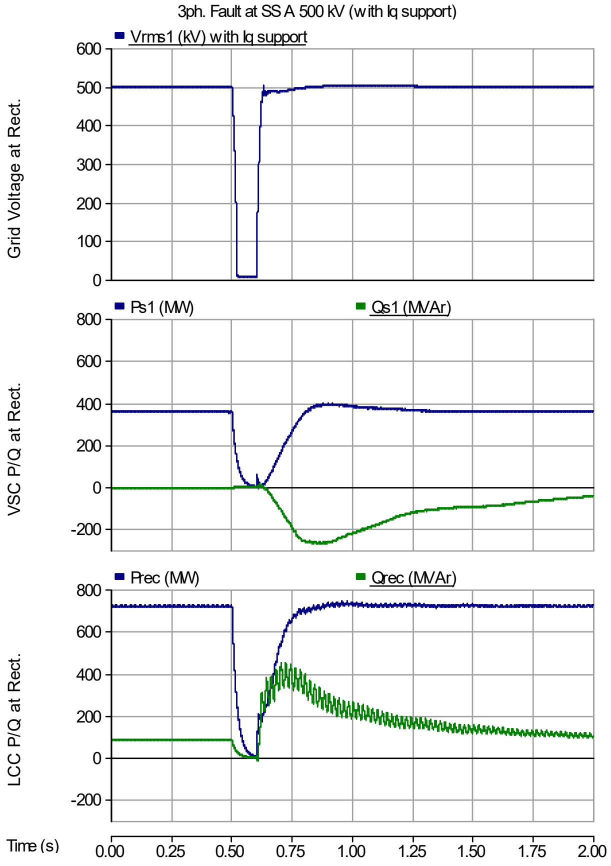

Fig. 5. Case 1b: 3 Phase, 100 ms solid Fault at 500 kV (rectifier) side of SS A with VSC dynamic voltage support

The VSC provides continuous dynamic AC voltage control, compensating the increased net reactive power consumption of the LCC and accelerating the voltage recovery. The overall effect on voltage recovery, with and without dynamic voltage support from the VSC, is shown in Fig. 6. The AC voltage recovery is accelerated significantly by the action of the VSC.

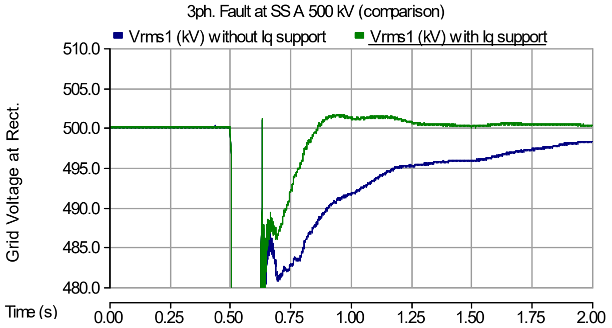

Fig. 6. Comparison of Cases 1a and 1b, 3 Phase, 100 ms solid Fault at 500 kV (rectifier) side of SS A without and with VSC dynamic voltage support

Case 2 was selected to investigate whether the VSC could minimize disruption to the LCC for remote faults by providing dynamic voltage support. The fault location was on the 220 kV side of the 500 / 220 kV transformer located at SS A. Dynamic simulation results with and without dynamic voltage support are shown in Fig. 7, Fig. 8 and Fig. 9 respectively.

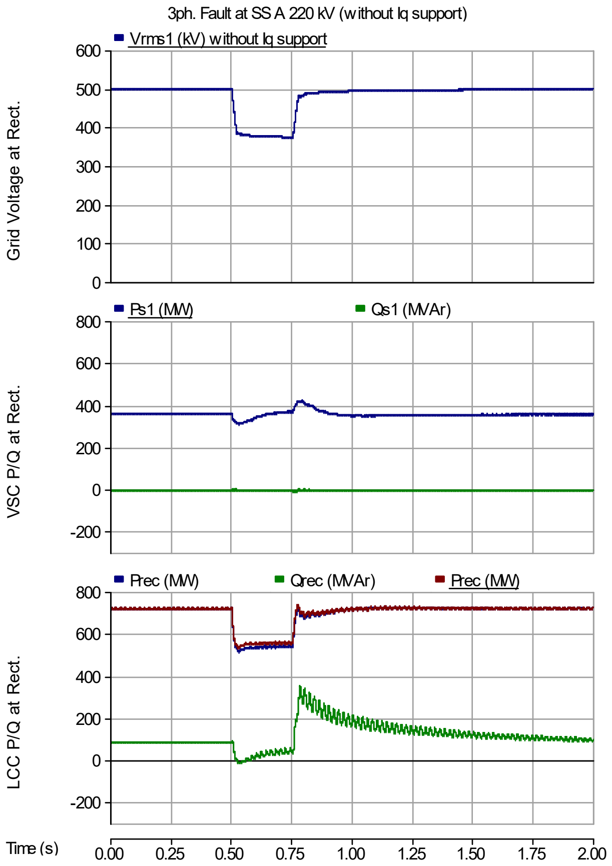

Fig. 7. Case 2a: 3 Phase, 250 ms Fault in 220 kV network of SS A without VSC dynamic voltage support

Unlike in Case 1, the voltage disturbance is not severe enough to trigger the under-voltage strategy of the VSC. During the fault, the DC voltage of the LCC reduces as a result of the AC voltage dip. The control action of the LCC reduces the firing angle to the minimum value of 5 degrees, which is not sufficient to maintain the DC voltage to 1 pu.

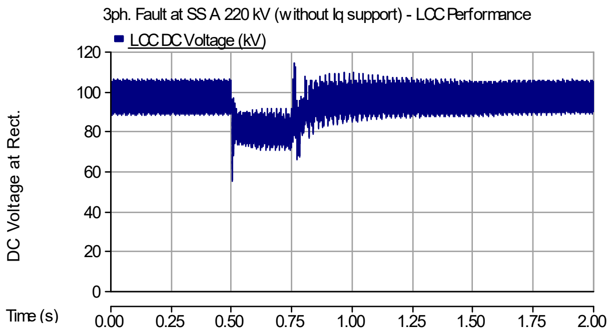

Fig. 8. Case 2a: 3 Phase, 250 ms Fault in 220 kV network of SS A without VSC dynamic voltage support, DC Voltage of LCC

In Case 2b, during the fault, reactive current is injected to support the AC network voltage. The effect of voltage support is shown in Fig. 10. The AC voltage disturbance is reduced by around 10 kV which also results in less disturbance (around 20 MW less) to active power flow through the LCC. In this case, the performance improvement is relatively minor, however, there may be other remote fault scenarios where a moderate amount of dynamic reactive power support from the VSC would reduce the likelihood of commutation faults, particularly for faults on the inverter station side.

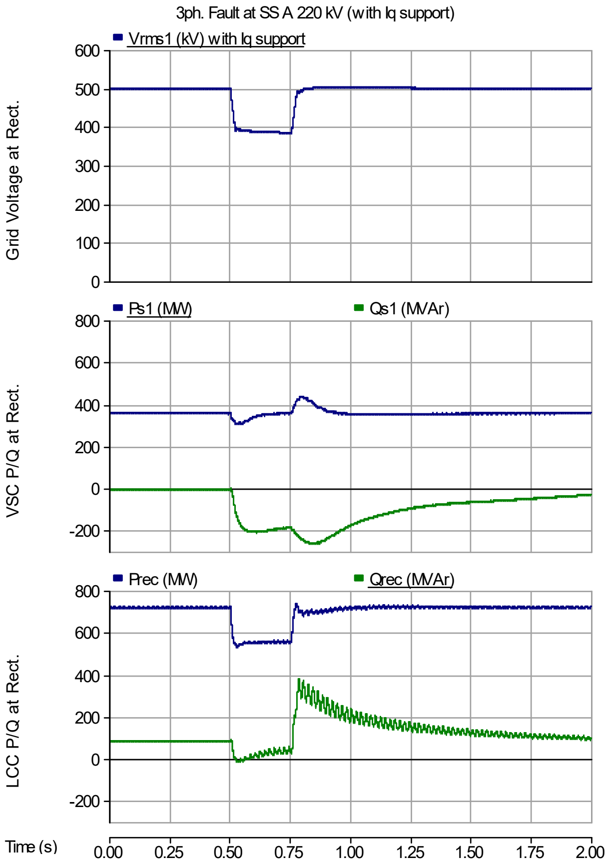

Fig. 9. Case 2b: 3 Phase, 250 ms Fault in 220 kV network of SS A with VSC dynamic voltage support

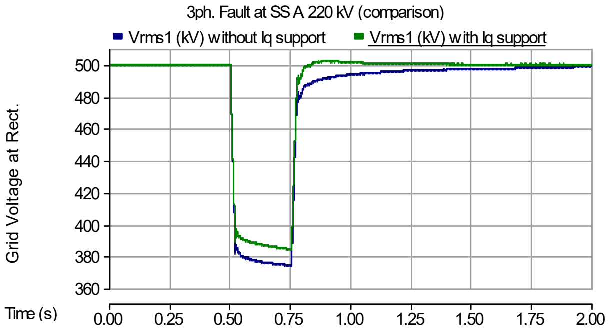

Fig. 10. Comparison of Cases 2a and 2b, 3 Phase, 250 ms Fault in 220 kV network of SS A without and with VSC dynamic voltage support

Dynamic performance for an AC (400 kV) fault on the inverter side of SS A was investigated in Case 3 and is shown in Fig. 11 to Fig. 13.

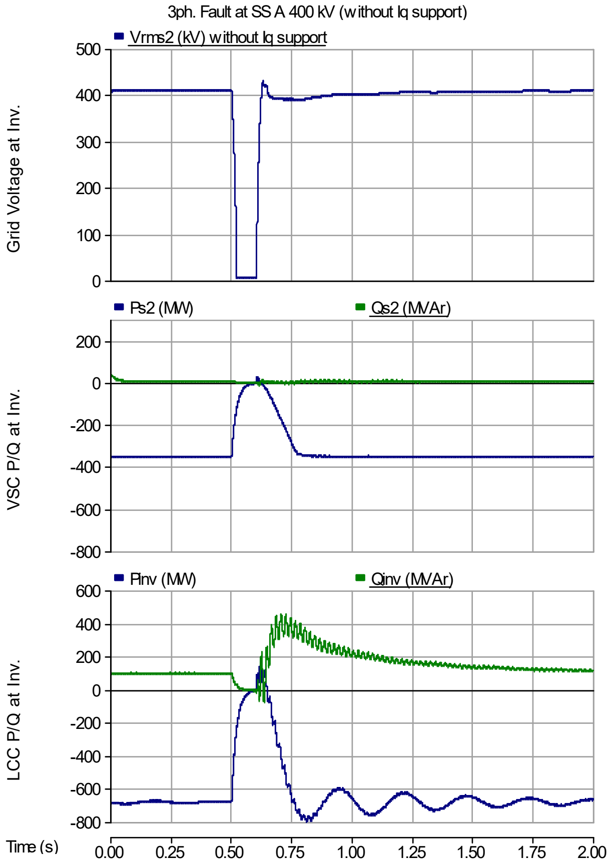

Fig. 11. Case 3a: 3 Phase, 100 ms solid Fault at 400 kV (inverter) side of SS A without VSC dynamic voltage support

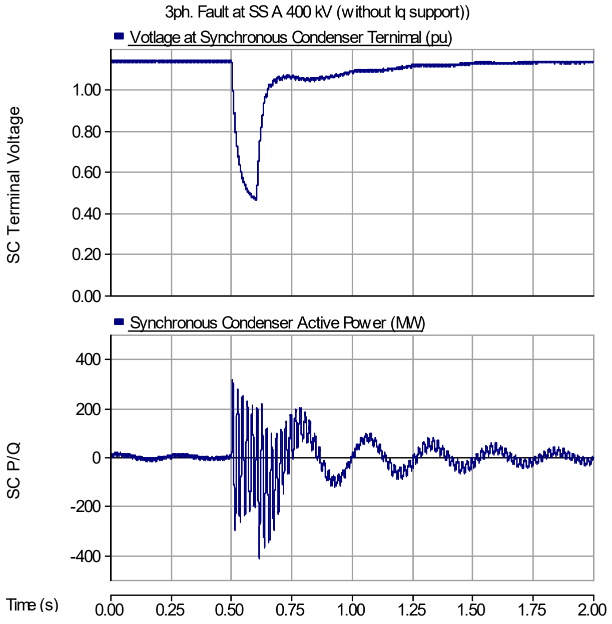

Fig. 12. Case 3a: 3 Phase, 100 ms solid Fault at 400 kV (inverter) side of SS A without VSC dynamic voltage support, Synchronous Condenser Oscillation

Similarly to Case 1, the VSC provides dynamic reactive power support following fault clearance at the inverter station, as can be seen in Fig. 11, in which the net reactive power consumed by the LCC during fault recovery is compensated by the VSC. The damped active power oscillation, which can be seen in Fig. 12, is an electromechanical effect and related to the synchronous condensers located directly at the inverter station. Fig. 13 shows that the voltage recovery is accelerated by dynamic voltage support from the VSC. A comparison of system performance in both cases is indicated in Fig. 14. There could be potential to coordinate the steady-state and dynamic voltage control between the synchronous condensers and the VSC during the engineering design phase to minimize losses and ensure correct operation of multiple voltage control devices connected to the same bus, for example by implementation of a voltage droop controller.

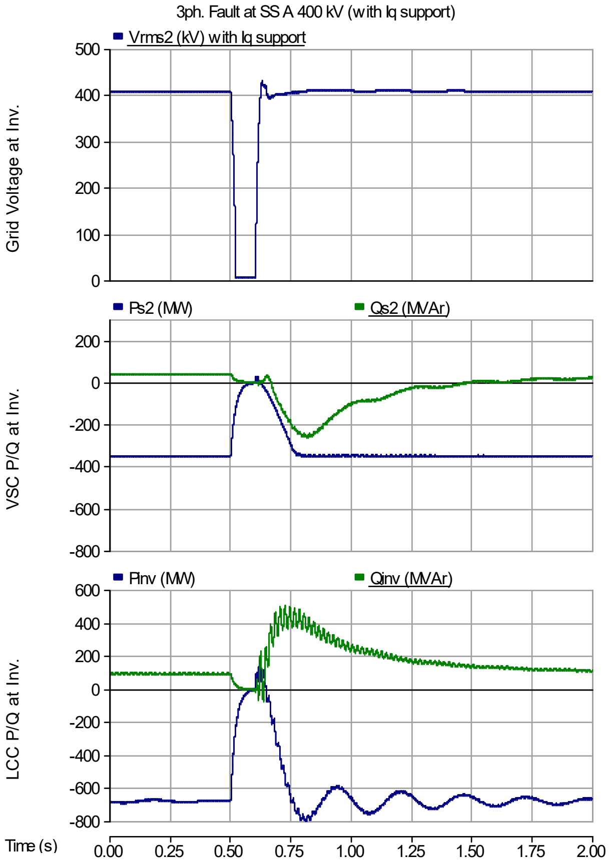

Fig. 13. Case 3b: 3 Phase, 100 ms solid Fault at 400 kV (inverter) side of SS A with VSC dynamic voltage support

VI. CONCLUSIONS

The simulations performed have demonstrated that VSC can provide dynamic voltage support, which can improve the AC voltage recovery profile and reduce the magnitude of voltage dips. Further studies are recommended in the design phase, to define the performance requirements of the new converter, for example to determine the requirements for reactive power capability and prioritization between active and reactive power. It is highly recommended that the existing LCC Back-to-Back model and synchronous condensers shall be included in any further studies due to the proximity and potential interactions. Furthermore, it is recommended that a preliminary dynamic performance study should be carried out at the start of the engineering phase of the project to confirm the basic design of the VSC is suitable prior to procurement of the main components.

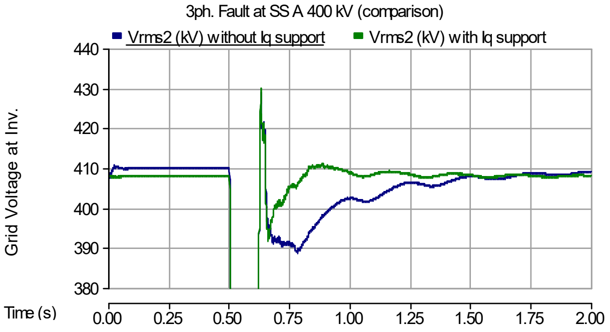

Fig. 14. Comparison of Cases 3a and 3b, 3 Phase, 100 ms solid Fault at 400 kV (inverter) side of SS A without and with VSC dynamic voltage support

Another topic for investigation in the engineering phase of the project include the potential to reduce the number of synchronous condensers required to be in service at the inverter station, if it can be demonstrated during the detailed design stage that the steady-state and dynamic performance is satisfactory. Although the synchronous condensers have already been constructed, the operational expenditure (OPEX) for losses and maintenance could be reduced if fewer units are required.

It may also be possible to accelerate the active power recovery ramp of the LCC to take account of the VSC and other network developments. Whether this would be beneficial for system stability has not yet been analysed.

Ongoing research and developments activities in the area of grid-forming converters, instantaneous active power reserve and dynamic voltage support without current reference could be applied to the VSC to investigate the potential for additional contribution to system stability in a weak network in parallel to existing LCC systems.

Further cases including larges AC network models may be challenging in an EMT environment and could necessitate the use of advanced modelling techniques such as parallel processing and/or hybrid simulation.

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