Assessment of Saturable Reactor Replacement Options

D.T.A Kho, K.S. Smith

Abstract-- **The performance of the dynamic reactive power compensation provided by the existing variable static compensation (STC) on the UK side of the Cross-Channel HVDC link has been assessed. These uniquely designed STCs are now being considered for replacement. Alternatives to provide the same performance as delivered by the existing STCs have been proposed and their overvoltage suppression performances have been assessed against the existing STCs using a PSCAD-EMTDC model of the England-France HVDC link. The paper demonstrates how the PSCAD-EMTDC simulation has been used to make informed design decision concerning the STC replacement option.**

Keywords: **Saturable reactor, Temporary overvoltage, HVDC link, Thyristor Controlled Reactor (TCR), PSCAD-EMTDC.**

I. Introduction

THE original Cross-Channel HVDC link was on the UK side, designed with three Saturable Reactors installed, two at Sellindge and one at Ninfield. These were installed with their primary function to manage the transient overvoltages (TOV) following HVDC converter blocking.

The saturable reactors show signs of aging and there is a need to plan for their replacement. Five initial replacement options are being considered, (i) Like for like replacement – 3 x 150 MVAr saturable reactors to be installed at the existing locations, (ii) Thyristor Controlled Reactors (TCR) units have been proposed at existing locations and potentially at additional locations, (iii) Shunt reactor solutions – 5 x 200 MVAr standard 400 kV shunt reactors with auto switching system, (iv) auto-tripped ac harmonic filters and (v) a hybrid combination of TCRs and auto-switched shunt reactors or auto-tripped ac harmonic filters.

The technical risks involved in each of the above options need to be carefully considered. Although the existing saturable reactors resolve the transient overvoltage, their unique design means there is limited support. The alternative options of TCRs and auto-switched shunt reactors appears to be feasible, however the specification required to enable satisfactory operation across the period of the initial overvoltage is unclear. Given that the original TOV characteristics on which the design of the saturable reactor operation is based is not available, and that the actual requirement may have changed over time, it is difficult to design and specify the control systems for both the TCR and auto-switched shunt reactor options. This paper summarises the study undertaken to assess the voltage waveform during transient disturbances, particularly following ac side faults, leading to converter blocking, filter islanding and ultimately bipole connection trip. The PSCAD-EMTDC model of the recent IFA2000 refurbishment project had been used throughout the study. The performance of the three replacement options have been compared in the context of TOV suppression due to faults.

II. STC Replacement Options

A. Like for Like Replacement - Variable Static Compensation (STC)

The existing STC at the Sellindge side (one on each Bipole) consists of one saturable reactor, four filter banks (2x84 MVAr switched and 1x47 MVAr, 1x15.6 MVAr unswitched) and one earthing transformer as shown in Fig. 1.

The saturable reactor provides the variable reactive element which has an automatic overload capability. To obtain the desired slope characteristics, a slope correcting capacitor is connected in series to increase the slope of the STC. The voltage-current characteristics of the PSCAD-EMTDC saturable reactor model with and without the slope-correcting capacitors are shown in Fig. 2. A bypass damping filter was provided for the overall series capacitor arrangement to inhibit sub-harmonic oscillations. More background information on the existing dynamic compensation is available in the technical literature. [1], [2], [3], [4].

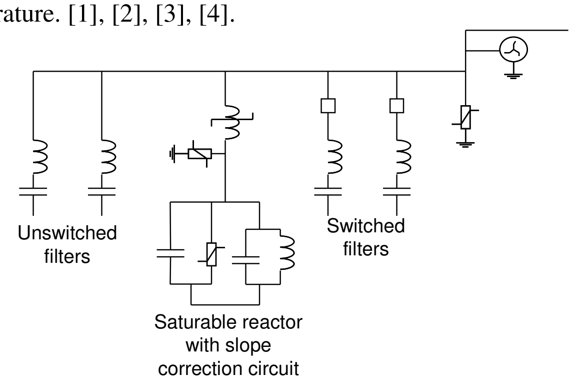

Fig. 1. PSCAD representation of the STC

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Paper submitted to the International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada July 18-20, 2013.

Each STC is fed from a 150 MVA 400/56.6 kV star-delta step-down transformer. During normal operating condition, the STC will be expected to operate in an approximately "floating condition", i.e. zero reactive absorption. This is achieved by appropriately setting the tap on the step-down transformer. A simple control scheme has been implemented to control the switched filter banks based on a typical STC operating characteristic shown in Fig. 3. The control scheme will switch the filter banks based on current in the saturable reactor, i.e. when the reactor current is maximum, a bank is de-energised; when the reactor current falls to a minimum, a bank is energised. The bank switching is time delayed by 1 s, which is not expected to operate during the transient time frame considered in the study.

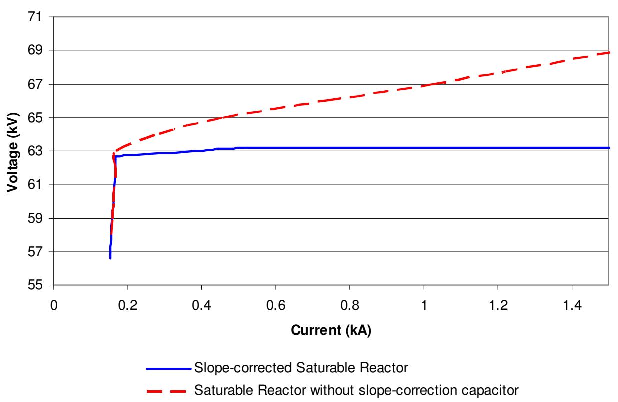

Fig. 2. VI characteristics of Saturable Reactor

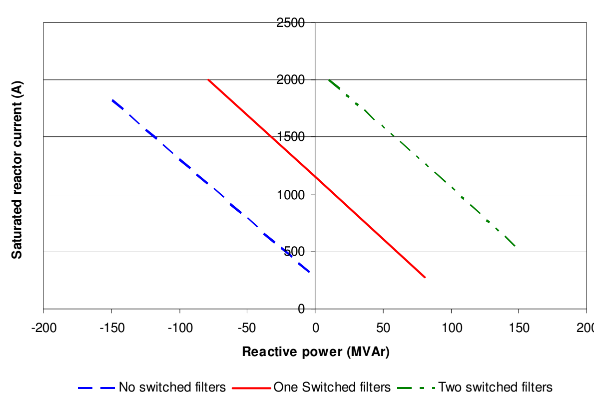

Fig. 3. STC operating characteristics

B. TCR Option

One of the potential replacement options is the use of Thyristor controlled reactors (TCR). It is assumed that the saturable reactor and the associated 56 kV switched capacitor banks on each bipole will be replaced by a TCR. A three-phase delta connected TCR as shown in Fig. 4 has been implemented in PSCAD-EMTDC using a typical standard thyristor model with typical snubber circuit of resistance and capacitance values. Different reactor sizes have been considered.

A typical voltage regulator used in a Static VAr Compensator (SVC) [5] as shown in Fig. 5 has been adapted for the TCR control. The measured control variables V_{meas} are compared with a reference signal V_{ref}, and an error signal is input into the controller transfer function. The output of the controller is a per-unit susceptance signal B_{ref}, which is generated to reduce the error signal to zero in the steady state. The susceptance signal is subsequently transmitted to the gate-pulse-generation circuit, which produces appropriate firing pulses for the thyristor-controlled reactor and the thyristor switched capacitors in the case of SVC.

A typical PSCAD-EMTDC phase locked loop based firing angle control has been used to generate the firing pulses for the thyristors. The TCR model and its control circuit have been tested in a simple PSCAD-EMTDC model with 200 MVAr reactive load rejection and acceptance. The calculated firing angle, the reactive power and the per unit RMS voltage at the TCR terminal are shown in Fig 6 to Fig. 8. The response of the TCR control circuit to the transient voltage disturbances is acceptable.

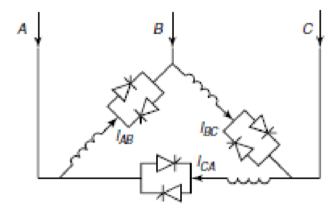

Fig. 4. Three phase delta connected TCR

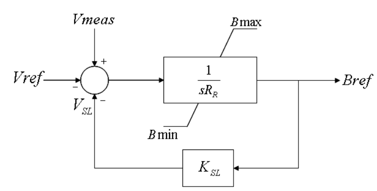

Fig. 5. Three phase delta connected TCR

C. Auto-switched Shunt Reactor Option

The overvoltage suppression performance utilizing auto-switched shunt reactors at the Sellindge converter station has also been assessed. With this option, two 400 kV shunt reactors will be connected on each bipole at Sellindge. The study has assumed a star-grounded connection for each shunt reactor. The automatic switching scheme is implemented based on the rate of change of the 400 kV RMS voltage at Sellindge converter station calculated without the dynamic compensation.

D. Auto-tripped AC filters

The tripping logic will compare the ac RMS voltage at Sellindge and send the switching signals to the respective filters at Sellindge converter station. The time delays were originally set to 200 ms, 250 ms and 300 ms for the filter no. 2, filter no.3 and filter no.4 respectively for each bipole. Shorter time delays have been considered to examine the benefit and effectiveness of tripping the filter to control the dynamic ac overvoltage at Sellindge.

E. Combined Solutions

The combined 56 kV 2x250 MVAr TCR and the 400 kV 2x100 MVAr auto-switched shunt reactor configuration has been considered as an alternative option to replace the existing STC.

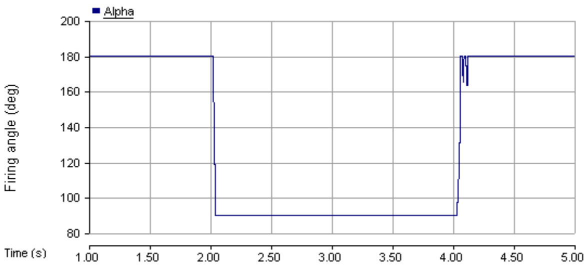

Fig. 6. TCR control test – firing angle

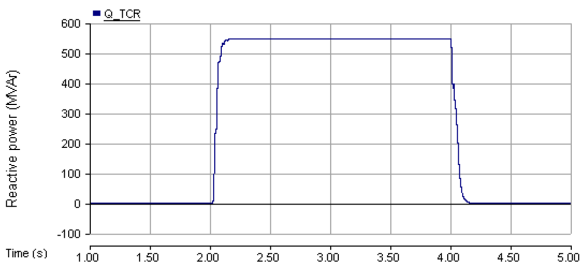

Fig. 7. TCR control test – reactive power absorption

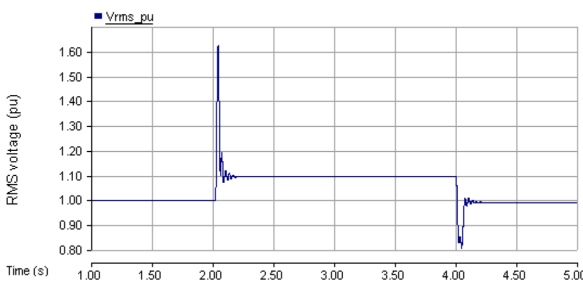

Fig. 8. TCR control test – RMS voltage at the TCR terminal

III. Simulation and Results

A. Short Circuit Ratio (SCR) Consideration

The short circuit level of 4800 MVA was used to represent the Sellindge 400 kV ac equivalent in the PSCAD-EMTDC model, which corresponds to the extreme minimum short circuit level. This gives a short circuit ratio (SCR) of less than 3 which corresponds to the worst case scenario in the context of dynamic overvoltage. For example, when there is an interruption to the dc power transfer, the reactive power absorption of the HVDC converters drops to zero; with a low SCR system, the resulting increase in the alternating voltage due to shunt capacitors and harmonic filters could be excessive. This worst case scenario has been considered in the study so that the performance of the existing STCs can be determined to provide the base criteria for the STC replacement option.

The drawback in terms of the study is that it is necessary to increase the ac terminal voltage of the equivalent source at Sellindge and Les Mandarins to a high value in order to obtain the required ac system voltage level of 1.03 pu and the desired power transfer of 2000 MW across the HVDC link. In cases where a sustained fault has been considered, the converter will block the power transfer in 300 ms and the 400 kV circuit breakers will open to isolate HVDC link from the ac equivalent source. Consequently, the calculated 400 kV ac system voltage level returns to the high initial set point.

B. PSCAD-EMTDC HVDC Link Model

The PSCAD-EMTDC model of the HVDC link created during the recent refurbishment exercise has been used for the study. The HVDC transmission scheme consists of two bi-directional bipole HVDC links between England and France, each of 1000MW capacity; thus, each 12 pulse bridge converter has a power capability of 500 MW giving the two bipoles a rating of 2000MW. The nominal HVDC voltage per 12 pulse monopole is 270 kV, and so the nominal maximum current is 1.852 kA. The DC current is carried by undersea cables, the land sections of these being buried underground. The transmission scheme connects to the 50 Hz 400 kV AC network on either side of the link. The England side converters are located at Sellindge and the France side converters are located at Les Mandarins. The PSCAD HVDC link model, with a modified short circuit ratio has been verified against recorded data during a recent fault incident. The PSCAD-EMTDC calculated Sellindge RMS voltage profiles for the single phase to ground fault at Les Mandarins for the first 200 ms after the fault occurrence plotted against the recorded RMS voltage waveforms from the fault incident are shown in Fig.9 to Fig.11. The results show that the PSCAD-EMTDC model used for the study is accurate reproducing the measured fault response.

In addition, a transient three phase fault (150 ms) at the Les Mandarins side of the converter station has been simulated, with power transfer from France to UK at the worst case short-circuit ratio. Assuming all the filter banks at the STCs are switched on, the RMS voltage profiles calculated at Sellindge with and without the existing STCs are shown in Fig. 12. The results show that the initial voltage transients contain damped oscillatory component at subsynchronous frequency (30 Hz – 40 Hz). It is observed that the combined series capacitor and the damping filters are tuned at round about 35 Hz. The inductance of the saturable reactor reduces to 0.029 H during the fault period, wtih reactive power absorption of approximately 600 MVAr on each saturable reactor. Note that the inductance (0.029 H) when connected in series with the slope correcting capacitance of 451 μF has a natural frequency of 44 Hz, which is close to the frequency of the initial voltage oscillation. Furthermore, this voltage oscillation can be replicated using a simple test network model consisting of the Sellindge voltage source and the saturable reactor model and some capacitive and inductive loads to represent the reactive power absorption of the HVDC link. These results are consistent with the transient overvoltage results documented in [1] and [4].

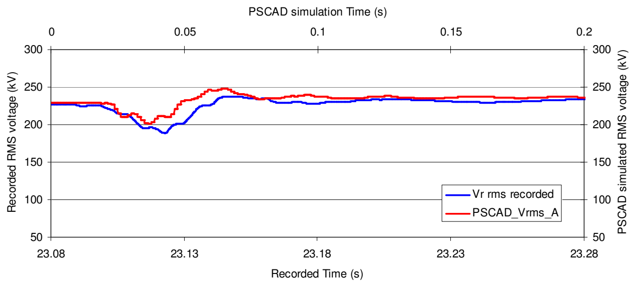

Fig. 9. Comparison of the PSCAD simulated RMS voltage plots and the recorded data from the single phase to ground fault incident (Phase A voltage)

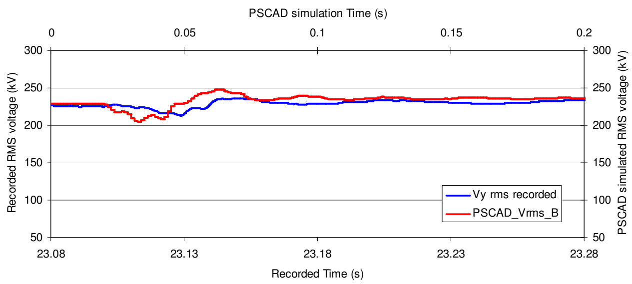

Fig. 10. Comparison of the PSCAD simulated RMS voltage plot and the recorded data from the single phase to ground fault incident (Phase B voltage)

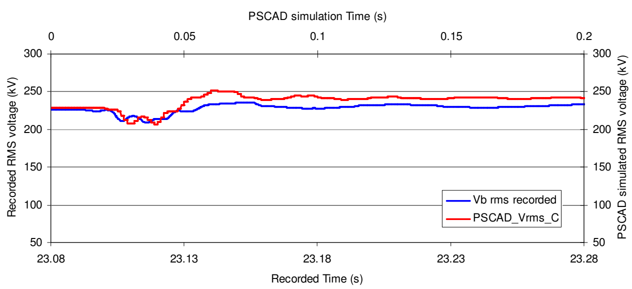

Fig. 11. Comparison of the PSCAD simulated RMS voltage plot and the recorded data from the single phase to ground fault incident (Phase C voltage)

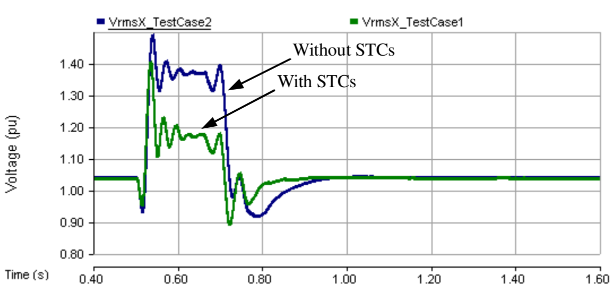

Fig. 12. Simulated RMS voltage profile at the Sellindge converter station obtained from the initial model validation exercise for the HVDC link with and without the existing STCs.

C. Dynamic Overvoltage Suppression with the Existing STC (Saturable Reactor)

The overvoltage suppression performance of the existing STCs have been assessed using the PSCAD-EMTDC model of the HVDC link. The study has focused on transient and sustained three phase to ground faults at the Les Mandarins converter station with different pre-fault power transfer directions. The results of the overvoltage suppression performance during a transient three phase to ground fault, with and without the saturable reactors for different power transfer directions are shown in Fig. 13 and Fig. 14.

The results indicate that the existing saturable reactors do not have a significant influence on the initial RMS voltage dip at Sellindge when the fault occurs. The influence of the saturable reactors on the transient overvoltage can be observed during the transient/sustained fault period before the fault is cleared. The results also show that the saturable reactor has little impact on the rate and the percentage of RMS voltage rise during the fault clearing period, which is apparent for the case with pre-fault power transfer from UK to France (Fig. 13).

D. Dynamic Overvoltage Suppression with the TCR Option

When a three phase fault occurs close to the rectifier (Les Mandarins), the ac voltage collapses to zero and the dc system shuts down. The converter reactive power absorption reduces to zero, while the TCR control reduces the firing angle to increase the reactive power absorption, offsetting the surplus of reactive power at Sellindge during the transient fault duration. This is shown in Fig. 15. The overvoltage suppression performances of different TCR sizes have been compared with that of the existing STCs and are shown in Fig. 16.

The study results show that replacing the existing STCs with 350 MVAr TCRs at the Sellindge converter station (one at each bipole) can match the performance of the existing STCs under both power transfer directions between UK and France.

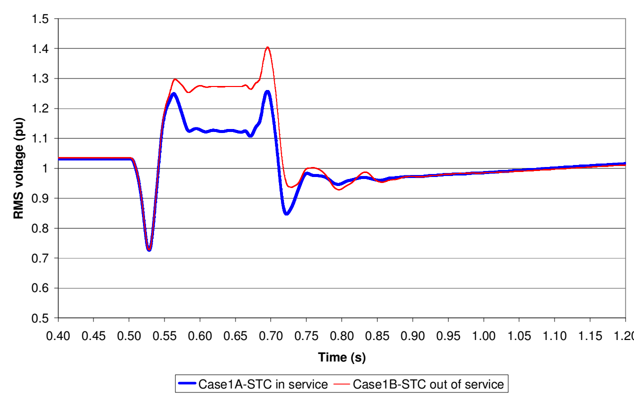

Fig. 13. Comparison of the average RMS voltages at Sellindge converter station with and without saturable reactor, when a transient three phase to ground fault occurred at Les Mandarin, pre-fault power transfer from UK to France

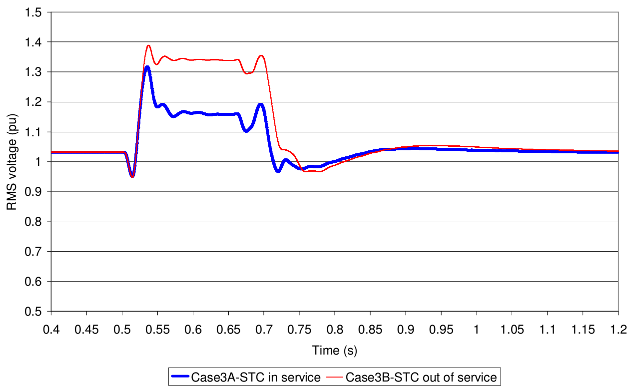

Fig. 14. Comparison of the average RMS voltages at Sellindge converter station with and without saturable reactor, when a transient three phase to ground fault occurred at Les Mandarin, pre-fault power transfer from France to UK.

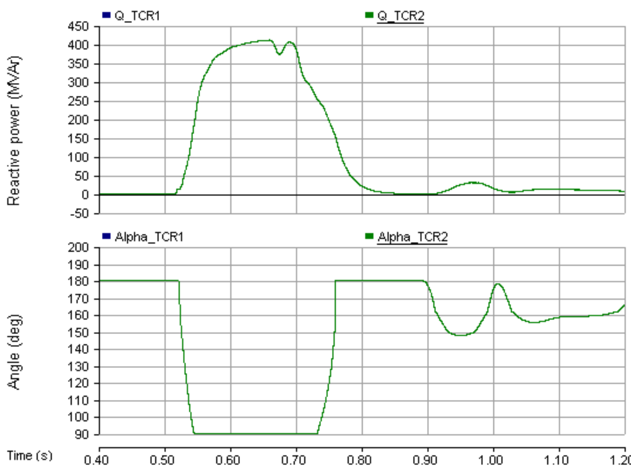

Fig. 15. TCR option - reactive power absorbed by the TCR (upper plot), TCR firing angle (lower plot)

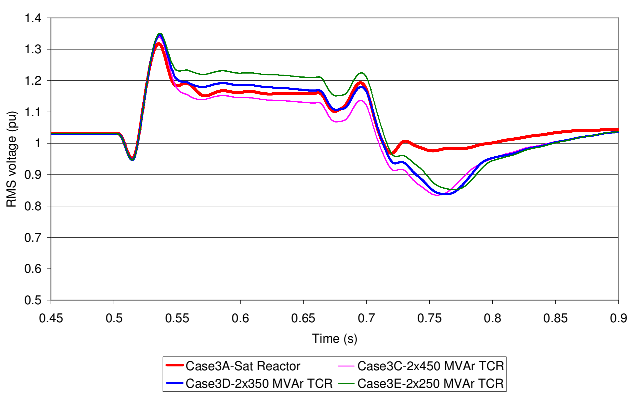

Fig. 16. TCR options - comparison of the average RMS voltages at Sellindge converter station for a transient three phase to ground fault at Les Mandarin, pre-fault power transfer from France to UK.

E. Dynamic overvoltage suppression with the auto-tripped harmonic filters

The dynamic response of the existing saturable reactor cannot be matched using auto-tripped harmonic filters. The auto-tripped ac harmonic filters option does not contribute towards the overvoltage suppression during short duration transient three phase fault conditions. This is due to the time delay required for the overvoltage detection and circuit breaker operation. The overvoltage suppression effect by the auto-tripped ac harmonic filters can be observed in Fig. 17 for a sustained three phase fault. However, this cannot match the fast response of the existing STCs (saturable reactors and the switchable capacitor banks) during the first 150 ms / 200 ms of the fault depending on the time delay settings.

F. Dynamic Overvoltage Suppression with the Auto-switched Shunt Reactors

The 1x200 MVAr, 1x150 MVAr auto-switched shunt reactors configuration (per bipole) has been considered for the transient three phase fault scenario. The simulations show that the response of the auto-switched shunt reactors cannot match the response of the saturable reactors in terms of transient overvoltage suppression. The results also show that the system may experience an undesirable voltage dip when the fault is cleared and subsequently the shunt reactors switch off. These voltage depressions are more severe as the size of the shunt reactors increases. Sustained three phase fault conditions have been considered with different sizes of shunt reactors. In the case with the pre-fault power transfer from the UK to France and a three phase fault occurring close to Les Mandarins converter station, the study has shown that 1x200 MVAr auto-switched shunt reactors can be used to match the existing STCs performance, if the initial average transient overvoltage of 1.26 pu with a duration of 150 ms is acceptable as shown in Fig. 18. In the case with the pre-fault power transfer from France to UK and a three phase fault occurs close to Les Mandarins converter station, 1x200 MVAr, 1x50 MVAr auto-switched shunt reactors can be used to match the existing STCs performance, if the initial average transient overvoltage of 1.33 pu for a duration of 150 ms is tolerable. This is shown in Fig. 19.

G. Dynamic Overvoltage Suppression with the Combined TCR and Auto-switched Shunt Reactors

The study shows that a combination of TCR and auto-switched shunt reactor can be used to match the existing STCs response for both transient and sustained three phase fault close to Les Mandarins, if the initial transient overvoltage of slightly above 1.2 pu within the first 200 ms after fault occurrence is acceptable. This is shown in Fig. 20. Alternatively, a combined TCRs and auto-tripped ac harmonic filters may also be used, which will be more economically favorable.

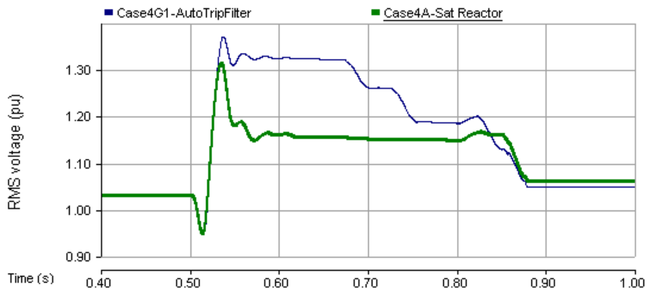

Fig. 17. Auto-tripped AC filters - comparison of the overvoltage suppression performance at Sellindge between saturable reactor and the auto-tripped filters option for a transient three phase to ground fault at Les Mandarin, pre-fault power transfer from France to UK

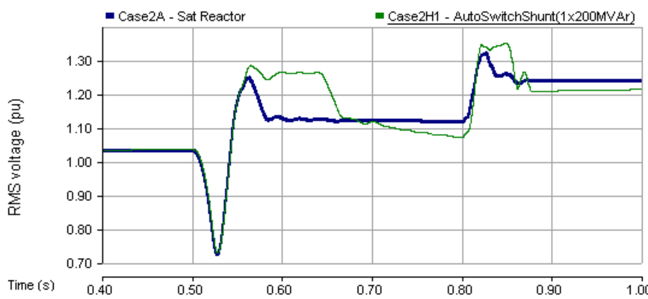

Fig. 18. Auto-switched shunt reactors - comparison of the overvoltage suppression performance at Sellindge between saturable reactor and the auto-switched shunt reactors option for a transient three phase to ground fault at Les Mandarin, pre-fault power transfer from UK to France

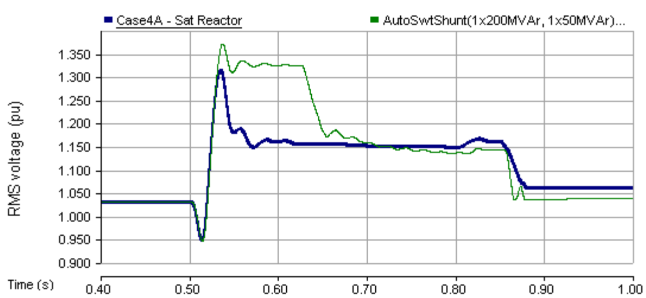

Fig. 19. Auto-switched shunt reactors - comparison of the overvoltage suppression performance at Sellindge between saturable reactor and the auto-switched shunt reactors option for a transient three phase to ground fault at Les Mandarin, pre-fault power transfer from France to UK

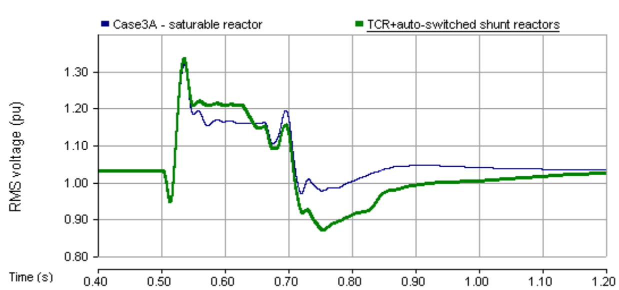

Fig. 20. Comparison of the overvoltage suppression performance at Sellindge between saturable reactor and the combined TCR (2x250 MVAr) and auto-switched shunt reactors (2x100 MVAr) option for a transient three phase to ground fault at Les Mandarin, pre-fault power transfer from France to UK

IV. Conclusions

This paper has described the basic operation of the existing variable static compensation implemented at the English terminal of the Cross Chanel HVDC link. The STCs utilise three 56 kV 150 MVAr saturable reactors, two at Sellindge and one at nearby Ninfield 400 kV substation. Several replacement options for the existing STC have been described. The dynamic overvoltage suppression performance of the replacement options have been benchmarked against that of the existing STC units using PSCAD-EMTDC simulation studies. The paper demonstrates how such computer simulations are used in practice as an engineering tool to assess the viability of the proposed replacement options for the existing life expired STCs.

The PSCAD-EMTDC study shows that it is possible to match the existing overvoltage suppression performance with appropriately sized TCRs. The auto-tripped filters and auto-switched shunt reactors options only show marginal benefit if they are implemented as a standalone replacement option to the existing STCs. The study has shown that due to the time delay settings and the circuit breaker operating time, these two options are unable to match the overvoltage suppression performance of the existing STCs during a transient three phase fault. The possibility of a hybrid auto-switched shunt reactor and TCR solution may be a favourable option in terms of cost effectiveness and further work has been carried out to examine the appropriate balance of static and dynamic equipment that would be required.

V. References

[1] H. Allon, G.E. Gardner, L.A. Harris, I.M. Welch, H.L. Thanawala, D. J. Young, "Dynamic Compensation for the England – France 2000 MW HVDC Link," Cigre International Conference on Large High Voltage Electric Systems 1982 Session 14-04-1982.

[2] A. R. Wells and M. Dang, “Reactive Power Compensation Requirements for the 2000 MW D. C. Link with E.de.F. Under Light Load and Peak Load Condition”, System Technical Branch Report TPR-ST/3/82, Central Electricity Generating Board, 25 February 1982.

[3] H. Allon, G.E. Gardner, “Voltage Disturbance Control For 2000 MW HVDC Link”, System Technical Branch Report PL-ST/8/80, Central Electricity Generating Board, June 1980

[4] G.L Brewer, I.M. Welch, C. Horwill, H.L. Thanawala, D.J. Young, “The Application of Static VAR Compensators to the English Terminal of the 2000 MW HVDC Cross Channel Link”, Cigre International Conference on Large High Voltage Electric Systems 1986 Session 14-07.

[5] R. Mohan Mathur, Rajiv K. Varma, *Thyristor-based Facts Controllers for Electrical Transmission Systems*, IEEE Press, Wiley-Interscience, 2002, p.114.