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Research & Development Requirements for UHVDC

Mohamed Rashwan, TransGrid Solutions Inc. (TGS)

During the 1980s, anticipating the next stage of high power HVDC transmission, there was considerable R&D work underway on various aspects of HVDC transmission beyond ±600kV, notably ±800kV and ±1000kV. However, even though there was considerable amount of work being done, the lack of an actual project slowed down the process. In 2000, Cigre Study Committee 14 currently B4 established WG 14.32 to look at converter stations for voltages above 600kV.

The report was prepared by WG 14.32 at a time when none of the utilities were planning HVDC transmission systems beyond 600kV. Although WG 14.32 did use 800KV as the reference voltage, there were no actual projects at that time that were considering HVDC transmission voltage at 800kV. However, the situation today is different in view of the fact that there are several 800kV HVDC projects that are being actively pursued and the equipment manufacturers are in the process of developing and testing equipment for these HVDC transmission projects. There is great interest in UHV DC transmission in countries such as China, India, Brazil and parts of Africa.

There is already considerable experience on ±500 to ±600kV, which was not gained without some problems. However, given that experience, it would not seem to be a big problem to go up to the next level of ±800kV. Furthermore, the R&D work carried out during the 1980s did not reveal

major road blocks. Also, given input from manufacturers of converter stations, who have indicated that they are ready to take orders for 800kV DC, it is clear that China and India will proceed with ±800kV DC installations on the assumption that no major problems are expected for the design and construction of HVDC transmission lines and converter stations for ±800kV. The challenges of an 800kV HVDC system are not unique, and the industry went through similar challenges when DC voltages were increased to 500 and 600kV. No one is saying that HVDC at 800kV will not have the typical teething problem, however the key is not to extrapolate from the current experience but to gain from it.

Issues for HVDC at 800kV The following items are the key issues for HVDC at 800kV:

- DC insulation is affected by pollution (overhead line and station insulation)
- Transformer reliability, which has been below expectation for even current converter transformers
- AC system faults and their impact on performance, especially at the level of bipole power being considered (upward of 5000MW)
- Monopolar operation size and ground currents, even on a temporary basis
- Equipment size
- Transportation limits
- Testing facilities

The following paragraphs convey the state of the art and where R&D would help reduce risk, improve reliability, reduce cost and improve performance.

Transmission Lines Based on R&D carried out by EPRI, IREQ, CRIEPI, CESI, CEPEL and NIIPT, there is enough electrical data available to suggest that several transmission line design companies have and can design ±800kV lines. Nevertheless, there is a need for further research related to design data on air clearances, corona, RI, and audible noise.

Regarding air gap clearances for steady state and switching surge withstand, the relationship appears to be almost linear up to ±800kV and even ±1000kV.

Although four conductor bundle configurations seem adequate for ±800kV from the point of view of corona for very long lines, conductor and bundle size may have to be larger, determined not only by the value of losses, but also the impact of total voltage drop in the line.

Research on various insulators reveals a big problem with regard to the effects of pollution, particularly urban, automobiles and industrial, and to a lesser extent agriculture, on the insulator surface and its effect on the steady state and switching surge withstand levels. Salt in the air is also a big problem. Under DC voltage, insulators electro-statically collect airborne particles so much so that often the flashover level of outdoor insulation under DC is lower than AC rms levels. A large number of tests have been carried out on insulators, porcelain, glass, non-ceramic and a wide variety of shapes. These tests include laboratory and field tests. Methods of artificial pollution for laboratory testing, and sophisticated instrumentation and data gathering have been developed. Anti fog shaped porcelain insulators seem to have better performance, and so do the non-ceramic insulators. V insulator strings seem to have better performance than I strings. For a given route of a proposed transmission, it is possible to rely on gathered field data from test sites along the route to determine the required insulation.

Bushings Bushings represent another problem, not only in terms of pollution, but also for internal stresses and unequal wetting. Bushings perhaps are one of the highest risk equipment for HVDC at ±800kV. It is clear that composite bushings will be used. Basic research is needed on internal stresses, and relationship between internal and external stresses.

Transformers Transformers including their bushings for ±800kV are also considered high risk equipment. Concern largely relates to the presence of DC stress and combined AC/DC stress on oil/paper combinations and chemical interactions. Basic work would help understand short term and long term effects of DC stress, combined DC/AC stress and use of appropriate insulation grading, barriers, oil flow, chemical composition of oil, and proper testing of the transformers. It seems there is a gap between the test standards and the defined stress on the transformers.

Converter Technology At present, high power HVDC schemes are based on 12-pulse converters using conventional thyristors.

Significant advances continue to be made in the conventional thyristor based technology. Today, one can expect thyristors with an 8kV, 4500A rating. The modular design of the valve seems to be efficient and economic. There may be a need to increase the level of power per module to optimize the size.

Much can be done to improve conventional thyristor technology itself. R&D can help reduce forward voltage drop, conduction losses, switching losses and gate power requirements. Particularly important is the improvement of thermal performance of thyristor packaging. This can be done by reducing and even eliminating dry press-pack junctions. These junctions have high thermal resistance, which in turn reduces the current carrying capability. The thyristor happens to be the component that limits short-term overload capability of HVDC systems.

…real time simulation could also support operation and maintenance of the installed system and support operator training…

One cannot rule out that voltage source converters based on the IGBT technology may reach higher levels of power.

There is no reason to believe that with research and development on converter technology, Voltage-Sourced Converter technology could not be projected to UHV and thousands of MW levels. Such converters require much smaller AC filters, provide reactive power and do not require AC voltage support on the AC side; significant advantages over thyristor-based technology.

Ground Electrodes and Metallic Return
Still today, design and location of ground electrodes represents a level of uncertainty with regard to the risk of saturation of transformers and pipe corrosion. While this is not a specific problem for UHVDC schemes, higher current levels involve greater difficulty in finding suitable electrode locations. This uncertainty results from the unknown formation of deep layers of earth with a few tens of miles of the electrode sites. It is necessary to investigate techniques used by oil/gas and mining exploration companies.

For some schemes, ground return, even for emergency purposes, is needed.

Control and Protection Control and protection for such a large HVDC system will follow the lines of the current systems. The control and protection will follow:

• Micro processor based systems
• Redundant systems
• High reliability

Dynamic Over-Voltages For such long distance, high-voltage, high-current schemes, it would be extremely important to minimize AC system over-voltages and over-currents during disturbances and ensure stable recovery from disturbances.

The role of dynamic voltage control devices for AC side voltage control needs to be defined. Apart from reduced DC voltage operation during DC line insulation problems, it may also be important to reduce the level of polarity reversal during dynamics. Simulation based R&D is needed to refine control and protection strategies.

Synchronized switching of transformer and capacitor bank breakers should be looked into with the objective of reducing over-voltages and resonances and prolonging equipment life.

For control of dynamic over-voltages, it is necessary to evaluate the use of STATCOMS, SVCs and high power arrestors.

Simulation Tools Simulation technology continues to advance. The days of physical/analog simulators seem to have gone. Many non real-time digital simulation tools, such as PSCAD®, have been developed and continue to be refined. However, for designing digital control and protection, it is essential to have real time simulation with hardware/software in the loop capability.

Real time simulation could also support operation and maintenance of the installed system and support operator training. Such an onsite simulator could receive available online data form various monitoring devices and provide information on the missing data, as well as run contingency calculations to predict potential problems.

Mechanical Design and Seismic Requirements
It is clear that due to the size of the equipment at 800kV, there has to be a very innovative approach to the mechanical design, especially if there are any seismic requirements.

If anyone would like to discuss the aspects of UHVDC further, please feel free to contact the author at *mrashwan@transgridsolutions.com*

PSCAD®/EMTDC™ Large Scale Computer Models and Applications

Juan Castaneda, Southern California Edison

Electromagnetic Transients Programs (EMTP), such as PSCAD®/EMTDC™ have been used successfully for many years to study and evaluate electromagnetic switching transients. Computer models developed to study these phenomena are for the most part reduced to a few busses away from the area of interest. One reason for limiting the models to a few busses is that switching transients usually affects only a few busses where the transient is generated. Another reason for using fewer busses in research models is the large amount of memory and computer time required to solve computer models, which tend to include greater system detail. This is becoming less of a problem as computers become more powerful allowing researchers the freedom to increase the size and complexity of their computer models without compromising the computing time and/or memory.

As the number of fast switching devices installed on the system increases (e.g. Flexible AC Transmission Systems (FACTS) devices and the need to understand their impact on the system), this requires larger system models using time domain programs like PSCAD®. The large scale PSCAD® computer model may not only be useful for studying fast switching transients, but they could also be used to study slower type transients caused by the mechanical oscillations produced by rotating machines in the system. In order to capture these mechanical oscillations, the PSCAD® model needs to include models of actual rotating, synchronous and asynchronous machines in the system and their respective controls. However, if a switching transient study must be conducted, a large model can be effectively reduced using the frequency scanning method, without a separate computer model (such as those used for short circuit programs) to perform the system reduction. Another advantage of generating a large-scale model of the system is it provides a better understanding of how the entire system performs.

The process of producing this type of model begins by obtaining short circuit reduced models from an available database, most often generated by a protection engineer. The smaller models are then pieced together as subsystems. Using a load flow solved case, real power, reactive power, voltage and angles for the bus are then used to set up the system's initial conditions. Once the large system is put together, a validation process is conducted by comparing the short circuit data (single and three phase faults) to the short circuit program results, and the base case load flow. This process helps identify possible errors. Once the short circuit and load flow are validated, the source equivalents can be replaced by the actual rotating machine models and the respective controls (exciters and governors) available in the PSCAD® library.

The large scale PSCAD® model of the Southern California Edison (SCE) system (500kV and 230kV) includes all synchronous generators, series compensated lines, and FACTS devices in the SCE system. This model includes about 50 generators, 80 busses, 190 transmission lines, 2 Static VAR Compensators (SVC), and 9 Series Capacitors. The model was successfully validated against the SCE short circuit data and base case load flow.

The SCE PSCAD® model was not only validated using the two methods described above, but the findings were also confirmed using field data, such as digital fault recorders (DFR) and phasor measurement units (PMU) records. Utilizing the validation method against real system disturbances provides additional assurances that the data for the model and its behavior to potential disturbances are accurate. The plots in Figures 1, 2, and 3 show the DFR line currents captured in one of the series compensated lines successfully cleared within approximately three cycles.
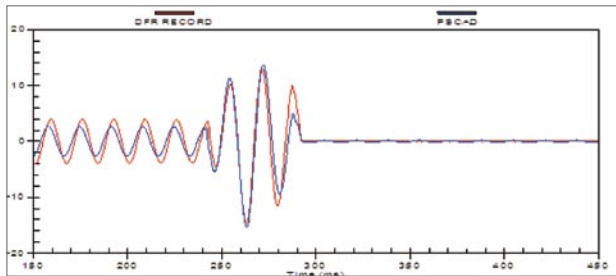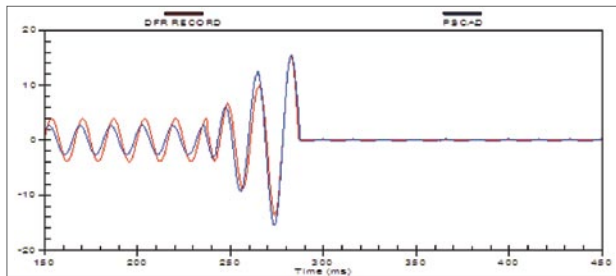
Figure 1 Phase A line current.
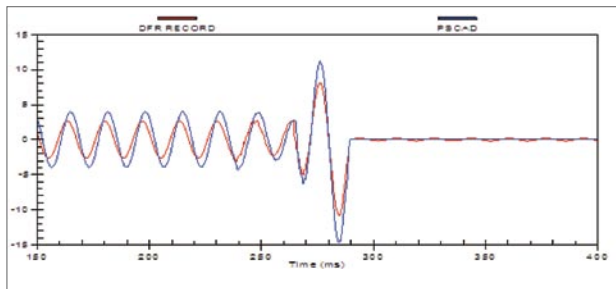

Figure 2 Phase B line current.

Figure 3 Phase C line current.

The same fault is then simulated in the PSCAD® model and compared to the actual fault record. The records for all three phase currents show a close correlation between the real system and the computer model. This model is not only compared to one record, but several captured from different locations in the system, all with similar results.

The same fault is compared to the affected bus PMU disturbance (Figures 4 and 5) record where the real and reactive power flowing into the un-faulted area is compared to the PSCAD® simulation showing a close correlation between the actual disturbance and the computer simulation.
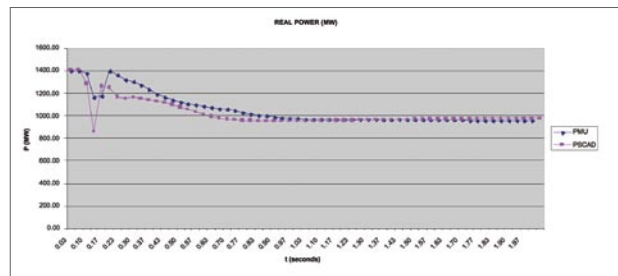

Figure 4 500kV Bus Disturbance Real Power PMU Record.
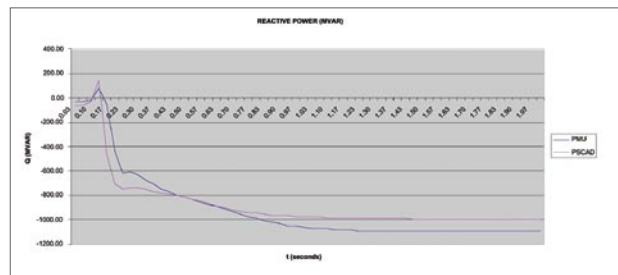

Figure 5 500kV Bus Disturbance Reactive Power PMU Record.

The PSCAD®/EMTDC™ model is currently used at SCE for different types of studies, including switching shunt devices, FACTS devices impact, rating the series capacitors' metal oxide varistors (MOV), slow voltage recovery, and dynamic testing of distance protection relays.
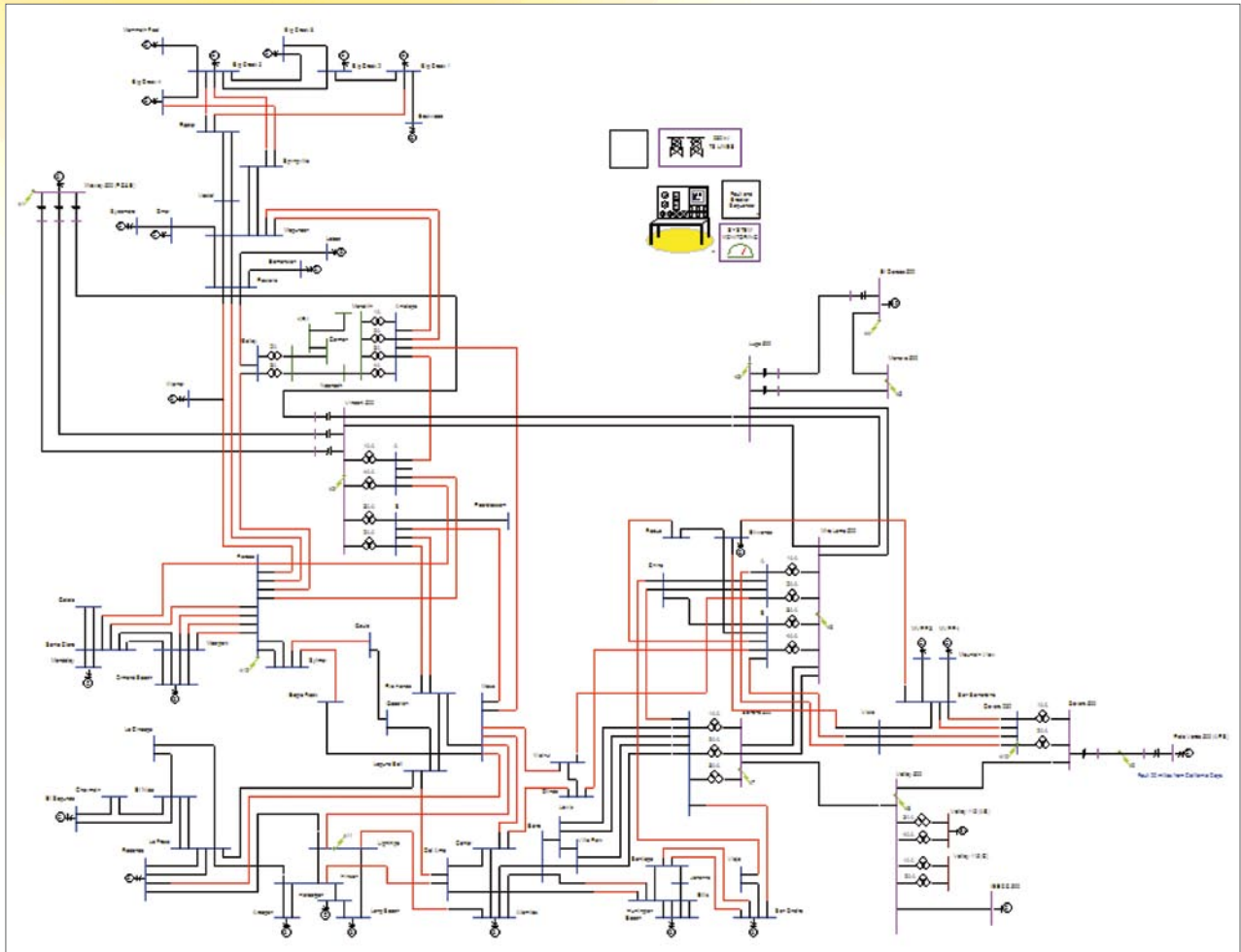
Figure 6 System diagram.

It does take effort and continuous adjustments to build a large scale computer model (Figure 6), but the number of studies and their accuracy are without a doubt invaluable and makes the effort worthwhile.

Using PSCAD® to Study Multi-Terminal HVDC Converters

Dan Kell, TransGrid Solutions Inc. (TGS)

Over the past 3 years, TransGrid Solutions (TGS) has been involved in the feasibility studies for four different multi-terminal schemes, involving powers up to 3000MW, cable lengths of 1500km, and overhead line lengths of up to 1000km. A multi-terminal link's basic topology is as shown in Figure 1.
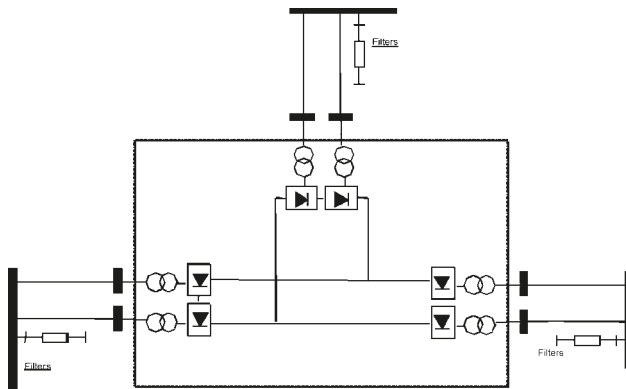

Figure 1 Multi-terminal link.

The multi-terminal links studied looked at a variety of topologies, including classic line commutated converters (LCC), voltage sourced converters (VSC) and a combination of both. This discussion will focus mainly on the development of the line commutated converter, as the projects utilized very high power ratings and/or overhead lines. VSCs in combination with overhead lines greatly increase the exposure of the DC line to ground faults. This was found to be an issue in some cases as these DC faults draw short circuit current from the AC system. In saying this, a VSC offers many technological advantages, especially when a multi-terminal tap is required that is quite a bit smaller than the other terminals (it was found that the smallest terminal that could be operated effectively was approximately 0.25pu of the largest terminal). The VSC multi-terminal configuration has actually been adopted for study of one of the links, and a second link may become a Hybrid LCC/VSC link.

Modeling Issues In order to study the complex interactions that are present when tying three remote systems together using a DC link, one needs to model each AC system in sufficient detail, as well as the DC link response (controls). At the start of the multi-terminal projects, a suitable multi-terminal model was not available in either PSCAD® or the transient stability programs commonly used by our clients. The classic transient stability models are based on response type models, but given the lack of operational history of how a multi-terminal DC link will respond, TGS created the following models for each project:

• A detailed multi-terminal model in PSCAD®
• A detailed two-time step multi-terminal model for use in transient stability

The PSCAD® model allowed us to relatively quickly develop and tune the controls for the variety of multi-terminal links, which can change substantially given the transmission medium, and the short-circuit level and dynamic performance of the three systems to be connected.

Once the detailed PSCAD® model was performing adequately, the detailed two-time step multi-terminal transient stability model was validated against the PSCAD® model and then used to study the impact on the extended AC system.

Some issues that could not easily be studied using the transient stability model were issues such as commutation performance, which will be presented here, and power reversal at one station (requires the use of high speed transfer switches to change the polarity of the poles).

Basic Control Topology In most two-terminal HVDC links, the standard method of controlling the link is to have the inverter in voltage control and the rectifier in current control, which has proven to be a very robust control method.

In a multi-terminal HVDC link, where there are three (or more) terminals; the standard control mode becomes a little more difficult to implement, as there are numerous configurations of rectifiers and inverters that may require very complex controls if one assumes all the inverters are in voltage control, and all the rectifiers are in current control. For example, if the multi-terminal link is running with two inverters, and one rectifier, that would mean two of the converters are in voltage control and only one in current control. In terms of setting a stable operating point, both inverters are asking for a given power, but are only setting the voltage. The rectifier knows how much current the inverters want but not how to split the current. Now, based on the inverter voltage set point, the proper current may flow, but this is very dependent on proper line parameter estimation being available. Further to this, if one inverter station suffers a slight voltage dip, which may not even cause a commutation failure, due to the sudden reduction in DC voltage, all the current will want to flow to this faulty inverter.

As such, the method of control utilized by TGS has the rectifier with the highest voltage controlling the voltage, and all other converters, regardless of whether they are rectifiers or inverters, controlling the current. Utilizing this method, only the rectifier running at the highest voltage will control the voltage (i.e., one rectifier may be running at 500kV, while another a few hundred km away will have to run at a level slightly below this to ensure a proper power flow). This allows the other converters to "set" their current requirements, and should help to alleviate the problem mentioned above.

Further to this, if one inverter requires a rescheduling of power, it only has to change its current order; the other inverter does not even need to know about it as it is only concerned about what current it requires. If both inverters were in voltage control, when one converter changed its current order, the other inverter would see the voltage drop or increase due to the increase or decrease in current, and without proper co-ordination, would counteract any changes.

Power Reversal A multi-terminal HVDC system depends very much on having a very reliable control, protection and telecommunication system. Certainly, there are differences between a two terminal and a multi-terminal HVDC. Handling the strategy of reversal of power direction is one of the differences, because of the unidirectional current carrying capability of the valves.

In a two terminal HVDC system the reversal of power direction is achieved through the reversal of the polarity of the DC voltage. In a two terminal bipolar HVDC system, the positive pole becomes negative and the negative pole becomes positive, while the current still flows in the same direction.

In a multi-terminal system, again the DC current direction cannot be reversed through the thyristor valves. Therefore a different strategy must be applied for the reversal of power direction. In addition, to make a multi-terminal system as flexible as possible, the reversal of power direction has to be on a terminal basis. Obviously, if the reversal of power direction is performed for the complete HVDC link, then the same two terminal strategies can be applied.

Referring to Figure 2, station A is operating as a rectifier, station B as rectifier, and both stations are transmitting power to the inverter at station C.
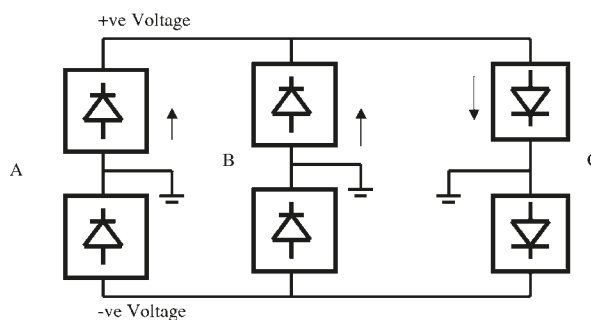

Figure 2 Multi-terminal link.

…the PSCAD® model allowed us to relatively quickly develop and tune the controls for the variety of multi-terminal links, which can change substantially given the transmission medium.…

A decision is made by the operator or power scheduler that requires station B to change from a rectifier to an inverter. Since stations A and C are to be kept in the present operating mode, the DC voltage polarity cannot be reversed and since the direction of the DC current cannot be reversed, then other measures must be applied. Referring to Figure 3, switches must be installed as shown on each pole in order for the pole to change the current direction in station A.

As station B is operating as a rectifier, the starting point for both converters at station B shall be:

• The high speed switches HSS1 and HSS2 are closed together with the disconnect switches 1 and 2.
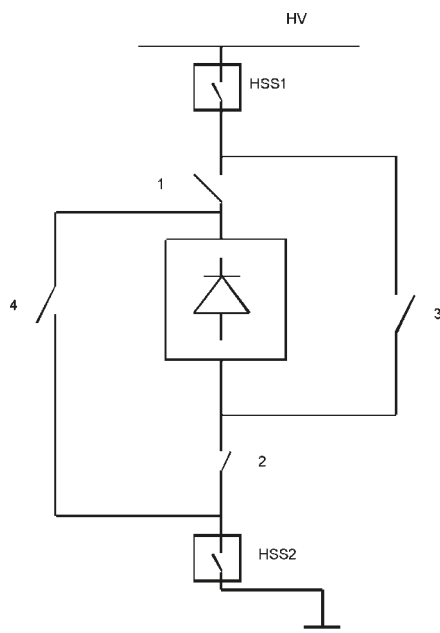• Disconnect switches 3 and 4 are open.

Figure 3 Reversing switches.

When the command is issued to reverse the power direction for station B, meaning to change it from a rectifier to an inverter, the following will happen:

• The DC current in station B is brought to zero.
• As soon as the DC current is zero in station B, the high speed switch HSS1 followed by HSS2 are commanded to open. The function of these switches is to isolate station B from the DC line and the neutral busbar as quickly as possible. Then once HSS1 and HSS2 are opened, the converters are blocked.
• Disconnect switches 1 and 2 are commanded to open and disconnect switches 3 and 4 are commanded to close. This will physically reverse the direction of the thyristor valves.
• The switch HSS2 is commanded to close followed by HSS1.
• The converters are deblocked at maximum firing angle to maintain zero DC current.
• The current reference of the new inverters is released by ramp in coordination of the stations A and B through the master power controller and current order coordination.

Figure 4 (see page 10) shows the power reversal sequence. Station 1 is originally running as an inverter, transmitting 1600MW to stations 2 and 3. Station 1 trips, and in order to maintain the power flow to station 2, station 3 switches to inverter mode.
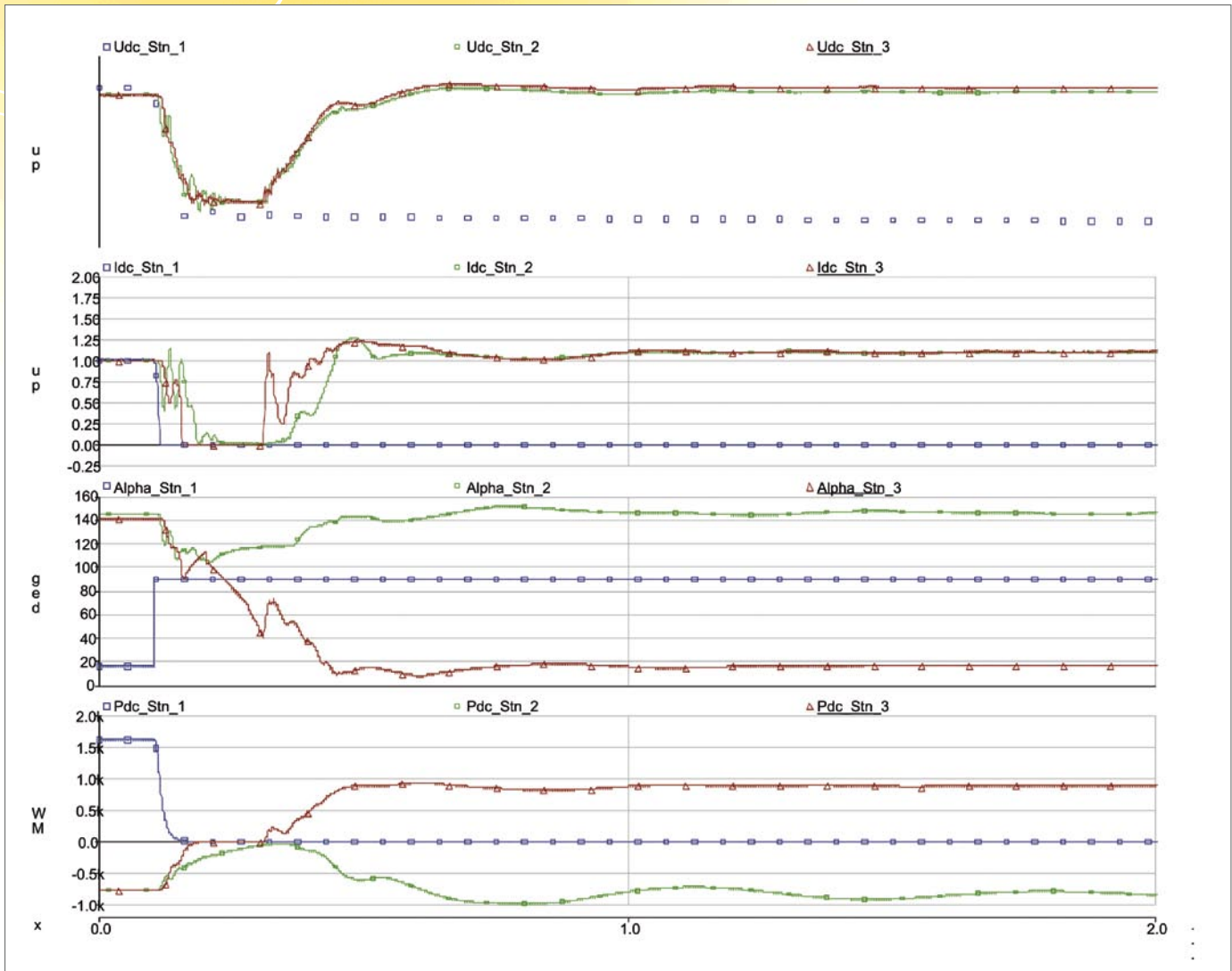
Figure 4 Power reversal sequence.

Conclusions PSCAD® has proved to be a very valuable tool in the simulation and design of multi-terminal HVDC schemes. It enables the user to develop detailed models of the HVDC system and its extended AC network.

If anyone would like to discuss multi-terminal HVDC further, please feel free to contact the author at *dkell@transgridsolutions.com*

References

[1] R. Brandt, U.D. Annakkge, D.P. Brandt, N. Kshatriya, "Validation of a Two-Time Step HVDC Transient Stability Simulation Model including Detailed HVDC Controls and DC Line L/R Dynamics," IEEE Power Engineering Society General Meeting, 2006.

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