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# Energization Study of Five-terminal Multi-level HVDC Converter Station

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**Abstract**—Impact of HVDC converter energization connected to multi-terminal hub on network performance is presented in this paper. Due to capacitors used in HVDC converter, its energization produces a higher inrush current causing a severe voltage dip in both the ac and dc systems potentially exceeding the allowable limits. Similarly dc cable and HVDC transformer energization also causes a higher inrush current that can damage the semiconductor devices used in the converter system. The paper discusses fundamental principles, energization schemes and pre-insertion resistors as a mitigation measure among other. A case study was selected and the results are presented under various grid-conditions.

**Index Terms**—Energization, Insulation Coordination study, HVDC

## I. INTRODUCTION

DUKE to greater emphasis on reducing carbon footprints, generation based on renewable energy resources has gained upward momentum particularly generation based on wind power. A number of countries have been witnessing a substantial growth of wind generation and its inter-connection into the national grids. Despite availability of wind energy that is abundant and renewable, its deployment is slow due to planning permission issues and public objection for onshore wind farms. Offshore wind farms present a good alternative due to steady and high speed wind offshore resulting in high energy yields. However offshore wind farms present different challenges such as high cost, supply chain management issues and constraint of transporting the energy to onshore. Particularly if the distance of the offshore wind farm is far from the shore, the power carrying capability of an ac transmission cable is greatly reduced due to charging current. HVDC is considered as an alternative solution, as a result it poses exciting challenges and opportunities for enhancing understanding of various aspects of system studies related to DC grid. The scope of this paper is limited to energization aspect of HVDC converter and related circuitry and uses commercially sensitive models.

This paper presents outcome of an energization study of a multi-terminal multi-level HVDC converter stations connected to a dc hub using long dc cables. HVDC converter stations consist of power converters, transformers, cables and filters are characterized by low impedance paths. When HVDC

converter station is energized, some or all of them are energised causing a large inrush current in the circuit due to capacitor charging and energization of the transformer, cables and associated filters. This results in system voltage distortion, undesired harmonics generation and over-voltages leading to potential malfunctioning of protection equipment, equipment failures [1] and non-compliance with the grid codes. As during most of the cases converters are blocked during energization, inrush current can also potentially damage diodes if preventive measures are not taken.

This paper is organized in six sections: the first section deals with the background information related to the study. The second section briefly describes modeling methodology adopted during the study and the limitations, whereas the third section explains in detail about the network, its operational requirements and limitations, and the case studies. In section four, information about simulation is presented together with results. A discussion of results is presented in this chapter, followed by the last section which draws the conclusion.

## II. MODELING METHODOLOGY

This section briefly describes about the modeling methodologies and limitations. The study has been carried out using commercially available EMTP software PSCAD.

### A. Grid

The grid was modeled as a voltage source representing its fault level and X/R ratio at the point of common coupling (PCC). The standard PSCAD library model was used and the damping was represented for the fundamental frequency and the fifth harmonics. During the case studies, both minimum and maximum fault level were considered.

### B. Converter and Control

A multilevel multi-terminal converter stations were modeled based on VSC having capability to operate as either rectifier or inverter depending on the operating conditions of the HVDC transmission link. Due to commercial sensitivity and defined scope of this work, details of converter topology and control system are not discussed in this paper. ABB HVDC Light technology are widely deployed and hence a proven technology. It is therefore fair to assume that the model do not require further scrutiny and/or validation.

### C. Transformer, Filters and Cables

Transformer is modeled using standard library component

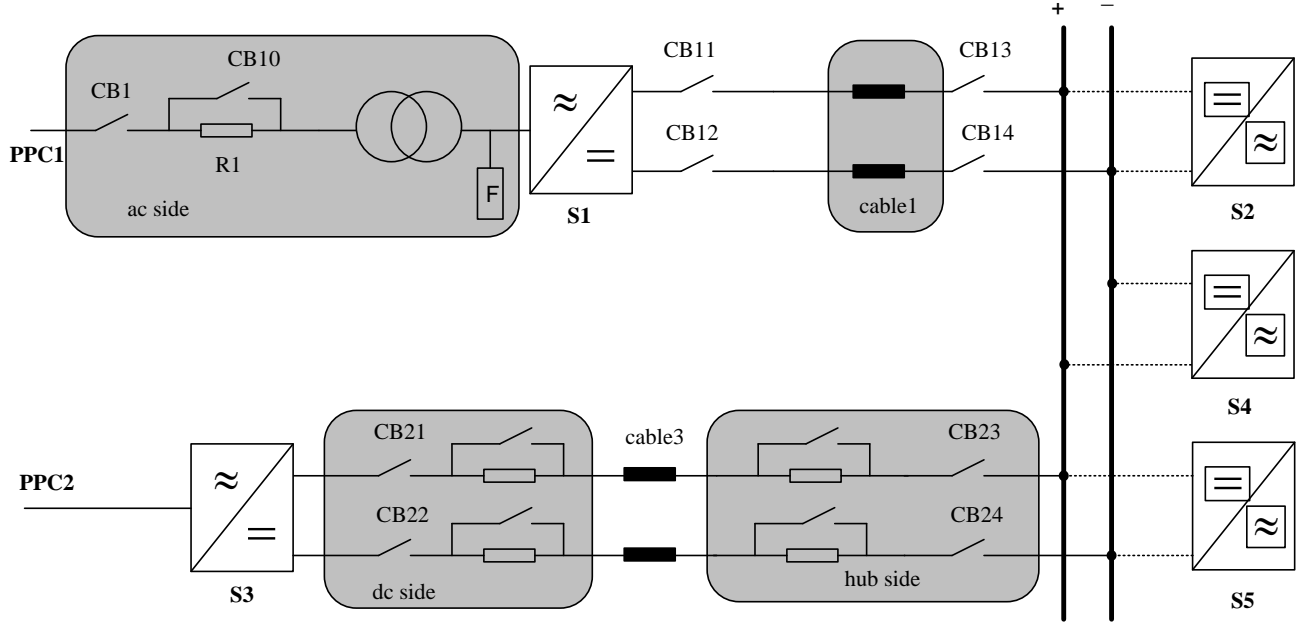


Fig. 1. Five-terminal HVDC transmission system connected to the grid at PCC1 and PCC2

with additional emphasis on two features: saturation characteristics (core flux/current relationship) and residual core flux. Transformer model includes core losses (kW) to represent resistor and magnetizing current to represent the parallel inductance. The model allows modification to include the saturation characteristic; however there is no inbuilt model option to represent core residual flux which is done by injecting dc current from external source.

Transformers are designed and operated at the knee point of the core saturation characteristics implying that any dc shift of core flux or asymmetry in the phases may drive the operating flux point into saturation zone. This in turn will generate a very high inrush current as saturation region is characterized by low impedance [4].

Underground dc cables are used to transmit the power from one to another point. To represent those cables, geometrical models are created and used to represent them requiring structural geometry and material properties. This is done using standard library component. This approach of modeling offers a number of advantages over the distributed pi-model such as less computational burden and representation of skin effect at higher frequency current and voltage. Skin effect cannot be ignored as cables are subjected to these high frequencies currents and voltages during switching events. The length of cable1, cable2, cable3, cable 4 and cable5 are 90 km, 250 km, 64 km, 10 km and 30 km.

Filters are represented as a combination of R, L and C components and their parameters are chosen to account for current limiting reactor and the quality factor.

Circuit breakers and high speed dc switches are modeled as ideal circuit breaker or switches having a big resistance when they are open and a very small resistance when they are closed.

#### D. Pre-insertion resistor (PIR)

PIRs at the AC side of S1 and S3 are modelled as resistive component using the PSCAD library component. DC PIR was also modelled as a resistive component. with the following parameters:

### III. STUDY NETWORK AND CASE STUDIES

#### A. Network

A five-terminal HVDC transmission system is chosen for analysis and its simplified version is shown in Fig. 1. Converter stations S1, S2, S3, S4 and S5 are connected to a common dc hub using dc cables. S1 is rated for 1200 MW, S2 and S3 are rated for 600 MW and remaining S4 and S5 rated for 300 MW each.

The converter stations are connected to ac side using a transformer, an ac circuit breaker and a pre-insertion resistor (PIR) with a by-pass switch. For simplicity, measuring and protection equipment are not shown in the figure and for the sake of tidiness, not all the components are labeled.

The dc side switches include high-speed switches (HSS), for example CB21 and CB22, and the PIRs with by-pass switches. Similarly the hub side switches include HSS and PIR. To minimize the physical size of the figure, dc and hub side switches of S2, S4 and S5 are not shown. These switches are similar to those of S3. Similarly ac side circuit breakers and PIRs are not shown for any of the converter stations except for S1. The ac side switching arrangements for all the converter stations are similar to that of the converter station S1.

#### B. Operational Requirements and Case Studies

Due to operational requirement, S1 converter will always operate in inversion mode, S3 will normally work in

rectification mode unless S1 is out of service, and S2, S4 and S5 will always work in rectification mode. For this study, it is considered that the converter stations S3, S4 and S5 are connected to the wind farms or other source of distributed generation implying that the power will be fed into the grid via dc transmission system. This operational condition requires that those converter stations operate in rectification mode. Power generated by wind farms transported through S2, S4 and S5 together with power flowing through S3 would then be supplied into the grid via S1 at the PCC1.

Operational requirements during energization are influenced by many factors such as the grid code, converter capability, device ratings and tolerances, and protection settings. The national grid codes in various countries set limits for ac or dc voltage dip that should not be violated during transient or dynamic condition including energization. Likewise converter (semiconductor valve) rating and protection system set the limit for inrush current. For analysis and conclusion, the results of this study are benchmarked against ac and dc voltage dip of 10% and 20%.

In a network as shown in Fig. 1 energization of converter, cable or dc hub can be done in a number of ways. For example, S1 and its associated cable can be energized from ac side by closing CB1. The dc hub in itself does not contain any element generating inrush current, so it can be energized by closing CB13 and CB14. If other circuits are connected to the dc hub, then dc hub can only be energized by closing CB1. From design prospective, CB11 to CB14 are required to connect the energized dc hub to the energized S1 when S1 returns from out of service state to conducting state with all other converters operating as normal.

The S1 and S3 circuits are different at the dc side arrangements; S3 dc side has PIRs as S3 requires energization from both ac and dc sides.

In this paper the following cases were run to assess impact of energization on system voltage:

- Case 1: AC energization of HVDC cable and converter
- Case 2: DC energization of HDVC cable and converter

#### IV. SIMULATION AND RESULTS

During energization of the dc cable and converter station, inrush current lead to voltage dip in the system, therefore these parameters (voltage and current) are recorded. Similarly dc pole voltage at the converter stations and dc hub voltage profiles are also recorded. Simulation results are presented for the two cases bus different combinations in Fig. 2 and Fig. 3. Each figure shows five profiles: from top to bottom, ac voltage (rms) at the pcc, instantaneous voltage at the pcc, dc pole voltage of the converter, inrush current and the dc hub voltage. Fig. 2 shows voltage and current profiles of the network at the different buses when a) the converter S1 and the cable are energized from ac side by closing CB1 and b) dc cable of converter S3 is energized by closing CB23 and CB24.

AC energization of converter station S1, cable and hub is done simultaneously using an ac PIR. The ac circuit breaker is

switched on at 500 ms, the pre-insertion resistor (PIR) is bypassed at 900 ms and before de-blocking the converter at 1.5 s, transformer tap was changed to enhance the dc pole to pole voltage to its near rating to minimize any disturbances. Command for transformer tap changing is given at 1.2 s. Fig. 2 shows six transient events at 500 ms, 900 ms, 1.2 s, 1.5 s, 2.4 s 1.9 s and 2.9 s. Clearly the biggest inrush current is observed at 500 ms when the converter, filter, transformer and the dc cables were enegized using a PIR to limit inrush current and to avoid unacceptable system ac and dc voltage dips. If current is not controlled it will not only cause a voltage dip, but damage to the semiconductor devices used in the converter.

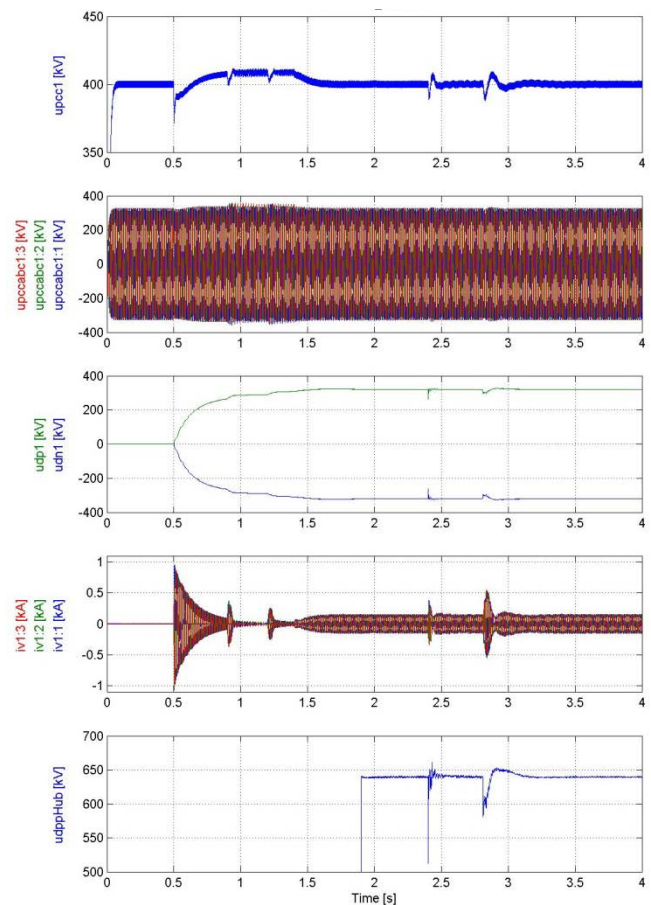


Fig.2: Energization of S1 converter and dc cable from the ac side and dc energization of dc cable of S2. From top to bottom- ac voltage profile at the pcc1 (rms), instantaneous voltage profile, dc pole voltages of the converter S1, inrush current, dc hub voltage

Voltage start building up at the dc poles of the converter (fig. 2) as dc link capacitor charges. The rate of charge of dc link capacitor depends on the current drawn. A smaller magnitude of PIR results in faster charging of capacitor, but a larger in-rush current and visa-a-versa for larger PIR. As long as PIR remains connected to the circuit, it is subjected to energy dissipation in the form of joule loss requiring its removal from the circuit at the earliest to optimize its size and reduce its cost. At 900 ms the PIR is bypassed resulting in a smaller ac voltage dip and smaller inrush current. Before de-blocking the converter, the dc link voltage was restored to near

its rating by changing the tap of the transformer at 1.2 s. Finally the converter is de-blocked at 1.5 s and the IGBTs become operational. The converter operational mode after de-blocking is fully controllable and voltages at the ac and dc sides are maintained at their rated values. Once the dc link voltage reaches its rated value, dc hub is energized by closing CB13 and CB14 that can be observed in fig 2 and 3.

The second part of the fig. 2 is a period after 2 s representing case 2 mentioned in the previous section. Transients in the fig. 2 at 2.4 s is related to energization of dc cable connecting converter station S3 which is performed by closing hub-side circuit breakers CB23 and CB24 using hub side PIR. The PIR value and pre-insertion time can be selected to minimize the dc and ac voltage dips to allowable limits both during switching in and by-passing the PIR. PIR of  $70 \Omega$  with pre-insertion time of 10 ms resulted in a smaller ac dip, but a bigger dc voltage dip reaching 18.75%. This value is less than allowable dc voltage limit of 20%. Transients at 2.9 s are related to energization of dc cable connecting S2 using PIR  $1500 \Omega$  for 500 ms. The optimization of this PIR is done by selecting largest PIR value when cable 2 is energised from S1 and S2, normally at pcc1 and pcc2 using minimum FCL.

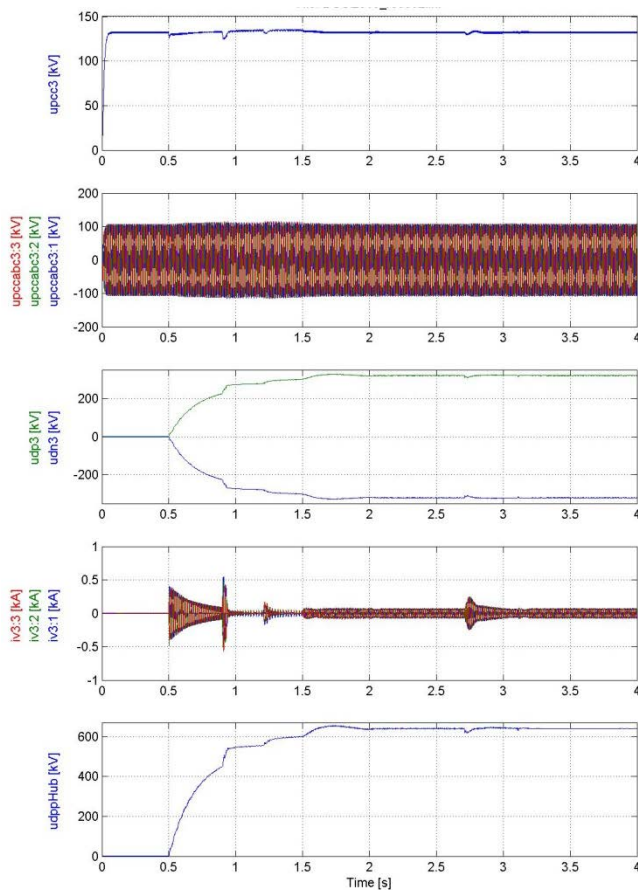


Fig.3: Energization of S3 converter and dc cable from the ac side. From top to bottom- ac voltage profile at the pcc2 (rms), instantaneous voltage profile of the pcc2, dc pole voltages of the converter S2, inrush current, dc hub voltage

The maximum ac voltage dip during energization was found to be 7% when the pcc1 was modeled with minimum fault

current level (FCL). The dip is reduced when pcc1 was modeled with higher FCL.

Fig. 2 represents transients related to energization of S1, S2 and S3 amongst which S1 is always energized first. In unfortunate event, when S1 is out of service or is not available, energization must be carried out via S3. It is worth recalling that only S1 and S3 are connected to the ac networks of the grid. Fig. 3 represents transients related to energization of S3 and S2. For a weaker network (pcc2 with FCL of 2500 MVA at 132 kV) ac energization poses challenge, specially while selecting the PIR. For a smaller FCL at the pcc bypassing of the PIR may result in a voltage dip more than the allowable limit requiring a special consideration. A study has been carried out to analyze the impact of energization through weak grid (pcc) onto the voltage and current. While pcc1 represents stiff grid, pcc2 represent weak grid. The sequences of energization events of S3 are similar to those mentioned for Fig. 2 until 2 s. Clearly it is seen that the PIR by-pass resulted in a higher voltage dip than when the converter station is energized. The highest voltage dip reaches to 3.8% which get worse when the energization is carried out with reduced FCL at the pcc2. The voltage dip reached 8.9% when FCL at the pcc2 is modeled as 1000 MVA.

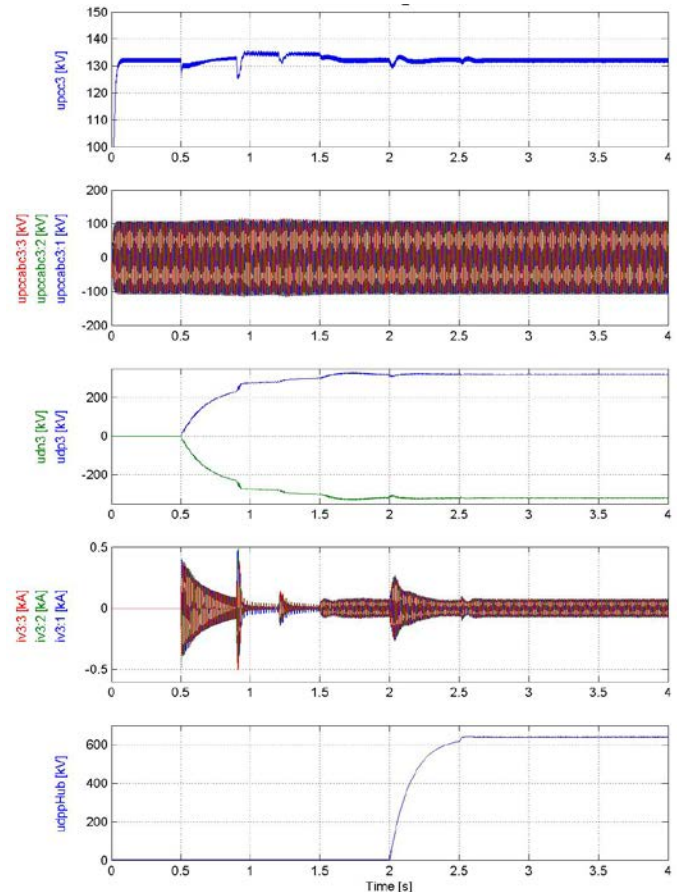


Fig.4: Energization of S3 converter and all the dc cable from dc side (pcc2 fault level 2500 MVA). From top to bottom- ac voltage profile at the pcc2 (rms), instantaneous voltage profile of the pcc2, dc pole voltages of the converter S2, inrush current, dc hub voltage

Figs.4 and 5 show plots when cables 1,2,4 and 5 are energised by switching in CB23 and CB24 for PCC2 fault level of 2500 and 1000 MVA.



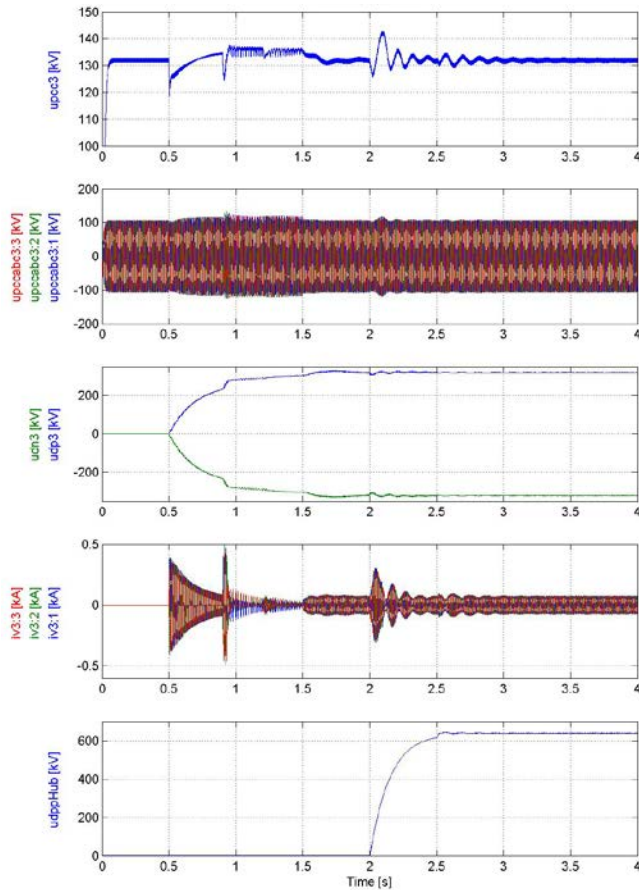


Fig.5: Energization of S3 converter and all the dc cable from dc side (pcc2 fault level 1000 MVA). From top to bottom- ac voltage profile at the pcc2 (rms), instantaneous voltage profile of the pcc2, dc pole voltages of the converter S2, inrush current, dc hub voltage

Until 2 s, the energisation sequences are similar to that of Fig.2 and Fig.3. At 2 s all the cables are energised from dc side as opposed to ac side in Fig.2. A dc PIR at the hub side (Fig.1) is used to energise the cables to comply with the grid code related to transient voltage. The ac voltage dip when pcc2 was modeled with fault level of 2500 MVA (Fig.4) was found to be 2.27%. The same events are simulated with pcc2 fault level of 1000 MVA. The voltage dip for this case was found to be 4.55%, however Fig.5 clearly shows an oscillation when all the cables are energised and PIR was bypassed at 2.5 s.

This implies that for a weak to very weak ac networks, the optimization of PIR becomes challenging and PIR alone may not be a solution. It may require the retuning of HVDC converters controls or altogether avoid this kind of energisation sequences

## V. CONCLUSION

The study shows that a PIR is required to energize the S1 dc cable either individually or with maximum dc circuit. The PIR and the insertion time are selected to limit the ac voltage dip to the acceptable limits during energization of the cable or cables and disconnection of PIR from the circuit. Specially energization from ac side having low SCR poses challenge in optimizing PIR requiring special consideration. The requirement for PIR is network dependent and should not be considered as a general requirement. Each network should be studied for individual cases to optimize PIR if required.

## REFERENCES

- [1] H R Puente, M L Burgess, E V Larsen and H Elahi, "Energization of Large Shunt Reactors near Static VAR Compensators and HVDC Converters," *IEEE Trans. On Power Delivery*, vol. 4, No.1, pp. 629–636, Jan 1989.
- [2] D Goldsworthy, T Rpseburg, D Tziouvaras and J Pope, "Controlled Switching of HVAC Circuit Breakers: Application Examples and Benefits," Schweitzer Engineering Laboratories, Inc, 2007, 2008.
- [3] X Wang and M R Iravani, "Energization Transients of Shunt Reactors," *IEEE Trans. On Power Systems*, vol. 12, No.4pp. 1626–1631, Nov. 1997.
- [4] John H Brunke and Klaus J Frohlich, "Elimination of Transformer Inrush Currents by Controlled Switching- Part 1: Theoretical Considerations," *IEEE Trans. On Power Delivery*, vol. 16, No.2, pp. 276-280, April 2001.

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