Export Cable Energization in Offshore Wind Farms

G. WU, D.F. CANON, W. EDMONDSON, R. HARIHARAN
Mott MacDonald
USA

SUMMARY

Many large-scale offshore wind farms have been proposed for interconnection to the electric grid in the Northeast United Sates. Key components of these offshore wind farms are high-voltage AC subsea cables that export power from the offshore wind turbine generators to onshore substations for interconnection to the transmission system.

Many of the feasible points of interconnection for these projects are characterized by weak system strength, due to the lack of high-capacity transmission infrastructure near the seashore. With weak grid conditions, the power system is prone to issues with power system transients caused by the energization of these long cables. Special cable energization equipment and switching techniques are needed to minimize the transient impacts of cable energization on the offshore wind facility and transmission system.

This paper presents the study process used to size the cable energization equipment and evaluate the impacts of export cable energization through detailed electromagnetic transient simulations. These studies were performed as part of the development for an 800 MW offshore wind farm. The methodology used for the sizing of pre-insertion resistors is presented along with the various cases that were studied for energization of the cable. The impacts to transient voltages that were observed in the simulations are also presented.

KEYWORDS

Offshore Wind, Cable Energization, Zero Missing Phenomenon, Wind Energy, Export Cable, Pre-Insertion Resistor, Controlled Switching Device, Transients

ramesh.hariharan@mottmac.com

1   INTRODUCTION

Offshore wind farms use high-voltage AC export cables to transfer power generated by the offshore wind turbines to an onshore substation, where the project is connected to the grid. The energization of these long high-voltage export cables presents several challenges that must be addressed during the design of the equipment and of the operational arrangements used to energize the cable. During cable energization, there may be large transient voltages due to cable capacitance [1][2]. Current zero-missing phenomenon (ZMP) through the energization circuit breakers may occur due to the shunt reactors used to compensate the cable [3].

ZMP can lead to circuit breaker failure when the breaker attempts to open. AC circuit breaker operation relies on current zero crossings to extinguish the arc that forms between the circuit breaker contacts during opening [4]. Without a current zero crossing, the arc will persist in the breaker for a long duration, which could damage the breaker; furthermore, devices that are adjacent to circuit breakers experiencing current ZMP can also be damaged.

The offshore wind farm consists of two parallel export systems carrying the power to the point of interconnection (POI). An onshore substation steps the voltage at the POI down from 345kV to 275kV for connection to the high-voltage export cables. These subsea cables connect to the offshore electrical service platform, where the offshore wind turbine generator collector system is located.

Due to the large capacitance of the export cable, fixed shunt reactors are connected at both the onshore and offshore ends of the cable to compensate for the reactive power gain of the cable. The compensation of the cable capacitance is needed to control the reactive power flow within the system and ensure that the project can operate at its required leading and lagging power factor at the POI. Onshore static synchronous compensators (STATCOM) provide the fast-acting reactive power control to the system, and help with voltage control of the system during the transients caused by the export cable energization.

The high-voltage export cable and the associated shunt compensation reactors are energized simultaneously by closing the onshore circuit breaker. This circuit breaker, used to energize the cable, is equipped with a controlled switching device that controls the closing time for each pole of the breaker, allowing for point-on-wave switching of the breaker. The breaker is also equipped with a pre-insertion resistor (PIR) that helps to dampen the transients caused by energization of the export cable. The circuit breaker at the offshore end of the export cable is open during energization of the cable.

In order to study the energization behavior of the export cable, detailed electromagnetic transient simulations of the system are performed to size the PIR and predict the transient overvoltages that may occur on the cable during energization.

2   MODELS, TOOLS, AND STUDY APPROACH

Cable Energization Equipment

To reduce the transient impacts of energizing the high-voltage export cables, both controlled switching devices and PIRs are used.

The controlled switching devices allow for point-on-wave closing of each individual phase of the circuit breaker. This allows for optimization of the voltage point at which the cable is energized on each phase to control the overvoltage caused by the energization. The controlled switching device is typically a specialized controller that is connected to a single-pole-operated breaker.

PIRs are used to dissipate the DC shunt reactor current and provide general damping to the transients caused by cable energization. Pre-insertion resistor circuit consists of a resistor that is connected in series with the circuit breaker so that all current through the breaker also flows through the resistor. After a predefined amount of time, known as the pre-insertion time (PIT), the PIR is bypassed and removed from the circuit. While the PIR is active in the circuit, a large amount of energy can be dissipated in the resistor if currents are high.

Three main factors need to be considered in the selection of a PIR.

1. Resistance: This is the resistance of the device in ohms. Selecting too small a resistance will prevent the PIR from providing appropriate damping to the energization transients. Choosing too large a resistance will delay the charging of the cable and reduce the damping while the PIR is in place, and transients will reappear once the PIR is bypassed.

2. Pre-Insertion Time (PIT): This is the amount of time the PIR is connected in series with the breaker and is typically expressed in milliseconds. At the end of the PIT, the resistor is bypassed and current no longer flows through the PIR. Too-short PIT will cause the PIR to have little impact on the transients; too-long PIT will increase the energy capability requirement of the PIR.

3. Energy Dissipation Capability: This is the amount of energy, in MJ, that the resistor must be capable of dissipating during the PIT. Longer PIT and higher currents through the PIR will increase the energy dissipation requirement of the PIR. Unnecessarily increasing the energy dissipation capability requirement of the PIR will typically increase the equipment size and cost.

Models and Tools

The cable energization and PIR sizing simulations were performed using PSCAD 4.6.3. The grid was modelled as a Thevenin equivalent at the POI. The PSCAD saturable autotransformer component was used to represent the onshore main power transformers. The shunt reactor was modeled using the PSCAD saturable reactor component with resistors to represent the copper and iron losses. The STATCOM was modeled using a detailed model provided by the manufacturer that accurately represents the dynamic response of the STATCOM.

The PSCAD frequency-dependent phase pipe-type cable component was used to model the three-core armoured export cables. Voltage along the export cable was monitored at each end, at the midpoint, and at quarter-length points.

Controlled switching devices with single-pole-operated breakers were used for point-on-wave energization of the export cable. An assumed error of +/- 1.6 ms was used for the operation of the controlled switching device from the point-on-wave switching at zero voltage [1].

Study Approach

The following approach was used to determine the specifications of the PIR needed at this offshore wind facility:

1. Perform cable energization simulations without a PIR to determine if ZMP occurs. Depending on the amount of shunt reactor compensation used for the cable, ZMP may not occur.

2. Once ZMP was observed, an iterative approach was used to find the PIR size during no-fault conditions that would avoid the ZMP. Resistor sizing started at 25 ohms and increased in 25-ohm increments up to 500 ohms with a PIT starting from 10 ms and increasing in 1-ms increments.

3. Using the selected PIR and PIT from Step 2, energization simulations were performed with cable faults present to determine whether any ZMP was observed with the faults simulated at different locations along the transmission circuit. Once the ZMP was observed with a faulted condition, the PIT was iteratively increased until no ZMP was observed for any cases.

During Steps 2 and 3, the system voltages were monitored to ensure they were below equipment voltage withstand limits. The PIR specification was set to obtain the best performance under normal no-fault cable energization conditions, as this will be the most common scenario during operation of the offshore wind facility. However, the cable energization equipment must be specified to survive energization onto a fault on the cable.

The energy dissipation across the PIR was calculated by integrating the active power loss across each phase of the PIRs over the PIT and then adding total energy from each phase. The PIT is the time that the PIR in each pole is maintained connected in series with the circuit.

Table 1 and Table 2 show the cases considered for the PIR sizing. During no-fault conditions, the energization was studied for different operational modes in which the plant may operate due to equipment outages within the facility. During fault conditions, the normal operating mode was studied for three line to ground faults (3LG) and single line to ground (LG) faults at different locations along the cable, with and without the other export circuit in service. All cases were studied under strong and weak grid conditions at the POI.

Table 1: Export Cable Energization Cases: No Cable Fault

Case #	Operational Mode	Other Export Circuit Status
1	Normal	Out of Service
2	Normal	In Service
3	STATCOM Out	Out of Service
4	STATCOM Out	In Service
5	Single Onshore Main Power Transformer Out	Out of Service
6	Single Onshore Main Power Transformer Out	In Service

Table 2: Export Cable Energization Results: With Cable Fault

Case #	Operational Mode	Other Export Circuit Status	Fault Type	Cable Fault Location
1	Normal	Out of Service	3LG	Electrical Service Platform Connection
2	Normal	Out of Service	3LG	Cable Midpoint
3	Normal	Out of Service	3LG	OSP Connection
4	Normal	In Service	3LG	Electrical Service Platform Connection
5	Normal	In Service	3LG	Cable Midpoint
6	Normal	In Service	3LG	Onshore Platform Connection
7	Normal	Out of Service	SLG	Electrical Service Platform Connection
8	Normal	Out of Service	SLG	Cable Midpoint
9	Normal	Out of Service	SLG	Onshore Platform Connection
10	Normal	In Service	SLG	Electrical Service Platform Connection
11	Normal	In Service	SLG	Cable Midpoint
12	Normal	In Service	SLG	Onshore Platform Connection

3   PERFORMANCE CRITERIA

The energization of the export cable mainly involves two transient phenomena:

- Switching overvoltage due to the charging of the cable capacitance
- DC offset of the reactor current due to the reactor inductance

Both transient events are mainly determined by the voltage at the instant of energization. For fully discharged cables, the cable charging switching overvoltages are minimized when the energization voltage is at zero. However, for fully demagnetized reactors, the DC offset is minimized when the energization voltage is at the peak [1][2]. The ZMP arises when the reactor inrush current AC component partially or fully cancels the cable-charging AC current so that current flowing through the breaker does not cross zero every natural half cycle [3].

Therefore, energization of the cable involves a careful compromise between controlling the overvoltage caused by the energization of the compensated transmission circuit and minimizing the reactor current DC offset, which is the main factor impacting the occurrence and duration of the ZMP. Taking into consideration that a controlled switching device is proposed to actively control the overvoltage caused by the compensated circuit's energization, the PIR and the associated PIT must be determined so that a switching sequence can be realized that eliminates the risk of ZMP occurrence under normal switching and under switching onto fault conditions. The following sets of criteria were used:

1. No ZMP should be observed in the breaker current under all studied cases.
2. The transient voltages along the cable should be kept at a minimum.
3. The PIR size and energy capability should be kept at a minimum if a PIR is found to be required.

4   EXPORT CABLE ENERGIZATION ANALYSIS

Cable Energization with No PIR

ZMP is observed under normal operation in Figure 1 during cable energization, when no PIR is used on the circuit breaker. The ZMP is present in the first several cycles and briefly reappears around the 1-second mark.
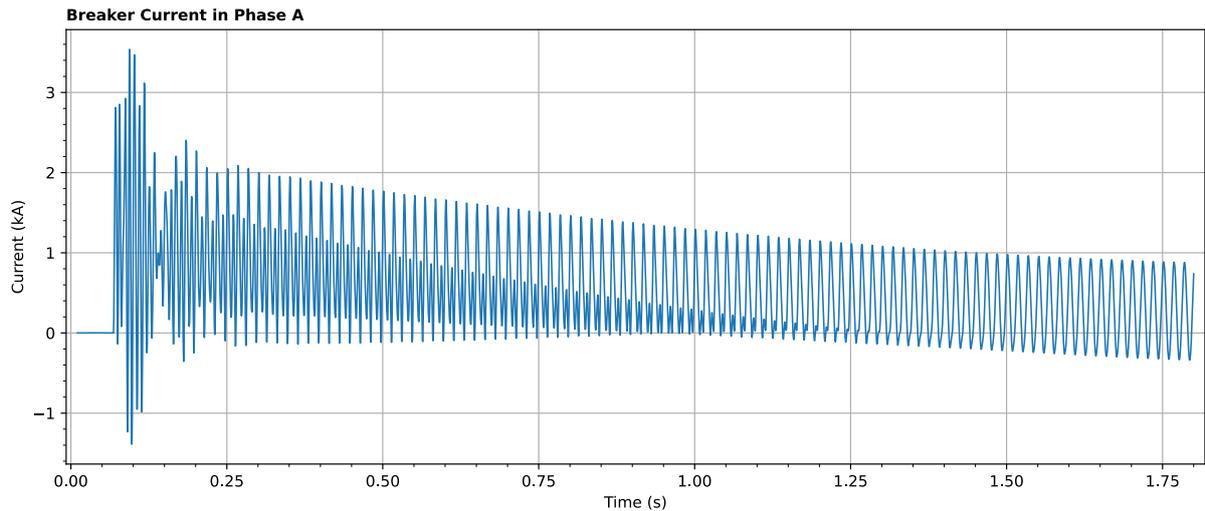
4

Figure 1: Circuit Breaker Current in Phase A with No PIR During Cable Energization: No Fault.

Iterative PIR and PIT Analysis: No Fault

Figure 2 and Figure 3 plot the results of the PIR iterative analysis without a fault. It can be observed that as more energy is dissipated across the PIR, the resistor becomes more effective in damping the DC current offset caused by the compensating shunt reactor that, in combination with the cable charging current, give rise to the ZMP. From this assessment it was concluded that a PIR larger than 50 ohms with a PIT of 10 ms would avoid the ZMP under no-fault conditions.
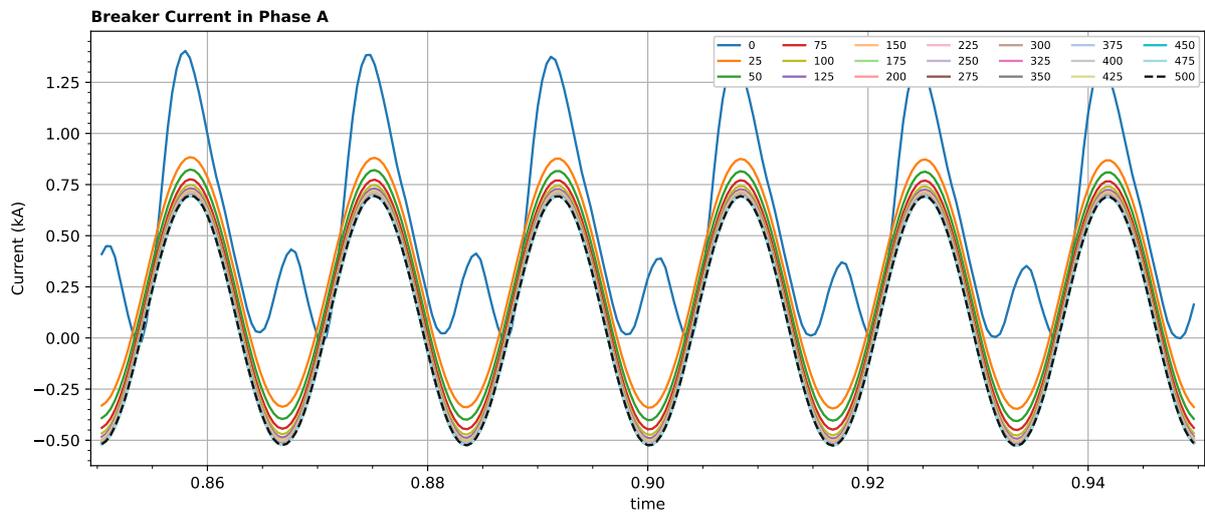
Figure 2: Circuit Breaker Current in Phase A with Different PIR Values with 10 ms PIT: No Fault.
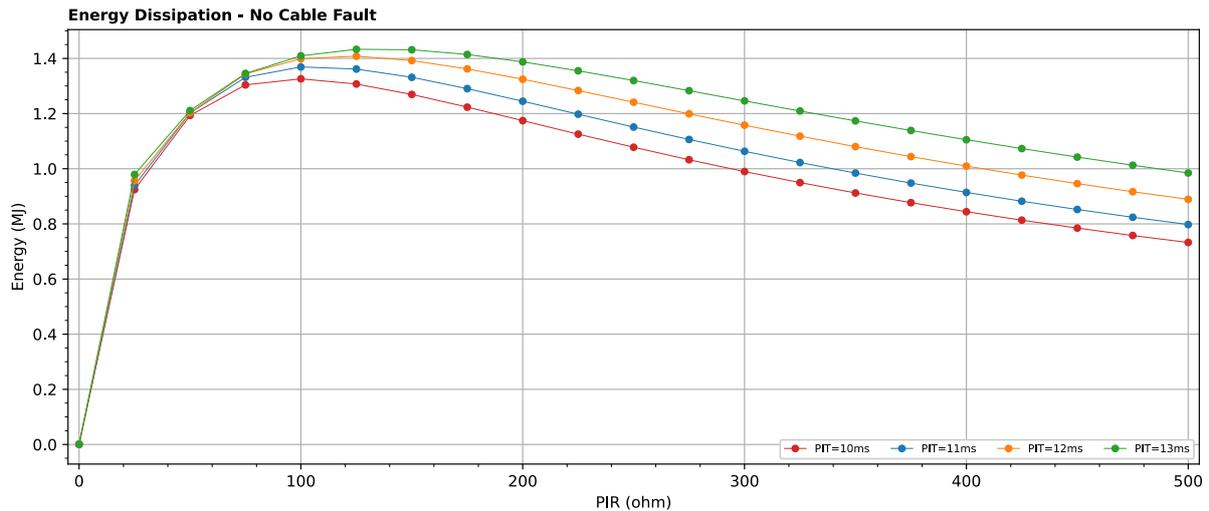
Figure 3: Energy Dissipation with Different PIR Values and PITs: No Fault.

Based on the results seen in Figure 3 above, the following can be concluded:

- Energy dissipation decreases for too-small or too-large PIR sizes.

- Increasing the PIT always increases the energy dissipation.

Therefore, given that the energy dissipation is directly proportional to the circuit damping, a PIR of 125 ohms with a PIT of 10 ms was selected, as it provides good damping while keeping the size of the resistor small and allowing potential larger dissipations at longer PITs.

Iterative PIR and PIT Analysis: With Fault

The 125-ohm PIR was then tested under fault conditions. During this assessment, it was concluded that a minimum PIT time of 13 ms was required in order to avoid the ZMP. Figure 4 shows the results of varying the PIT with a PIR of 125 ohms with a pre-existing 3LG fault at close to the onshore substation.

ZMP is more severe during fault conditions because the location of the fault along the cable changes the voltage impressed across the reactor (changing the magnitude of the DC and AC components of the reactor current) and of the voltage applied across the distributed capacitance of the cable (changing the magnitude of the charging current).
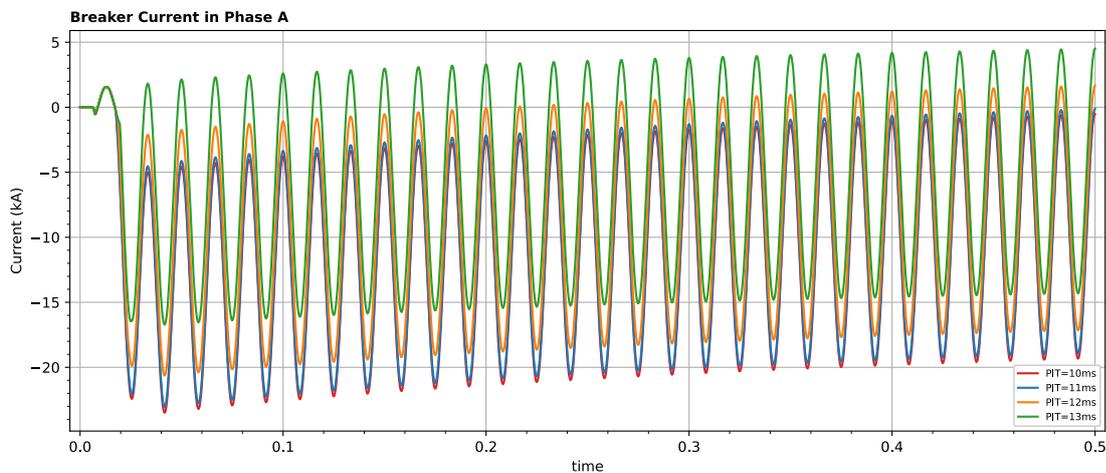

Figure 4: Current Through Breaker with Different PIT Values: 3LG Fault Close to the Onshore Substation.

Voltage and Energy Analysis: 125-Ohm PIR at 13 ms PIT

Figure 5 and Figure 6 show the maximum PIR energy dissipation and voltage respectively observed across the cable with the selected PIR size of 125 ohms with a PIT of 13 ms for both strong and weak grid conditions.

Figure 5 shows the worst-case energy dissipation across the PIR. The wort-case energy dissipation was observed in Case 5 under the strong grid scenario. The highest energy dissipation occurred during 3LG faults at the onshore end of the cable under strong grid conditions, as these conditions resulted in the least fault impedance.
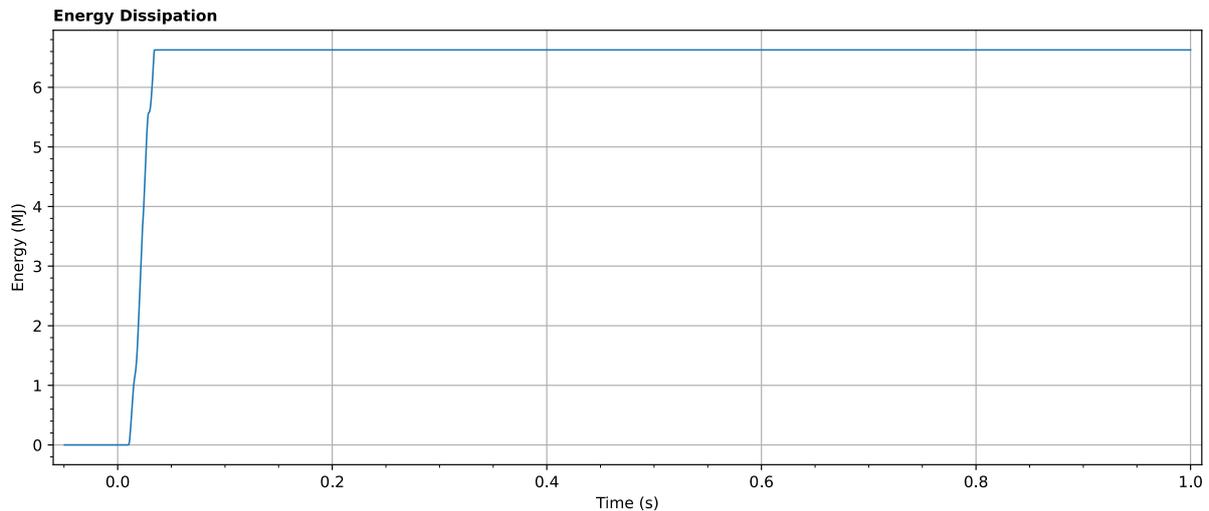

Figure 5: Energy Dissipation for Case 5 with Cable Fault.

Figure 6 shows the worst-case voltage observed along the cable. The worst-case voltage was observed at the cable endpoint for case 10 under the weak grid scenario. The highest voltages occurred during LG faults at the offshore end of the cable when weak grid conditions were simulated.
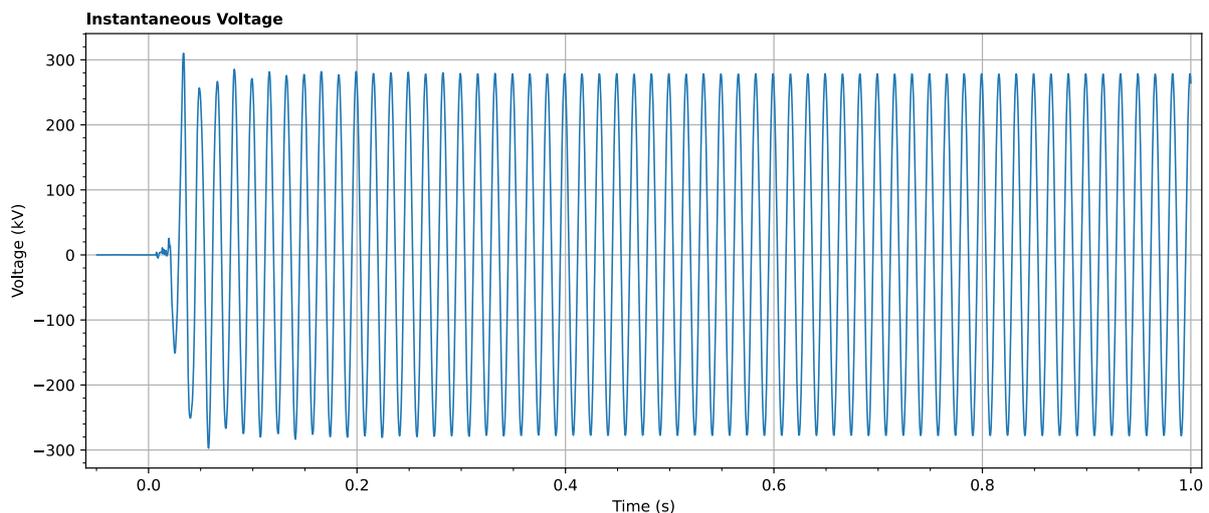

Figure 6: Instantaneous Voltage at Cable Endpoint for Case 10 with Cable Fault: Weak Grid.

5 CONCLUSIONS

Offshore wind farms are becoming an attractive alternative for increasing renewable penetration in North America. Offshore wind farms are often interconnected in the weak part of the grid due to lack of transmission system at the POI. ZMP is a common issue seen with cable energization along with a shunt reactor, which could potentially damage equipment. A combination of Controlled Switching Device and PIR could be used to mitigate the risk of ZMP. This paper proposes a systematic iterative methodology that could be adopted and used for energizing the export cable for offshore wind farms, which optimizes the selection of the PIR size utilizing energy dissipation. Results presented in the paper are geared towards the particular project studied. The PIR and PIT values are dependent on project configuration and short-circuit strength at POI.

As the project design is optimized further, this study should be repeated and further investigated to optimize the PIR value and PIT. Further analysis should be performed as equipment size and control logic/error of the procured controlled switching device and other as-built equipment data becomes available. A final as-built study should be performed validating the results before project is energized.

BIBLIOGRAPHY

[1] Allan Greenwood, *Electrical Transients in Power Systems: Second Edition* (New York, Wiley Interscience, 1991).
[2] Ariel L. Shenkman, *Transient Analysis of Electric Power Circuits Handbook* (The Netherlands, Springer, 2005).
[3] da Silva, F. M. F., Bak, C. L., Gudmundsdottir, U. S., Wiechowski, W., and Knardrupgård, M. R., "Methods to Minimize Zero-Missing Phenomenon" (*IEEE Transactions on Power Delivery*, 25(4), 2923-2930, 2010).
[4] Thomas E. Browne Jr., *Circuit Interruption: Theory and Techniques* (New York, Marcel Dekker, 1984).