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GROUP REF. : A3
PREF. SUBJECT : 1
QUESTION N° : 3

Introduction: offshore wind generation integration concern

Integration of offshore wind generation to the grid introduces new technical challenges for transmission system operators and T&D equipment manufacturer.
Long distance transmission systems to connect the power generated by offshore wind turbine generator (WTG) and collected by offshore substation (OSS) have been deployed over the last years considering two main technologies: HVDC links and HVAC links.
This contribution focuses on HVAC transmission through long compensated insulated submarine cables and the concern about current zero missing phenomena, also known as delayed current zero or non-zero crossing.

Collection and transmission of the power produced by wind turbine generators

The power generated by the WTG is, typically, collected at the OSS by a 33 kV a.c. to 66 kV a.c. submarine array cables, and transmitted to the 132 kV a.c. to 220 kV a.c. transmission network through submarine export cables connecting the OSS to the onshore substation (Figure 1).

The OSS design generally includes a gas insulated switchgear (GIS), to collect the power from the WTGs, a GIS to transmit the power to the transmission network, and a transformer to step-up the collected power to the transmission voltage level.

Before connecting the generated power to the grid, switching procedures include the energizing of the export cable, open at its remote end, from the land [1].

The main concern during this procedure comes from the current zero missing phenomena.

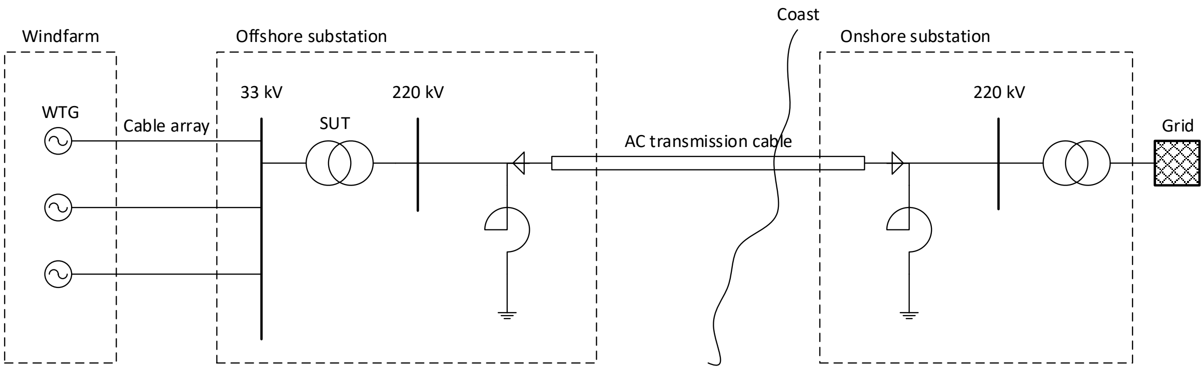

Figure 1 : offshore wind system

Current zero missing phenomena and effects

Need for inductive reactive compensation on long cable transmission systems and consequent current zero missing phenomena are documented in [2] and [3].
Basically, due to its capacitive nature, a long cable shall be compensated to control the voltage at its ends (reduce voltage raise effect) and to increase the active power flow. Compensation of the capacitive reactive power is usually close to 100%.
Theoretically, current zero missing phenomena can occur when the compensation level, using shunt reactors, is higher than 50%. This phenomenon is due to the reactors DC offset currents when switching on the cable and reactors together at or near voltage zero. The sum of the cable capacitive charging current and the shunt reactors inductive current, with opposite phase shift, shows current zero missing that lasts for several cycles, the decay of the DC offset in the reactors being related to the grid X/R ratio. An illustration of this phenomena can be observed in Figure 2.
If a protective relay is operated during the cable energizing sequence (closing on a fault, relay misoperation) there's a risk that the export cable circuit-breaker (depending on its capability to interrupt DC current, arc resistance, tripping philosophy) fails to interrupt the current and get damaged [4].

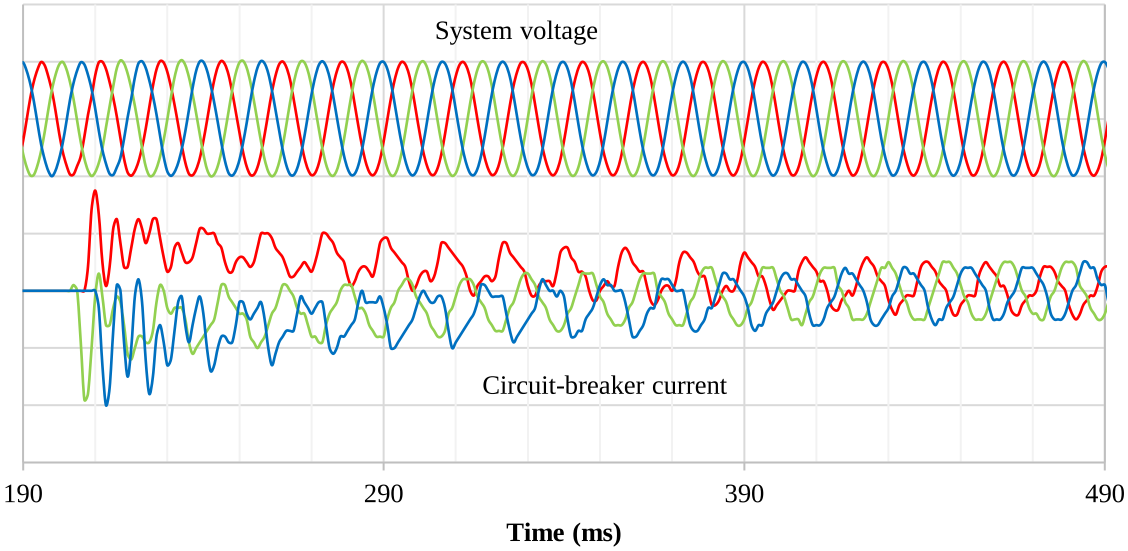

Figure 2 : current zero missing illustration (field record, energizing at voltage zero)

Countermeasure: how to defeat current zero missing phenomena

To defeat current zero missing phenomena, two approaches, with some methods listed in Table 1, can be enumerated:

- adapt protection strategy
- eliminate the cause of current zero missing

Table 1 : countermeasures to defeat current zero missing phenomenon

Countermeasure	**Pro**	**Con**
Fixed delayed tripping (< 20ms).	Achievable at reasonable cost and footprint.	Tolerate increased fault duration. Delay may not be sufficient to have current zero crossing achieved.
Adopt single pole tripping: trip only faulty phase and delay healthy phase tripping by protective relay action or pole discordance.	Achievable at reasonable cost and footprint.	Requires circuit breaker with IPO. Doesn't cover the event of protective relay misoperation.
Adapt energizing sequence, cable then reactor at onshore side.	Reduced compensation, lower than 50%, at the time of energizing.	Requires switchable reactor at sending end. Voltage variations.
Closing resistor.	Unique asset for voltage level higher the 362 kV.	Originally designed to reduce switching surge on lines, no closing resistor available at voltage level lower than 362kV. Case by case resistor value sizing, and pre-insertion time calculation. Long pre-insertion time (higher than 10ms), thermal design, short-circuit withstand.
Controlled closing at or near voltage peak to reduce current d.c. offset in shunt reactor [5] Field record of energizing at voltage peak is illustrated in Figure 2.	Mature technology. Flexible solution, applicable whatever the cable length and compensation rate. Reliable circuit-breaker available on the market. Achievable at reasonable cost and footprint.	Requires circuit breaker with IPO, stable and predictable operating time. Tolerate transient overvoltage and system voltage distortion.

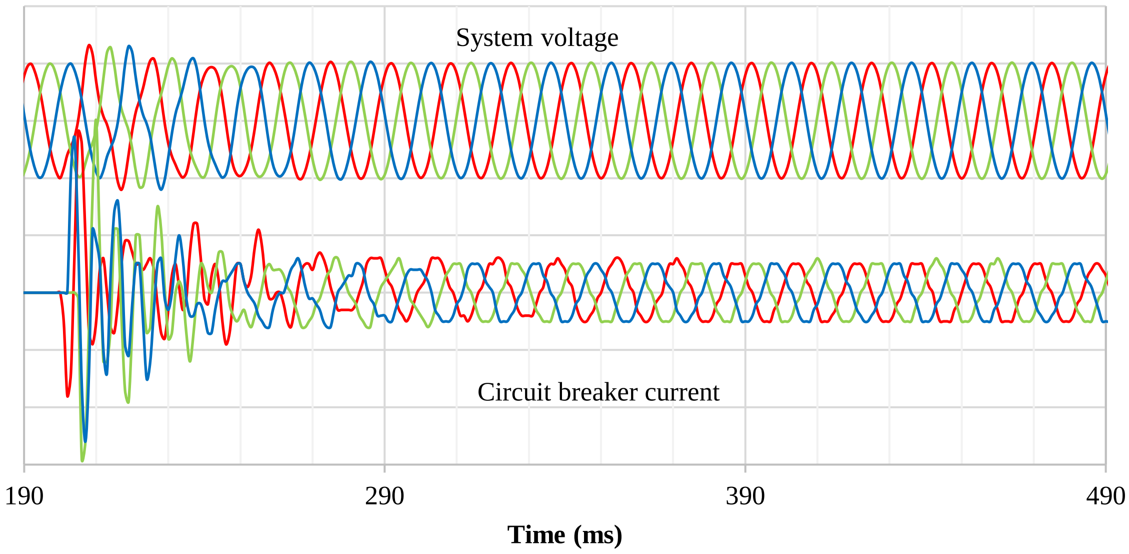

Figure 3 : controlled closing at voltage peak illustration (field record)

Conclusion: how controlled switching supports connection of offshore wind generation to the grid

Countermeasures to defeat current zero missing phenomena and help integrating offshore wind power to the grid have been introduced in this contribution. Some arguments are enumerated for each solution.
As the industry requires optimized solutions to reduce the cost, the footprint of their assets, and increase availability and reliability of their system, consideration of controlled switching technique seems the most appropriate to cover this need.
With its ability to cover a wide range of switching applications including transformer energizing on the OSS, shunt reactor switching… a common solution can be used for the global need of decentralization. The Controlled switching device (CSD) is one of the main bricks of the digitalization of the primary asset, and the most versatile solution able to adapt itself to network change.

References

[1] "Guidelines for the Design and Construction of AC Offshore Substations for Wind Power Plants", Cigre Technical brochure 483, Working Group B3.26, December 2011

[2] "Power System Technical Performance Issues Related to the Application of Long HVAC Cables", Cigre, Technical Brochure 556, Working Group C4.502, October 2013

[3] "Implementation of long AC HV and EHV cable systems", Cigre, Technical Brochure 680, Working Group B1.47, March 2017

[4] "Analysis of SF6 Circuit Breakers Failures Related to Missing Current Zero", Dmitry Chernoskutov, Vladislav Popovtsev, Sergey Sarapulov, Ural Smart Energy Conference, 2020

[5] "Solving Zero-Miss with Cable Energisation at Voltage Peak, Based on Insulation coordination Study Results", Unnur Stella Gudmundsdottir, Per B. Holst, IPST conference, 2013