SHUNT REACTOR COMPENSATION FOR SUBSEA CABLES IN INDUSTRIAL PLANTS

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Abstract - In Oil & Gas plants, there is sometimes the need to provide a transmission link at Extra-High voltage levels, typically from 132 kV to 245 kV, between an on-shore central process facility and other units installed on remote islands. In this scenario, the only way to provide the link is to use submarine cables.
The charging current of cables, especially for significantly long routes, raises however serious constraints about the maximum cable charging capacitive current which can be safely handled by Extra-High voltage circuit breakers under no-load switching conditions. In order to overcome this issue, shunt reactors are installed without circuit breaker feeders rigidly at one cable end or alternatively at both cable ends.
Electromagnetic switching studies are performed in order to determine the least amount and the lowest number of points of connection for the shunt reactor power compensation, and to avoid the use of special circuit breakers like those having non-simultaneous pole operation intended for controlled switching.

Index Terms — Shunt reactor, subsea cable, charging current, switching, Extra-High voltage.

I. INTRODUCTION

It is well known from technical literature that long Extra-High voltage AC cables pose in general serious concern in terms of allowable power that cables can transmit due to their inherent consumption of shunt capacitive power losses [4], [5].

Therefore, with AC power supply it becomes most often necessary to use shunt reactors in order to compensate the cable charging current and in such a way to best manage and control the reactive power flow inside extra-high voltage networks, especially when the transmission link is realized by means of subsea cables [3].

The aim of this work is to demonstrate the correct way of designing the shunt reactor compensation inside the Extra-High voltage transmission network of an industrial facility, with a particular focus on which is the correct electrical point of connection where shunt reactors can be installed: both steady state simulation with RMS analysis software [12], and electromagnetic transient simulations with EMT analysis software [9], are necessary in order to finalize the correct design.

A. System Data

The principle of the electrical distribution scheme of an industrial Oil & Gas facility, in which an off-shore central process plant supplies at 220 kV AC other process units installed on remote islands, is shown in Fig. 1. The interconnection between the central process plant and the remote process units is done through two redundant submarine cables, each three-core, 630 mm^2, copper conductor, each cable being designed to carry the whole power of the remote plant units.

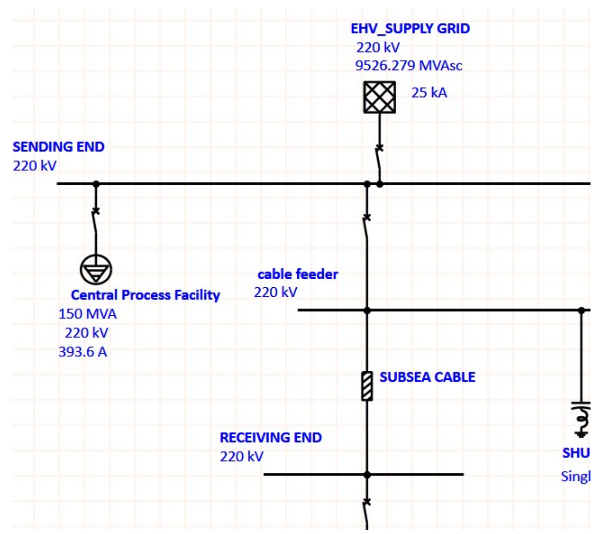

Fig. 1 Simplified single-line diagram of the electrical system

Main electrical parameters for the network components are reported in the Appendix.

B. Modeling

For the aim of numerical simulation of electromagnetic transient phenomena by EMT analysis software [9], the electrical network is simplified and modeled as shown in Fig. 2, following the general guidelines presented in [10].

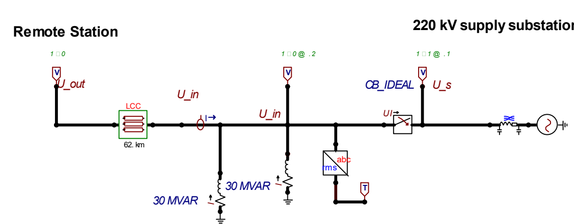

Fig. 2 EMT analysis software model of the electrical system

The 220 kV supply network is modeled with an equivalent impedance having a reactance and resistance derived from the minimum short circuit power of the supply source grid.

The subsea cable is modeled with a distributed parameter model (Bergeron model in EMT analysis software [9]): for the aim of studying the phenomena of cable energization and delayed current zeros, the Bergeron model is accurate enough [1], [2].

The shunt reactor is modeled as an impedance made of reactance and series resistance.

C. Requirements from Owner of the industrial facility

The final user and owner of the transmission network of the industrial facility imposed the following constraints:

- a power factor of at least 0.97 lagging shall be maintained at the point of common coupling where the industrial facility is connected. However, a leading power factor is never allowed;
- any reactive shunt compensation, if needed, shall be installed only at main substation side (central processing facility) and not on remote islands;
- no single-pole controlled switching [7], [8], for circuit breakers can be used: therefore, no Point on Wave (POW) switching technique is allowed, since 220 kV circuit breakers are based on 3-pole switching mechanism and not on 1-pole maneuvering.

II. STEADY STATE LOAD FLOW ANALYSIS

Here after the size of shunt reactor compensation is first determined based on steady state reactive power flow.

A. Need of shunt reactor compensation

A load flow simulation is performed to first check the voltage profile and the reactive power flow inside the 220 kV transmission system, without any shunt reactor compensation, as shown in Fig. 3.

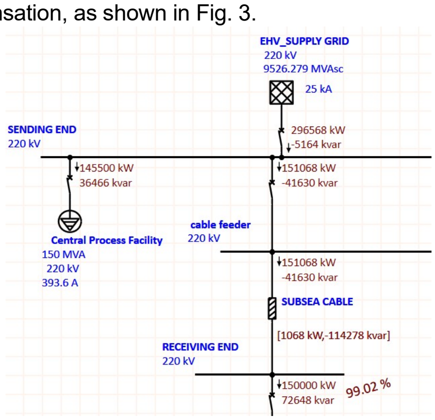

Fig. 3 Load flow calculation without any shunt reactor

The remote process unit absorbs a total power of 150 MW at 220 kV with a power factor of 0.9 lagging, which means that almost 72 MVAR of inductive power is absorbed by the remote plant facility. The subsea cable produces 114 MVAR of capacitive power: hence, the cable provides 72 MVAR needed by the remote facility, while the remaining 42 MAR flows towards the central processing facility which however cannot absorb all 42 MVARs since the central facility loads are already compensated by dedicated shunt capacitor banks.

Although there is no concern in terms of voltage profile at the receiving-end of remote process units, it is quite evident that the 62 km long submarine cable produces excessive capacitive power which impacts on the power factor at the point of common coupling: shunt reactors are necessary in order to prevent a leading power factor and to avoid penalties from the 220 kV Transmission System Network Operator.

For the sake of completeness, also the load flow simulation in case of no-load cable energization and without any shunt reactor is reported in Fig. 4, just to show that the Ferranti's voltage rise [5], occurring at the receiving cable-end, is not significant for this application.

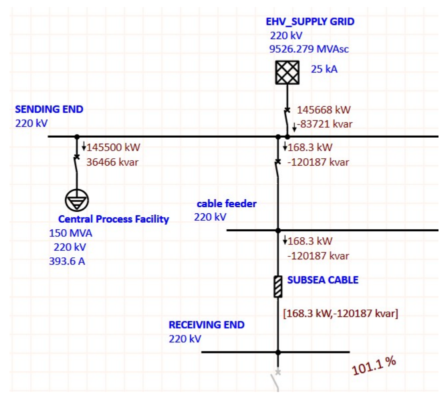

Fig. 4 Load flow calculation for no-load cable energization

Indeed, the actual voltage at the receiving-end is only 101.1% of rated voltage, in steady-state conditions after cable energization, and the cable provides 120 MVAR.

B. Total amount of shunt reactor compensation

The target on power factor at point of connection is reached by installing 60 MVAR of shunt reactor compensation (50% of cable charging power), as is shown in load flow calculation reported in Fig. 5.

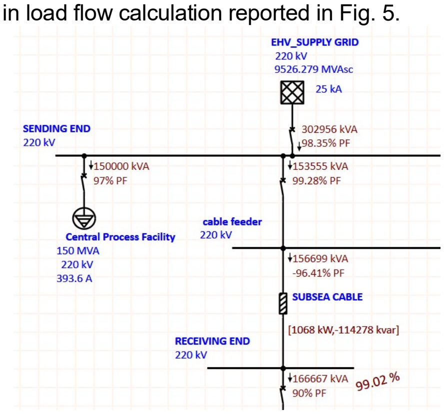

Fig. 5 Load flow calculation with shunt reactor

Now the minimum power factor of 0.97 lagging is guaranteed at 220 kV point of common coupling, without causing any leading power factor towards the external source grid.

III. ELECTROMAGNETIC TRANSIENT ANALYSIS

A. Location where shunt reactors can be installed

It is essential to remember that Extra-High voltage circuit breakers can safely handle the switching-off of cable charging current only up to a specific limit, depending on the supply voltage [6]. In our case, 220 kV circuit breaker can safely de-energize only up to 250 A of cable charging current.

The subsea cable has a charging current of 5.1 A/km, which means that 62 km cable length give a total charging current of 316 A greater than the allowable limit of 250 A for 220 kV circuit breakers.

Therefore, it is apparent the need of installing the shunt reactor compensation rigidly to the cable sending-end, such as the circuit breaker feeder which supplies both cable and reactor can safely break less than 250 A of charging current:
indeed, 60 MVAR shunt reactor gives 158 A of compensating current at 220 kV, and the residual charging current switched-off by the 220 kV circuit breaker each time that the cable is de-energized would amount to 158 A (difference between the charging current of 316 A and the reactor compensating current of 158 A).

B. 100% of shunt compensation (only cable-end side)

Anyway, due attention shall be paid also to the what happens each time that the cable is energized: the phenomenon of delayed current zeros (also name zero-missing) could occur due to the excessive amount of shunt reactor compensation. Usually, when the shunt reactor compensation is around 50% or more than the total cable charging current, the zero-missing event occurs [1], [2].

The energization inrush currents are shown in Fig. 6, while an enlarged view is shown in Fig. 7 for the phase where the zero-missing phenomenon is most apparent.

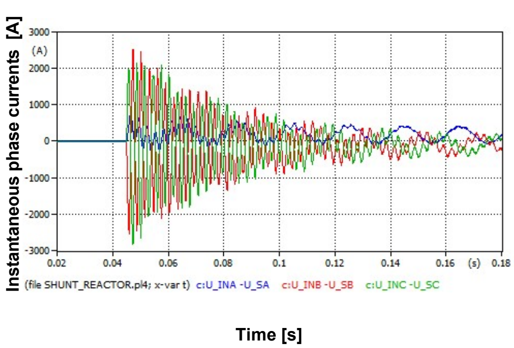

Fig. 6 Energization current with 60 MVAR shunt reactor

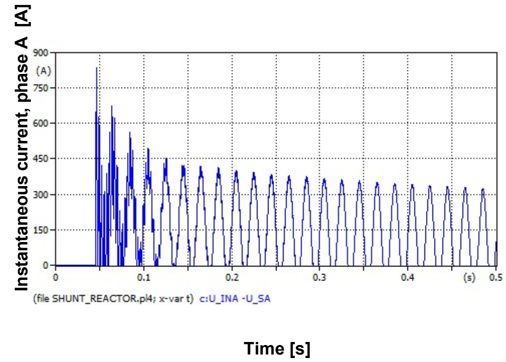

Fig. 7 Zero-missing phenomenon during energization

As can be seen, one phase current undergoes the delayed current zeros phenomenon, i.e. the current does not pass through zero for the first 100 ms (5 cycles at 50 Hz) after the occurrence of the energization event:
this means that in case the 220 kV circuit breaker is immediately tripped after the energization it will then be damaged by excessive arcing during its opening period without any zero crossing for the fault current: for example, this scenario could happen in case of some inadvertent maloperation of the circuit breaker control circuit, or in case there is already a fault inside the subsea cable before its energization and this fault is detected by phase differential relays or instantaneous overcurrent relays which then trip instantaneously the circuit breaker soon after the closing of the breaker.

C. 2 x 50% of shunt compensation (both cable-end side and supply substation side)

It is therefore necessary to split the power of the shunt reactor compensation in two reactors. Since it was forbidden by the final user of the plant to install shunt reactors also at the receiving-end of the subsea cables, the only practical solution is to install half of the compensating power (30 MVAR) rigidly at the cable sending-end, while the other half (30 MVAR) can be supplied and switched directly from the 220 kV GIS substation of the central processing facility.

The updated simulation of the energization current is shown in Fig. 8, whit an enlarged view in Fig. 9.

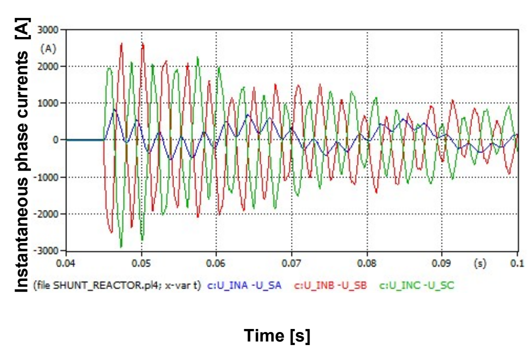

Fig. 8 Energization current with 30 MVAR shunt reactor

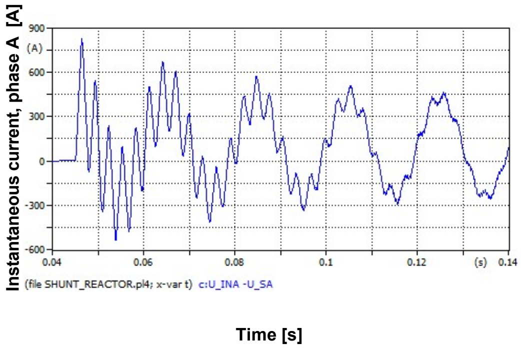

Fig. 9 Energization without zero-missing phenomenon

As can be seen now, the zeros current crossing is well pronounced for the inrush current, and consequently the circuit breaker can safely interrupt the current soon after cable energization.

IV. CONCLUSIONS

Extra-High voltage, from 132 kV to 245 kV, subsea cables are the only practical solution when an off-shore Oil & Gas facility has to supply remote processing units located on far away islands and having significant power consumption.

When the interconnection subsea cable link has a length of up to few hundreds of km, it is not common for industrial facilities to use the DC supply instead of the AC supply, considering also that an HVDC link would require AC/DC converter stations at both sending and receiving end of the cable and such converter stations would be too much expensive for the final user of the industrial facility. Therefore, the AC supply remains in this case the most common solution to be adopted.

The AC supply for the Extra-High voltage subsea cable causes a capacitive reactive power which must be compensated in order to manage the reactive power flow inside the high voltage transmission grid. The most affordable and easiest way for industrial facility to provide such compensation is to use shunt reactors which remain also more affordable than alternative most recent methods like static VAR compensators (SVCs) and static synchronous compensators (STATCOMs) [11].

In order to determine the correct size of the shunt reactors, the following design steps are recommended:

- to perform a steady state load flow, without any shunt reactor compensation, in order to check initially the reactive power flow, the voltage profile and the power factor at the point of common coupling;

- to determine, through steady state load flow simulations, which is the total amount of shunt reactor needed to reach the target power factor at the point of common coupling;

- to check which is the limit of capacitive breaking current which can be safely switched-off by a high voltage circuit breaker according to applicable IEC standards for HV switchgear equipment (e.g. 160 A for 145 kV, 250 A for 245 kV, 355 A for 362 kV, 400 A for 420 kV);

- the shunt reactor should be installed rigidly at one cable-end in order to give a residual charging current being less than the above limit.

- the shunt reactor should have a compensating power non-exceeding 50 % of the total charging capacitive power of the cable, in order to avoid the phenomenon of zero-missing / delayed current zeros when the cable is energized.

- if it is not possible to install the entire shunt reactor compensation power as rigidly connected at only cable ends (sending-end, receiving-end, or both ends), then the remaining portion of shunt compensation power has to be installed additionally in the main substation which supplies the subsea cable transmission link.

V. REFERENCES

[1] F. Faria da Silva, C. L. Bak, *Electromagnetic Transients in Power Cables*, Springer, 2013.
[2] A. Ametani, H. Xue, T. Ohno, H. Khalilnezhad: *Electromagnetic Transients in Large HV Cable Networks. Modeling and Calculations*, IET, 2022.
[3] E. Di Bartolomeo; A. Di Giulio; F. Palone; M. Rebolini; V. Iuliani, "Terminal stations design for submarine HVAC links. Capri-Italy and Malta-Sicily interconnections" *2015 AEIT International Annual Conference (AEIT)*, 14-16 October 2015.
[4] R. Benato, A. Paolucci, *EHV AC Undergrounding Electrical Power*, Springer, 2010.
[5] CIGRE Working Group C4.502, CIGRE Technical Brochure No. 556, "Power System Technical Performance Issues Related to the Application of Long HVAC Cables," October 2013.
[6] IEC 62271-100 High-voltage switchgear and controlgear, Part 100: Alternating current circuit-breakers.
[7] IEC 62271-319 High-voltage switchgear and controlgear, Part 319: Alternating current circuit-breakers intended for controlled switching.
[8] C.D. Tsirekis and N.D. Hatziargyriou, "Control of Shunt Capacitors and Shunt Reactors Energization Transients," in *Proc. IPST 2003 – International Conference on Power Systems Transients in New Orleans, USA,* Sept. 28th - October 2nd 2003.
[9] *Alternative Transient Program (ATP) - Rule Book*, Canadian/American EMTP User Group, 1987-92.
[10] H. W. Dommel, *EMTP Theory Book*, Microtran Power System Analysis Corporation, Vancouver, Canada, 1992.

[11] N. M. Tabatabaei, A. J. Aghbolaghi, N. Bizon, F. Blaabjerg, *Reactive Power Control in AC Power Sytems*, Springer, 2017.
[12] *ETAP Electrical Power System Analysis & Operation Software, www.etap.com*, OTI Corporation, Los Angeles, USA.

VI. APPENDIX

A. Electrical Network Component Data

TABLE A-I
SUPPLY NETWORK

Equipment	Parameters
External supply grid at the point of common coupling of the industrial facility	220 kV rated voltage
	50 Hz rated frequency
	9526 MVA Min. 3-phase short circuit power
	25 kA Min. 3-phase sub-transient short circuit current at rated voltage
	X/R = 10 reactance to resistance ratio

TABLE A-II
SUBSEA CABLE

Parameter	Numerical value
Conductor material	Copper (Cu)
Cable formation	3-core
Cross sectional area	630 mm^2
Conductor diameter	30.8 mm
XLPE insulation diameter	92.8 mm
Cable length	62 km
Shunt capacitance	0.127 μF / km
Phase resistance at 90 ° C	$36 \cdot 10^{-3}$ ohm / km
Series inductance	$0.460 \cdot 10^{-3}$ H / km
Surge impedance	62 ohm
Capacitive charging current with Uo = 220 kV / √3	5.1 A / km

TABLE A-III
SHUNT REACTOR

Parameter	Numerical value
Rated voltage (phase to neutral)	220 kV / √3
Highest continuous operating voltage (phase to neutral)	245 kV / √3
Rated 3-phase power	30 MVAR
Rated phase current	79 A
Rated phase reactance	1613 ohm
X/R quality factor	200
Dry type / Air-core reactor	

VII. VITA

Paolo Marini is Electrical Network Studies Group Leader in Tecnimont, Italy.
Mr. Paolo Marini received his Master of Electrical Engineering degree in 2005. In 2006 he joined the Department of Electrical Engineering of Tecnimont Company based in Milan, Italy. He is an Individual Member of the International Council on Large Electric Systems (CIGRE), an Individual Member of IEEE Industry Applications Society (IAS), and an Industrial Member of the Italian Electrotechnical Committee (CEI), Technical Sub-Committee SCT17 "HV Assemblies and Switching Devices".
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