DOI: 10.48011/asba.v2i1.1032

# Comparative Study of Technologies for Harmonic Propagation Mitigation in Subsea Power Systems ⋆

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**Abstract:** This article discusses the exhaustive study of resonances in Subsea Power Systems (SPS) through the interaction of harmonics, caused by diode rectifiers, and a comparative study of possible solutions to the problem. For this purpose, a large volume of simulations was carried out in the PSCAD/EMTDC simulation environment, in its parallel processing environment, to check for indications of the existence of problems in an subsea distribution system.

*Keywords:* Subsea Power Systems, Power Quality, Resonance, Harmonic Propagation, Diode Rectifier, Multi-pulse Converter, Active Filter, PWM rectifier, Variable Speed Drives.

## 1. INTRODUCTION

New equipment and marine electrical components have been announced by manufacturers for application in oil extraction in deep waters. In this context, the concept of Subsea Power Systems (SPS) arises from the effort to reduce operating costs in oil extraction, aiming to use safely various equipment in arrangements.

When operating subsea pumps for oil extraction, SPS has a radial topology and is composed of transformers, umbilical cables, electrical loads and power converters. The largest electrical loads installed on the seabed are composed of electric motors for processing and pumping oil, driven by Variable Speed Drives (VSD).

Despite the greater versatility in motor control, power electronics converters produce harmonics that deteriorate the power quality of the system. The propagation of harmonics in the umbilicals originated from the converters can cause resonances in the system, resulting in faults and premature aging of the cables. These consequences are especially undesirable because, due to the distance from the platform to the engines and the radial topology, umbilicals constitute the major part of the project cost.

⋆ This work was fully financed by Petrobras, through the Foundation for the Coordination of Projects, Research and Technological Studies - COPPETEC. In addition, was supported in part by the Coordenacão de Aperfeiçoamento de Pessoal de Nível Superior (Capes) and in part by the Conselho National de Desenvolvimento Científico (CNPq). The authors are with the Laboratory of Power Electronics and Medium Voltage Applications, Electrical Engineering Department, Instituto Alberto Luiz Coimbra de Pesquisa e Pós Graduação em Engenharia/Universidade Federal do Rio de Janeiro (COPPE/UFRJ), Centro de Tecnologia, Av. Athos da Silveira Ramos, 149, Ilha do Fundão, Rio de Janeiro - RJ

The level of detail in the SPS modeling required for this work will certainly subsidize companies to take on the greater challenge of equipment and control systems marinization for the most diverse elements used in this activity, such as cables, transformers, electrical machines and power converters, the latter used in VSD for subsea machines. This will contribute widely to a greater understanding of harmonic propagation and resonance problems in umbilical cables, in addition to the improvement of dc-links in specific applications at ultra deep water for the oil industry. These latter subjects are part of a single set and will be addressed in other two papers that, together with the present paper, are submitted for appreciation by the CBA2020 committee. They are: "Phenomena Analysis of Ferroresonance and Self-Excitation in Subsea Power Systems" and "DC-link project applied to Variable Speed Drives in Subsea Power Systems" .

This paper addresses the verification of resonances in a SPS powering induction motors driven by VSDs, possible solutions for mitigating the harmonic content of current and/or voltage and comparison of the behavior of these technologies. This work is organized in six sections: after the introduction, the second section addresses the problems of electromagnetic phenomena between cables and harmonics; the third presents a review on the influence of converter's topology on the harmonic behaviour, as well as technologies that present themselves as possible solutions; the fourth section describes the case study on which this work is based, the simulation methodology and the modeling of the components; the fifth section presents and discusses the results of the simulations; lastly, the sixth section presents the authors' conclusions regarding the present work.

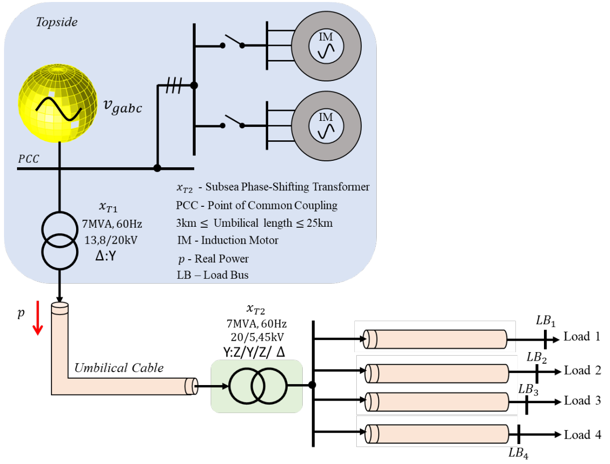


Figure 1. Representation of SPS

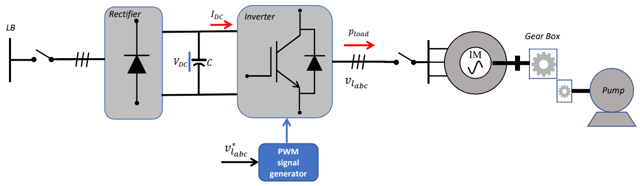


Figure 2. Representation of motors and converters

## 2. HARMONIC PROPAGATION IN SUBSEA POWER SYSTEMS

Underground or subsea power systems differ from overhead transmission systems. The use of insulated cables results in a capacitance of 20 to 50 times that of overhead lines (Jensen et al., 2011), which can cause overvoltages and high charging current. These effects are more relevant in SPS, especially in the presence of power electronics converters which behaves as a harmonic source generator. Fig. 1 illustrates a SPS model, while Fig. 2 shows the representation of the VSDs responsible for driving the machines connected to the subsea pumps.

The electromagnetic phenomena caused by the interaction of the converters with the network depend on several factors, such as switching frequency of the converters, length and parameters of the umbilicals, topside loads, subsea loads, etc. In addition, the higher capacitance of subsea cables reduces the resonance frequency in the system according to (1), where C and L are the equivalent capacitance and inductance.

$$F_{resonance} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Power supply and loads at Topside can be represented by a Thévenin equivalent voltage source and the rectifiers at the seabed as currents sources, as shown in Fig. 3. In steady state, the cable can be described with distributed parameters by (2), (3) and (4):

$$\begin{bmatrix} V_{PCC} \\ I_{PCC} \end{bmatrix} = \begin{bmatrix} cosh(\gamma\ell) & Z_c sinh(\gamma\ell) \\ \dfrac{1}{Z_c} sinh(\gamma\ell) & cosh(\gamma\ell) \end{bmatrix} \cdot \begin{bmatrix} V_{Load} \\ I_{Load} \end{bmatrix} \tag{2}$$

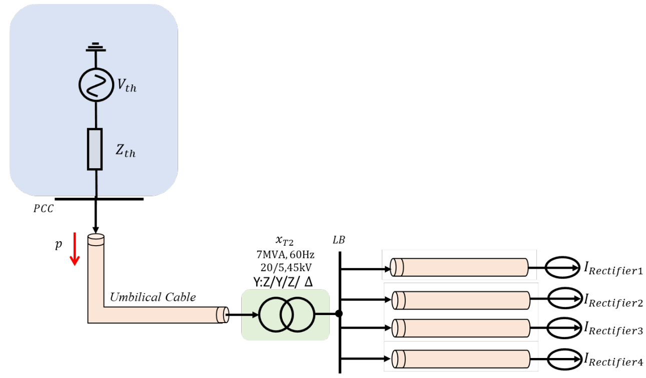


Figure 3. Representation of SPS with Thévenin equivalent

$$\begin{aligned} \gamma &= \sqrt{zy} \\ Z_c &= \sqrt{\frac{z}{y}} \end{aligned} \tag{3}$$

$$\begin{aligned} z(\omega) &= r(\omega) + j\omega l(\omega) \\ y(\omega) &= j\omega c(\omega) \end{aligned} \tag{4}$$

where $\gamma$ and $Z_c$ are, respectively, the propagation constant and the characteristic impedance of the umbilical, $\omega$ is the angular frequency, $\ell$, $z$, $y$, $r$, $l$ and $c$ are, respectively, length in meters, longitudinal impedance, shunt admittance, resistance, inductance and capacitance, all in per unit length, of the cable. It is worth mentioning that, in addition to the term $\omega$ in (4), the per unit length parameters also depend on the frequency due to the skin and proximity effects.

By considering the effects of only one current source at the load buses, and an equivalent unique umbilical connecting the rectifier to the Point of Common Coupling (PCC), through the superposition theorem the voltage source in Fig. 3 can be neglected, and the influence of each current source in the PCC voltage can be written according to (5), seen in (Bollen et al., 2014).

$$\frac{V_{PCC}}{I_{Load}} = \frac{Z_{th}Z_c}{Z_{th}sinh(\gamma\ell) + Z_c cosh(\gamma\ell)} \tag{5}$$

Notice through (5) that the influence on the PCC voltage depends on the cables' parameters, length of the cables, and the impedance at the PCC terminal. The cable's parameters depend on the frequency of the current, as seen in (4). Therefore, depending on the system's parameters and the frequency of the harmonics generated by the power electronics converter, the ratio in the right hand-side of (5) can reach very high levels at the harmonic frequency, resulting in a big disturbance in the PCC voltage caused by harmonic interaction.

This disturbance may produce circulating currents and can damage the cable's isolation, loads at the topside and others elements of the SPS. In addition, the influence of the impedance $Z_{th}$ in (5) shows an inversely proportional relationship between the influence of the current harmonic frequency and the short-circuit impedance of that terminal at the frequency in question.

## 3. INFLUENCE OF THE CONVERTER TOPOLOGY ON THE POSSIBILITY OF RESONANCE OCCURRENCE

The VSDs responsible for driving the motors have their dc-link formed by rectifiers connected to SPS, as shown in Fig. 2. As solutions to reduce the harmonic content of the converter current or of the voltage at the PCC, the Brazilian standard (NBR IEC 61892-1) proposes to consider the alternatives:

- Grid reactance;
- Pulse number of the rectifiers;
- Active rectifier with IGBT;
- Passive Filters;
- Active Filters.

Grid reactance couples a reactance on the dc-side of the converter in order to smooth the dc-current, mitigating the harmonic effects of the inverter propagated to the ac-side of the rectifier, and is outside the scope of this paper.

As a base scenario and initial solution, a three-phase diode rectifier was chosen at a lower cost and higher reliability compared to controlled converters, and the use of multi-pulse converter was chosen to improve overall THD values.

### *3.1 Base Case - VSDs with Three-Phase Diode-Rectifiers and Multipulse Configurations*

Three-phase diode-rectifiers have harmonic spectrum $6n \pm 1$, where $n$ is the pulse-number of the converter. Despite the lower number of switches, higher reliability, and lower cost, this topology does not allow control of the components and behaves passively. However, the use of a phase-shifting transformer makes it possible to cancel harmonics and improve the power factor due to the angular shift between the primary and secondary of multipulse rectifiers (Jiaopu Wen and Zhou, 2012). It is a simple and efficient solution for reducing harmonic propagation in power electronics converters, which is why they are widely used in high power applications (Paice, 1996).

Fig. 4 shows the three most common configurations of multipulse converters: 12 pulses, 18 pulses and 24 pulses. Depending on the number of converters (n), the transformer windings are designed to eliminate all harmonics up to the harmonic (6n-1), reducing the THD of the transformer primary current. For a single rectifier feeding the link of a VSD, a configuration known as a six-pulse bridge, the input current of the same has THD around 32.70 %, while for the 12 pulses it has 8.38 %, 18 pulses 3.06 % and 24 pulses to 1.49 % (Wu, 2006).

### *3.2 Active rectifier with IGBT*

Due to the ability to operate as a controlled voltage source, capable of synthesizing a symmetrical and balanced three-phase set of sinusoidal voltages at the frequency of interest, replacing diode rectifiers with IGBT rectifiers is a potential better solution. As the harmonic spectrum of the IGBT-rectifier is in the vicinity of the frequency modulation index $m_f$, according to (6), where $f_{sw}$ and $f_{fund}$ are, respectively, switching frequency and fundamental frequency, the high frequency switching allows a considerable reduction

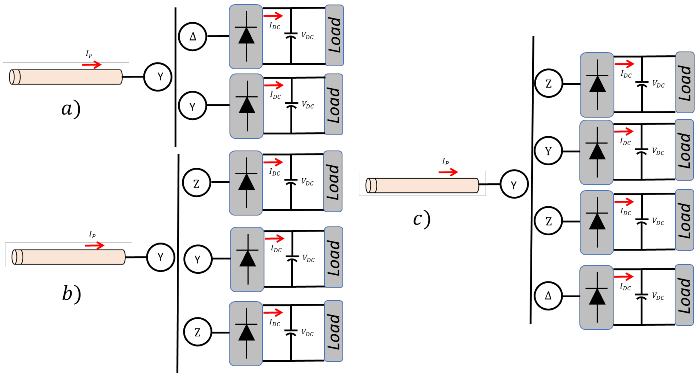


Figure 4. Representation of the a)12-, b)18-, and c)24-Pulse diode-rectifier

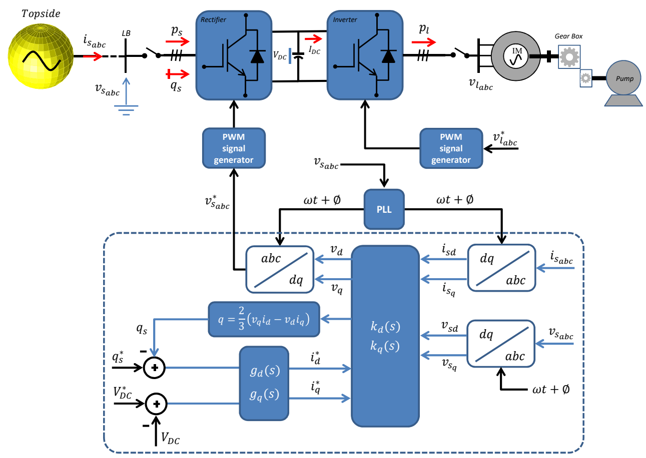


Figure 5. Simplified block diagram of the converter's current control scheme.

of the harmonic injection in the network. In addition, it also allows the control of the power factor, regulation of the dc-link in a more flexible way and bidirectional power flow.

$$m_f = \frac{f_{sw}}{f_{fund}} \tag{6}$$

The simplified block diagram in Fig. 5 represents one of the control methods adopted in this work and is referred to as a $dq$-Frame control scheme (Yazdani and Iravani, 2010). That block diagram illustrates two layers: the inner vector current loop, denoted by the transfer functions $k_d(s)$ and $k_q(s)$; and the outer power control loop, denoted by $g_d(s)$ and $g_q(s)$. Both layers contain conventional PI controllers, with time constant of outer PI designed to be slower than the inner PI, which receives the $i_d^*$ and $i_q^*$ references associated with dc-link $V_{DC}$ and the reactive power control. The $i_d^*$ component denotes the average real power ($\overline{p}$) that should be provided to the ac-network to keep the dc-link voltage in $V_{DC}$, while $i_q^*$ is associated with the desired reactive power reference ($q^*$). The Load Bus (LB) electrical quantities and the output of the inner loop pass through $dq$-to-$abc$-frame transformation blocks, the latter for generating the reference ($v_{sabc}^*$) to be synthesized at the AC converter side ($v_{sabc}$).

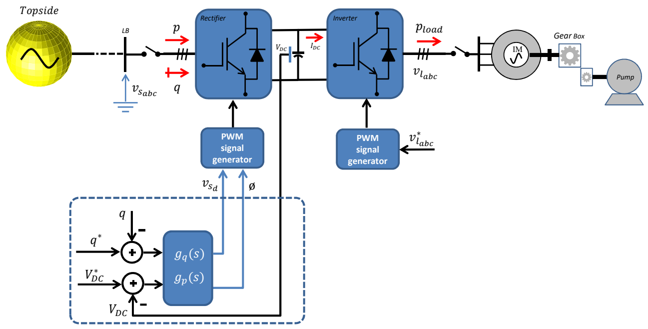


Figure 6. Block diagram of voltage control applied to the controlled rectifier

The other control adopted in this paper, similar to the first one, is the scalar voltage, where the reference of phase and voltage magnitude to the converter is given by the dc-voltage regulator and the reactive power control, as shown in Fig. 6.

### *3.3 Active Filter*

Active filters are converters connected to the frequency converter terminal to mitigate voltage harmonics (series filters) or current harmonics (shunt filters). This article only addresses the active shunt filter, whose controls determine and synthesize the compensation current in real time and which can be divided into: 'Selective FFT', which selectively compensates for harmonics, normally up to 15th or 25th harmonic; and Broadband, which eliminates everything that is not a fundamental component, not only the integer harmonics (A. H. Hoevenaars and Lawton, 2008), (Akagi et al., 2017). Active filters offer excellent results in terms of THD, but the disadvantage is the high additional cost of a converter, complexity of use and the possibility of resonance of the IGBT switching frequency with the system (A. H. Hoevenaars and Lawton, 2008).

Fig. 7 presents a simplified block diagram of the active filter's control scheme. In this case, the PI-controllers $g_1(s)$ and $g_2(s)$ were applied in the outer loop in addition to the *pq*-Theory (Akagi et al., 2017) block, named *Current Reference Calculator*, which equations are presented in (7). By controlling $i_\alpha$ and $i_\beta$ through variations of converter's terminal voltages $v_{s\alpha}$ and $v_{s\beta}$, it is possible to synthesize the reactive and active power references $q_c^*$ and $p_c^*$, respectively. The latter is added to term $p_{loss}$, related to dc-link voltage regulation.

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p^* \\ q^* \end{bmatrix} \quad (7)$$

### *3.4 Passive Filters*

There are several passive filter topologies (Arrillaga et al., 1985), (Jovcic, 2019): Filters tuned to a single frequency; Double tuned filters; Triple tuned filters; High-pass filters; Type-C filter, etc.

Regardless of the adopted type of filter, its implementation in a power system has 2 objectives: supply reactive power to the system at the fundamental frequency and

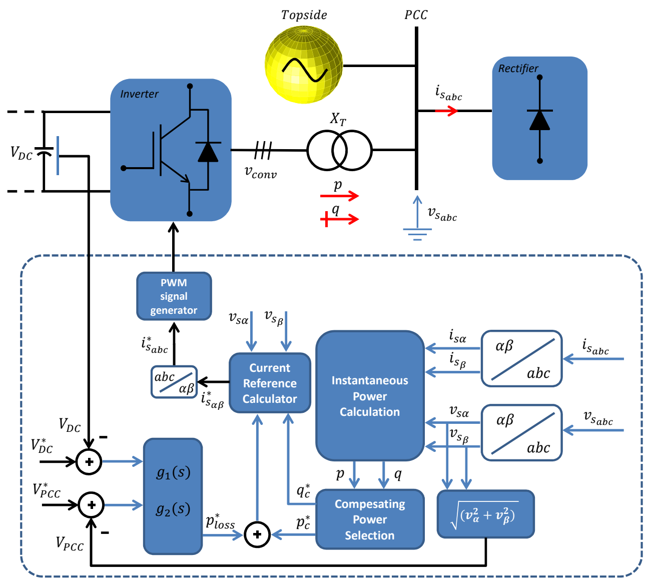


Figure 7. Control scheme of a shunt active filter for current compensation

present a low impedance path to the harmonics of interest (resonance frequency).

In view of the complexity of equipment marinization for oil extraction operations in deep waters, the performance of 3 passive filter topologies was verified:

- Filter tuned to a single frequency;
- Double tuned filter;
- High-pass filter.

Fig. 8 shows the diagram of these 3 topologies.

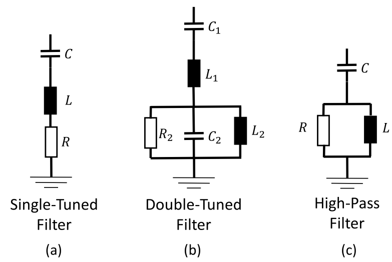


Figure 8. Three adopted filter topologies in the study of harmonic mitigation.

Passive filters, widely used due to their low cost, have advantages and disadvantages compared to the active filter. The authors in (Fujita and Akagi, 1991) point out that the impedance of the system has a considerable influence on the performance of the passive filter, including possible resonance between the network and the filter. In (Peng et al., 1990), the authors add that at a given frequency there is always a resonance between the network and the passive filter.

## 4. CASE STUDIES

This work intends to verify the harmonic propagation in a SPS due to power electronics rectifiers at seabed, and to compare with possible solutions to improve power quality issues. The comparative analysis is based on Brazilian's standard (NBR IEC 61892-1), that limits the voltage

THD at the Topside in 8.0% when the nominal voltage is between 1.0 and 69 kV, and in 5.0 % when the nominal voltage is between 69 kV and 230 kV. As to the current limits, THD lower than 15% for each load is acceptable.

The modeled elements of the SPS and all the parameters can be seen in Fig. 1. Each of the 4 load buses in Fig. 1 is represented by the diagram of Fig. 2, to which the rectifiers that form the dc-link to the VSDs units are connected. As seen in section II, several factors can influence the harmonic interaction with the SPS. The total analysis took into account:

- 23 possible lengths of the umbilical cable $L_U$ connecting the Topside to the phase-shifting transformer on the seabed, from 3 to 25 kilometers;
- 5 possible lengths $L_{load}$ of the cable from the phase-shifting transformer up to each load bus, from 1 to 5 kilometres;
- 4 possible quantities of VSDs in operation: 1 to 4 in operation;
- The load connected to the topside equivalent to 25 MW and power factor of 0.9 inductive (worst case scenario: minimum load);

As for the converter's technologies, seven main cases were considered:

- Base Case – 24-Pulse Diode-Rectifiers;
- Solution 1 – 24-Pulse Diode-Rectifiers with passive filters. Three different filter topologies were tested:
  - · Two Tuned Filters and a High Pass Filter;
  - · Double Tuned Filter and a High Pass Filter;
  - · Three Tuned Filters and a High Pass Filter;
- Solution 2 – 24-Pulse Diode-Rectifiers with shunt active filter;
- Solution 3 – IGBT-rectifier instead of Diode-Rectifiers. Two different control modes were tested:
  - · Current control in dq-Frame;
  - · Scalar Voltage Control;

Therefore, there are 460 combinations for each of the main cases, totaling 3220 possible combinations. For practicality, all possible cases regarding the loads combinations (the four VSD sets) were simulated in a unique simulation run, reducing the problem to 805 simulations. In the scenario with 2 VSDs in operation, the simulation set was modeled to consider the worst case, in which these VSDs are connected to windings with angular shift different from 30° to avoid the 12-pulse configuration, therefore the harmonics are not cancelled.

An integrated platform was developed to simulate and analyze data from multiple scenarios. It was implemented using the PSCAD automation library (in Python language) along with MATLAB. The flow chart of this automatic simulation platform is presented in Fig. 9.

## 5. SIMULATION RESULTS

The results of this paper are presented in Tables 1 to 5, that show the THD values in the base case, in the case with passive filters and in the active filter case. Each table is associated with one case and provides the lower and higher THD measured to every situation of subsea loads. Fig. 10 and Fig. 11 depict the harmonic spectra of the converter's current and of the PCC voltage for the base case.

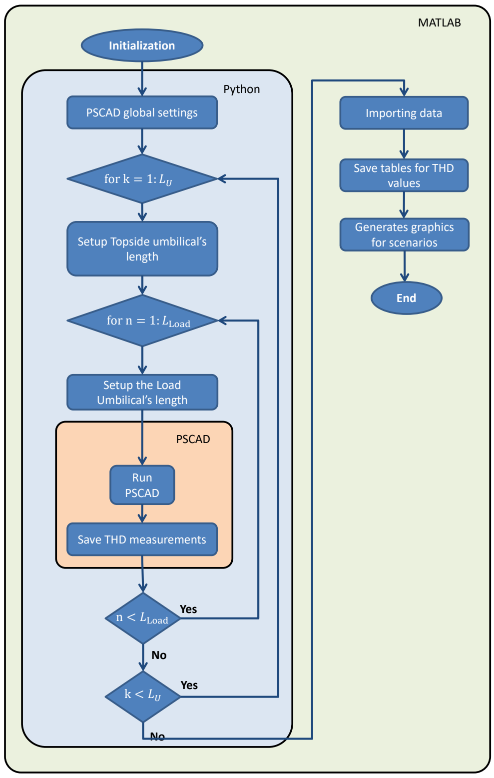


Figure 9. Flowchart of the automated-simulation procedure.

### *5.1 Base Case - 24-pulse Converter with three-phase diode-rectifiers*

For the base case, there is an improvement in the quality of energy when the number of VSDs in operation increases. The THD of the current, whose standard is not respected for only one rectifier and in several cases neither for two VSDs, is reduced by increased load due to the harmonic cancellation of the phase-shifting transformer windings. The THD of the voltage is respected, indicating that the harmonic interactions were not harmful to the voltage at the PCC.

Table 1. Base Case - Total Harmonic Distortion of topside voltage and of pulse-converter Input-Current

| VSDs in operation | THD (%) of Voltage | THD (%) of Current |
|---|---|---|
| 1 | 0.4-1.1 | 23.0-50.0 |
| 2 | 0.4-1.1 | 12.3-21.4 |
| 3 | 0.3-1.6 | 5.3-13.8 |
| 4 | 0.1-1.1 | 1.7-3.6 |

Analysing Table 1, it can be seen that current THD is smaller with 3 VSDs than with 2 VSDs. This is expected because, in this scenario, 2 VSDs have angular shift equal to 30° and form a 12-pulse configuration, therefore cancelling part of the 11th and 13th harmonics. However, voltage THD worsened despite the lower current distortion. This behavior can be explained due to the higher interaction between the harmonics and the cable.

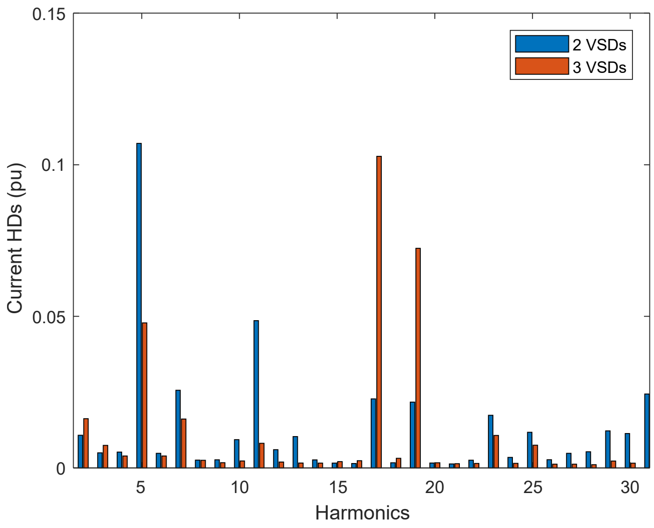


Figure 10. Harmonic spectrum of converter's current in the worst cases with 2 and 3 VSDs operating

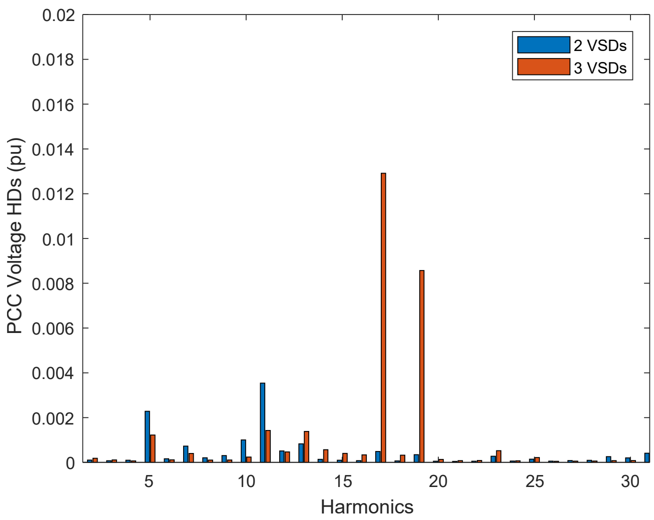


Figure 11. Harmonic spectrum of PCC voltage distortion in the worst cases with 2 VSDs and 3 VSDs operating

Fig. 10 and Fig. 11 compare the individual harmonics of both converter currents and the voltage at the Topside in the worst case for 2 and 3 VSDs. The worst-case when 2 VSDs are operating occurs in the configuration of 12 kilometers of umbilical from the Topside to the transformer at the seabed and 5 kilometers from the transformer to the diode rectifiers. Furthermore, the worst-case with 3 VSDs operating occurs in the configuration of 6 kilometers of umbilical from Topside to the transformer at the seabed and 1 kilometer from the transformer to the diode rectifiers

Fig. 10 confirms that the current harmonic content when 2 VSDs are operating is greater compared to 3 VSDs. However, Fig. 11 shows little influence of these harmonics for the PCC voltage distortion when only 2 VSDs are in operation. Meanwhile, Fig. 11 shows a higher distortion for the PCC voltage with 3 VSDs operating due to the 17th and 19th harmonics, exactly the bigger ones in the current distortion shown in Fig. 10.

This case illustrates that even when the current distortion is lower, the interaction due to the system's conditions can cause bigger distortions in PCC voltage, as predicted in (5).

### *5.2 Solution 1 - 24-pulse Converter with three-phase diode-rectifiers with passive filters*

As stated, one of the adopted solutions to reduce the THD of the current to less than 15% is the use of passive filters. Three cases were verified in order to analyze which would be the most suitable for use in the SPS system.

*Case 1 - Two Tuned Filters and High-Pass Filter*

The diode-rectifier (Fig. 2) produces harmonics in the current with order $6n \pm 1$, in which the amplitude of the harmonics is reduced with its harmonic order (Mohan et al., 2003). Thus, the objective is to reduce the THD of the current using the least amount of components. The filters tuned to a single frequency were tuned to filter 5th and 7th harmonics while the high-pass filter was tuned to filter harmonics from 11th to above. Table 2 shows the current and voltage THD values for all VSDs in operation.

Table 2. Case 1 - Total Harmonic Distortion of topside voltage and of pulse-converter Input-Current

| VSDs in operation | THD (%) of Voltage | THD (%) of Current |
|---|---|---|
| 1 | 0.1-0.3 | 5.9-18.2 |
| 2 | 0.1-0.4 | 3.7-7.9 |
| 3 | 0.1-0.4 | 2.1-5.0 |
| 4 | 0.1-0.5 | 1.3-2.6 |

The THD of the current is higher than 15% in only 4 situations when the SPS operates with 1 VSD. As the project of the filters was made in order to contemplate a large number of cable length combinations, it is expected that in certain situations the THD of the current is above that specified by the standard. Thus, for these 4 specific cable lengths, the project of the high-pass filter was redone in order to reduce the THD. Consequently, the THD of the current is reduced to $12.8 - 13.9\%$ in these 4 cases.

*Case 2 - Double-Tuned Filter and High-Pass Filter*

In Case 2 a double tuned filter is tuned to 5th and 7th harmonics while the high pass filter is tuned to filter harmonics up from 11th. The advantage of the double tuned filter over 2 individually tuned is that the double tuned filter uses two inductors in its structure, reducing the voltage impulses that each inductor is subjected to and reducing its voltage class when compared to inductors of individual tuned filters (Arrillaga et al., 1985). The results of the THD of the currents and voltages are shown at Table 3.

Table 3. Case 2 - Total Harmonic Distortion of Topside Voltage and of Pulse-Converter Input-Current

| VSDs in operation | THD (%) of Voltage | THD (%) of Current |
|---|---|---|
| 1 | 0.1-0.3 | 4.2-18.1 |
| 2 | 0.1-0.4 | 2.0-9.2 |
| 3 | 0.1-0.4 | 1.7-5.0 |
| 4 | 0.1-0.5 | 1.3-2.6 |

The THD of the current is higher than 15%, again, in only 4 situations when the SPS operates with 1 VSD.

Thus, for these 4 specific cable lengths, the project of the high-pass filter was redone in order to reduce the THD. Consequently, the THD of the current is reduced to $12.7 - 13.7\%$ in these 4 cases.

*Case 3 - Three Tuned Filters and a High-Pass Filter*

With the objective of verifying whether the THD of the current can be further reduced, the case of 3 individually tuned filters in the 5th, 7th and 11th harmonics was simulated while the high pass filter is tuned to filter out harmonics from 13th. Table 4 shows the obtained results of this analysis.

Table 4. Case 3 - Total Harmonic Distortion of Topside Voltage and of Pulse-Converter Input-Current

| VSDs in operation | THD (%) of Voltage | THD (%) of Current |
|---|---|---|
| 1 | 0.1-0.3 | 6.1-18.4 |
| 2 | 0.1-0.4 | 3.6-7.8 |
| 3 | 0.1-0.4 | 2.1-5.1 |
| 4 | 0.1-0.5 | 1.3-2.9 |

The THD of the current is above 15% for 9 combinations of length of the umbilicals, five combinations more than were verified for cases 1 and 2. Again, these specific situations were analyzed individually, altering the project of the high-pass filter in a way that the standard is obeyed again. The new THD values for these nine combinations present values between $7.2 - 14.5\%$.

*5.3 Solution 2 - 24-pulse Converter with three-phase diode-rectifiers with shunt active filter*

With the implementation of the active filter as a solution, both the THD standards for converter-current and voltage of the Topside are met. The THD of the current even for light subsea load is comparable to the case with 3 VSDs in the base case, showing a considerable improvement.

For heavy load, a worsening was noted in some cases, which can be explained by the greater electromagnetic interaction between the system and the high switching frequency of the IGBT, as warned in (A. H. Hoevenaars and Lawton, 2008). The THD of the voltage also showed a slight improvement in its maximum values, but remained practically at the same magnitude.

Table 5. Solution 2 - Total Harmonic Distortion of Topside Voltage and of Pulse-Converter Input-Current

| VSDs in operation | THD (%) of Voltage | THD (%) of Current |
|---|---|---|
| 1 | 0.1-1.1 | 4.0-14.3 |
| 2 | 0.2-1.1 | 3.3-13.4 |
| 3 | 0.3-1.0 | 6.4-13.9 |
| 4 | 0.3-0.8 | 2.6-11.6 |

*5.4 Solution 3 - Three-phase IGBT-rectifier instead of Diode-Rectifiers*

The two adopted control strategies show an excellent performance in comparison with the base case. The high switching frequency allowed a considerable reduction of the current harmonics, resulting in an overall THD less than 1.6%.

*Control 1 - Current Control in dq-frame*

The THD of the voltage at Topside is less than 0.2% for all analyzed scenarios, considerably smaller than the limit of 5.0% imposed by the standard. In turn, the THD of the current at the input of the transformer shows to be less than 1.6% for all scenarios, much smaller than the 15.0% limited by the standard. It should also be noted that:

- The worst result for the voltage THD occurs for the configuration of 3 kilometers of umbilical from Topside to the transformer at the seabed, 4 kilometers of umbilical from the transformer to the active rectifier and with four VSDs in operation;
- For this scenario, the THD of the current is 1.5%, much lower than the limit of 15.0%;
- The worst result for the current THD occurs for the configuration of 3 kilometers of umbilical from Topside to the transformer at the seabed, 4 kilometers of umbilical from the transformer to the active rectifier and with two VSDs in operation;
- In this case, the voltage THD is 0.15%, less than the 5.0% limit of the standard.

*Control 2 - Voltage Control*

For this type of control, the THD of the voltage at the Topside is less than 0.17% for all scenarios, while the THD of the current at the transformer input is less than 1.0% for all scenarios. It should be noted that:

- The worst result for the voltage THD occurs for the configuration of 21 kilometers of umbilical from Topside to the transformer at the seabed, 5 kilometers of umbilical from the transformer to the active rectifier and with three VSDs in operation;
- For this scenario, the THD of the current is 0.8%, much smaller than the limit of 15.0%;
- The worst result for the current THD occurs for the configuration of 21 kilometers of umbilical from Topside to the transformer at the seabed, 2 kilometers of umbilical from the transformer to the active rectifier and with two VSDs in operation;
- In this case, the voltage THD is 0.135%.

## 6. CONCLUSIONS

This paper included a study of analysis of resonances in a SPS model and a comparative study of technological solutions for improvements in the energy quality of the system.

As for the solutions with passive filters, the solution with three individually tuned filters for the 5th, 7th and 11th order harmonics, combined with a High Pass to act on the harmonics higher than the 13th shows to be the lest suitable solution. This was due to the presence of resonances in higher order harmonics caused by the joint operation of these three topologies. The performance of passive filters was similar for Cases 1 and 2.

The implementation of the active filter proved to be a technically feasible solution and capable to mitigate the harmonics coming from the rectifiers, guaranteeing compliance with the respective power quality standards. For the first two cases, the active filtering reached reduction levels above 39% (for one VSD) in relation to the operation without any type of filtering, while for two VSDs, the highest THD value did not exceed 13.4%. However, the additional cost of implementing another converter argues against this solution.

Among all the 3 analyzed solutions, the one that was observed most interesting for implementation is the PWM controlled rectifier. Between the technical advantages, the independent control of the active and reactive power consumed by the VSD, power factor control, bidirectional power flow and a lower voltage and current THD can be mentioned, when compared with the other solutions. Comparing this technology with the active filter, the active filter showed worse results that can be justified by the interaction with the system and the current control based on a tolerance band control. In this control scheme, the switching frequency changes along the waveform and generates an harmonic spectra difficult to be calculated and that can cause an unwanted interaction with the system. This can be avoided by applying an active filter with Selective FFT compensation with the control structure similar to that as was utilized for the IGBT-rectifier.

An economic advantage is that there is no need to use a 24-pulse transformer to match the current and voltage THD values to the standards, being able to use usual transformers (YY or Y-Delta) and of lower manufacturing cost. The possibility of implementing the PWM Rectifier in the same pressurized compartment as the Inverter should also be studied, in a back-to-back configuration, possibly further reducing the cost of the system.

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