HARMONIC MITIGATION IN OFFSHORE POWER SYSTEMS; 24 PULSE VSD IS NOT NECESSARILY THE ANSWER

Paper No. PCIC-(do not insert number)

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Abstract – The use of Electrical Submersible Pumps (ESPs) driven by Variable Speed Drives (VSDs) has dramatically increased due to the vast expansions of electrified offshore platforms in the Oil and Gas industry. Therefore, detailed analysis is required to study the impact on the offshore power system including harmonics associated with the operation of numerous VSD-driven ESPs, which could lead to distortion of voltage and current waveforms beyond acceptable standard limits. The problem becomes more pronounced when resonance is excited with the presence of long submarine cables and transformers. The authors conducted field measurements using power quality recorders and built a power system model to reproduce the field results using commercially available modeling software. Remedial solutions were studied to alleviate the impact of ESP operation on the offshore power system. Active and passive harmonic filters were studied in terms of effectiveness in meeting company standards for harmonic distortion.

Index Terms —Harmonic analysis, Industrial power systems, Offshore installations, Power harmonic filters, Power system harmonics, Power system modeling, Resonance, Variable speed drives

I. INTRODUCTION

Artificial lifting systems in offshore installations utilize numerous electrical submersible pumps (ESP). Each group consist of several ESPs with each ESP typically rated between two hundred (200) to five hundred (500) horsepower. ESPs are located downhole and are supplied through long cables that could reach three thousand (3000) meters in length. From the other end, ESP cables individually terminate to skid mounted variable frequency drives (VSDs) located on a wellhead platform. The wellhead platform (WHP) consists of a pad mounted switchgear that distribute power to two or more 13.8/0.48kV stepdown transformers. Each transformer is connected to a low voltage switchboard that distribute power to the VSD skids Fig. 1. Wellhead platforms receive power form tie-in platforms (TPs) through medium-voltage submarine cables that are typically five (5) to fifteen (15) kilometers long. The tie-in platform consists of two large power transformers and a double-ended medium voltage switchgear that distribute power to multiple wellhead platforms, Fig. 2.

From a process standpoint, the VSD will provide the required torque required by the pump to accommodate the varying load. The load typically increases with time as the water cut in the reservoir becomes greater. A twenty-four (24) pulse passive rectifier is an integral part of the VSD and is selected to provide very low harmonic content compared to other technologies. The 24-pulse rectification is derived through a multi-winding phase shifting transformer which also provides the required isolation to improve drive robustness during system disturbances. As a result, there is a tendency to believe that harmonics should not cause a system problem, since it is guaranteed by manufacturers that the VSD meets IEEE-Std 519-2014 [1] voltage and current harmonic distortion requirements at the low voltage switchboard bus, represented by LV SWBD1, Fig. 1 [1]. Unfortunately, this is not the case at the Point of Common Coupling (PCC) as defined by the company standards which asks for harmonic distortion limits to be met at the tie-in platform's switchgear bus (TP SWGR BUS) in Fig. 2. Harmonics could be easily amplified by system resonance, resulting from interaction between submarine cable capacitances and transformer inductance, leading to the violation of acceptable harmonic-distortion limits throughout the system.

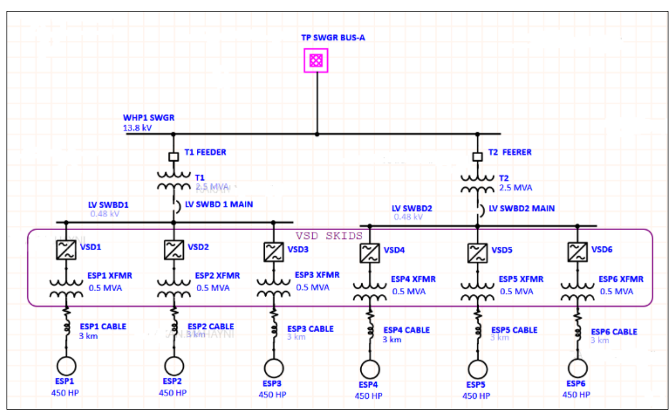

Fig. 1: WHPs single Line Diagram

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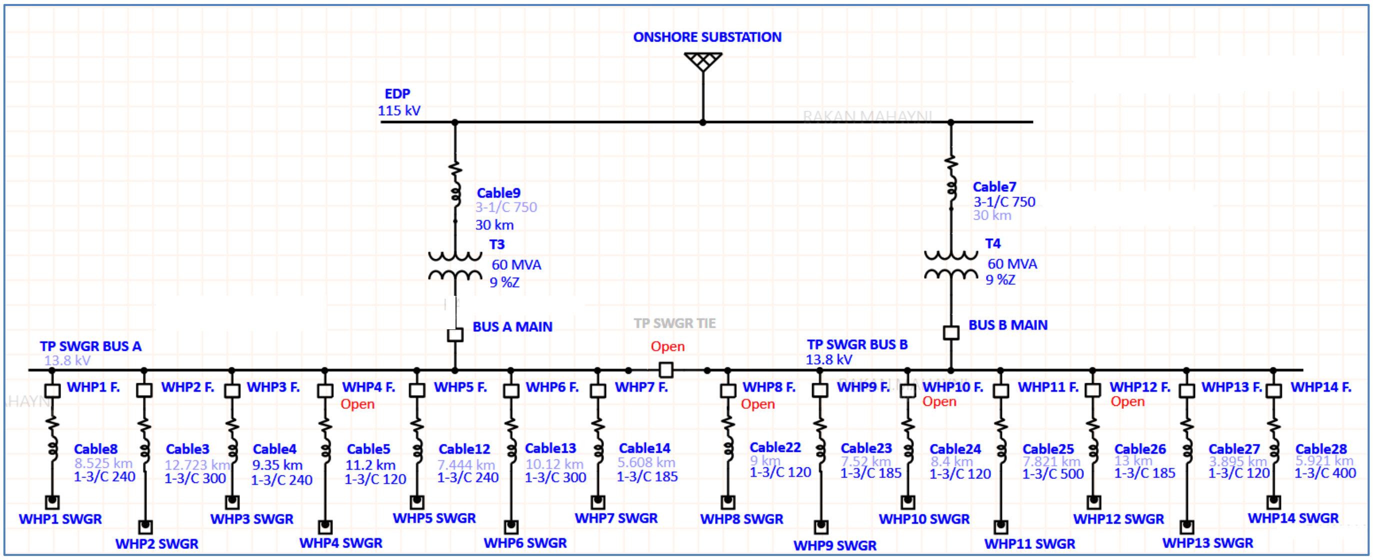

Fig. 2: TP Single Line Diagram

The company standard for voltage harmonic distortion limit is to maintain V_{THD} at less than 5% at TP SWGR A and B buses. For current harmonic distortion I_{THD}, the adopted limits are similar to those mentioned in IEEE Std 519, listed in Table I, and are to be enforced at the main incomers of switchgear TP SWGR.

TABLE I
IEEE Std 519 CURRENT TOTAL DEMAND DISTORTION LIMITS

Maximum Acceptable Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd harmonics)						
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤ h	TDD
<20	4	2	1.5	0.6	0.3	5
20<50	7	3.5	2.5	1	0.5	8
50<100	10	4.5	4	1.5	0.7	12
100<1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20
Where						
I_{SC}	Maximum short circuit current at switchgear bus					
I_L	Maximum demand load current (fundamental frequency component) at switchgear bus					

It should be noted that Total Demand Distortion (TDD) is different than I_{THD} since TDD considers the maximum demand loading (I_L) during a certain measurement period, whereas the I_{THD} is based on the instantaneous fundamental and harmonic readings provided by the meter. This difference comes into play when the plant has an appreciable amount of linear load that would result in more allowance for injecting harmonics in the system since the ratio $\frac{I_{sc}}{I_L}$ becomes smaller [2]. However, for the system under consideration the difference is minimal since the majority of the load is nonlinear.

II. POWER SYSTEMS ANALYSIS

For simplicity, the system under consideration is depicted in Fig. 1 and Fig. 2. However, in the actual offshore system, the number of ESPs may vary from one WHP to the other, but the analysis results in terms of concept do not really change with number of operational ESPs. The intent is to study the impact of system resonance on V_{THD} and I_{THD} at the TP SWGR.

A. *Power System Configuration and Cable Data:*

The system resonance points at the TP SWGR Bus depend on T3 and T4 transformer impedances and the total capacitance that is primarily determined by the amount of submarine cables connected to the bus. The total capacitance also changes based on the switchgear mode of operation (i.e. single ended/double ended) as well as based on the individual feeder's breaker position, which can vary based on operation requirements. The total number of switching scenarios that can be considered is 2×2^n (where n is the number of feeder breakers), which is 32 768 switching scenarios. This based on fourteen feeders that can be either in the ON or OFF position, and with two possible switchgear modes of operations. Any of the aforementioned switching scenarios could trigger a system resonance leading to harmonic amplification beyond what is allowed by company standards. The switching scenario under consideration is a double-ended configuration (i.e. tie breaker open) with feeder breaker positions shown in table II, which also shows the size and the capacitance of each submarine cable.

B. *System Data:*

1) *Source and Transformer Impedances*: The transformer base rating is 60 MVA with 9% impedance. Thevenin equivalence source short-circuit MVA at the 115kV level is 645 MVA.

TABLE II
FEEDER BREAKER POSITION/ CABLE DATA

WHP	Breaker Status	Cable length (km)	Cable size (mm^2)	Cable Capacitance $\mu F/_{km}$
1	Closed	8.53	240	0.298
2	Closed	12.73	300	0.324
3	Closed	9.35	240	0.298
4	Open	11.2	120	0.250
5	Closed	7.44	240	0.298
6	Closed	10.12	300	0.324
7	Closed	5.6	185	0.286
8	Open	9	120	0.250
9	Closed	7.52	185	0.286
10	Open	8.4	120	0.250
11	Closed	7.82	500	0.425
12	Open	13	185	0.286
13	Closed	3.9	120	0.250
14	Closed	5.92	400	0.384

2) *ESP's VSD Harmonic Spectrum:* Current harmonic spectrum is provided by the drive manufacturer for a 24-pulse drive as shown in Table III.

TABLE III
VSD HARMONIC SPECTRUM

Harmonic Order	Frequency (Hz)	Magnitude per unit current	Phase angle in Degrees
1	60	100.00	(13.40)
5	300	0.04	252.60
7	420	0.03	46.60
11	660	0.01	170.60
13	780	0.01	(19.80)
17	1020	0.01	63.60
19	1140	0.01	164.90
21	1260	1.21	89.10
23	1380	1.59	16.00
25	1500	1.61	82.30
27	1620	0.08	(19.00)
29	1740	0.02	240.60
31	1860	0.01	73.70
35	2100	0.02	104.50
37	2220	0.02	(84.00)
43	2580	0.01	238.50
45	2700	0.18	(1.60)
47	2820	0.67	78.80
49	2940	0.57	98.70

C. Measured Data

In order to verify if any significant background harmonics are present, power quality measurement devices were connected at Bus A and Bus B of TP SWGR. The baseline measurements revealed 0.45% V_{THD} under no load condition. Voltage harmonic measurements Fast Fourier Transform (FFT) is shown in Fig. 3.

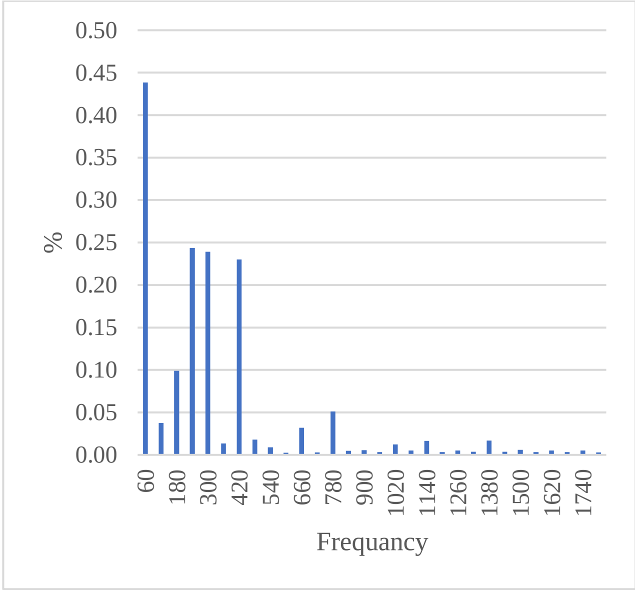

Fig. 3: Measured Voltage Harmonic Spectrum

D. Frequency Scan and harmonic Load Flow Results:

The parallel resonance point of the system at the TP SWGR bus can be estimated based on the following equation [3]

$$h_r = \sqrt{\frac{MVA_{sc}}{MVAR_{cap}}} \quad (1)$$

where

h_r harmonic resonance order;
MVA_{sc} combined source and transformer impedance in MVA;
$MVAR_{cap}$ total reactive power generated by the submarine cables

$MVAsc$ can be calculated based on the MVA method [4] as follows:

$$MVAsc = \frac{MVA_{\,source} \times \frac{MVA_{xfmr}}{Z_{pu}}}{MVA_{\,source} + \frac{MVA_{xfmr}}{Z_{pu}}} \quad (2)$$

where

$MVA_{\,source}$ source short circuit MVA;
MVA_{xfmr} transformer base MVA rating;
Z_{pu} transformer impedance in per unit

$MVAR_{cap}$ can be calculated as follows:

$$MVAR_{cap} = Q_{cable28} + Q_{cable27} + Q_{cable25} + Q_{cable23} \quad (3)$$

where

Q_{cable} reactive power generated due to cable distributed capacitance in MVAR;

MVA_{xfmr} transformer base MVA rating;
Z_{pu} transformer impedance in per unit

Q_{cable} can be calculated as follows:

$$Q_{cable} = 2\pi f c\, V^2 \quad (4)$$

where
f system frequency in Hz ;
c cable capacitance in μF ;
V system voltage in kV

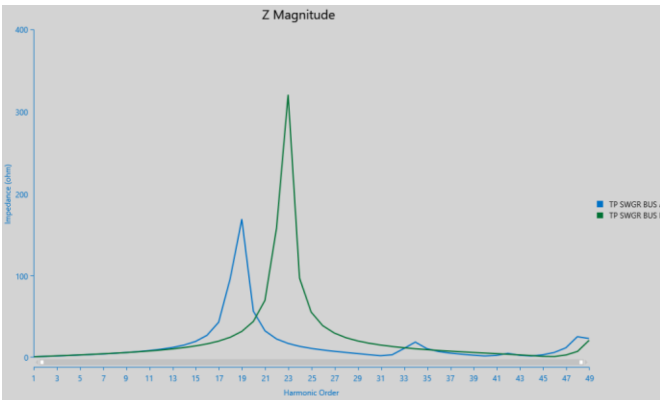

Fig. 4: Frequency Scan- TP Switchgear Bus

By substituting the provided values ($MVA_{source} = 328$ MVA, $MVA_{xfmr} = 60$ MVA, $Z_{pu} = 0.09, f = 60$ Hz, and $V = 13.8$ kV) along with cable capacitances provided in Table II, the calculated parallel harmonic resonance order would be 22.89. The calculations to conduct a complete system frequency scan are much more complicated and requires a power system modeling software. Therefore, frequency scans were conducted by utilizing a commercially available power system modeling software at BUS A and BUS B of TP SWGR, with results demonstrated in Fig. 4. It is evident that the system is sharply resonant at BUS B at the 23rdharmonic order. This is approximately in line with the simplified calculations done based on equations 1 through 4. Fig. 4 also shows that the system is resonant at the 19th harmonic order at BUS A. The impact on harmonic amplification is clear when voltage and current waveforms, as well as their harmonic spectrums, are compared as shown in Figs. 5 through 12. Had the selected VSD been an 18-pulse drive, the harmonic results would have been different with the system being resonant at the 19th harmonic order at BUS A (characteristics harmonics for 18- pulse drive are 17th, 19th, 35th, 37th, etc.) This is likely to result in unacceptable harmonic results at BUS A. Overall, considering the possible switching scenarios, no matter what type of VSD technology is selected, system resonance and subsequent harmonic amplification is very likely to occur.

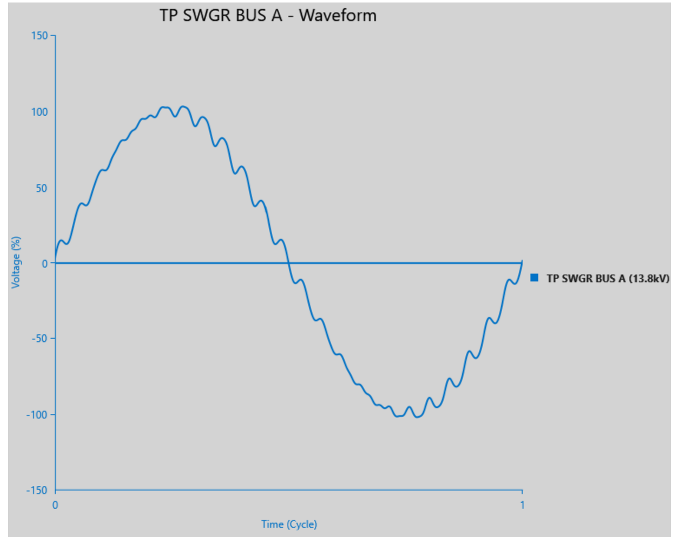

Fig. 5: Voltage waveform- TP Switchgear Bus A

Voltage and current waveforms on BUS A has much less harmonic content than the one on BUS B. in addition, the 24-pulse drive signature is much more pronounced on BUS B's current and voltage waveforms when compared to BUS A's waveforms. This is because the system at BUS B is resonant at a characteristic harmonic of the selected 24-pulse VSD (characteristics harmonics for 24-pulses drive are 25th, 27th, 47th, 49th, etc.). furthermore, figures 10 and 12 depict how the 23rd voltage and current harmonics are being amplified to reach 30% and 40% of fundamental respectively. The harmonic load flow resulted in 5% V_{THD} at Bus A and 30% V_{THD} at Bus B. With this kind of distorted voltage at Bus B, connected motors and cables will be thermally stressed and could fail prematurely.

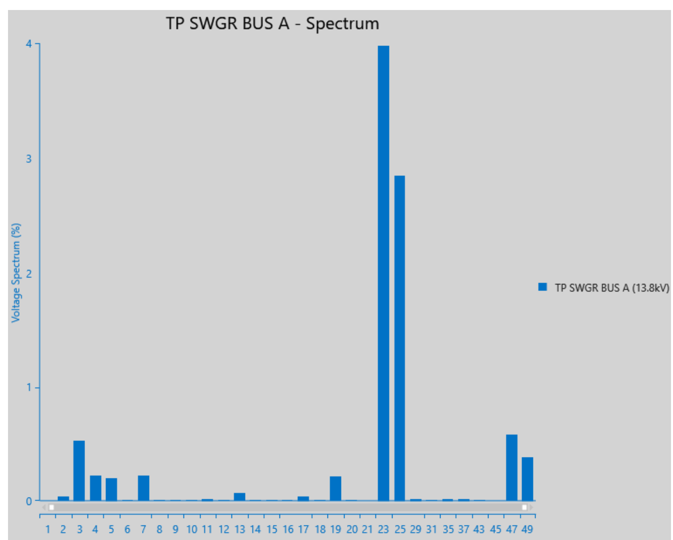

Fig. 6: Voltage Harmonic Spectrum- TP Switchgear Bus A

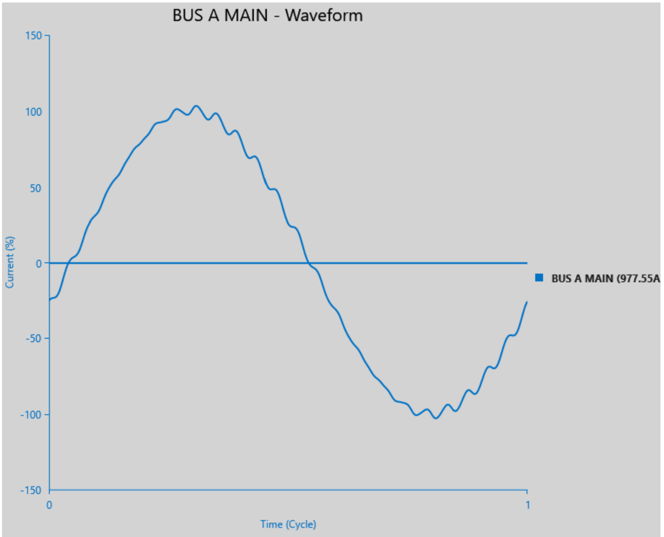

Fig. 7: Current Waveform TP Switchgear Bus A

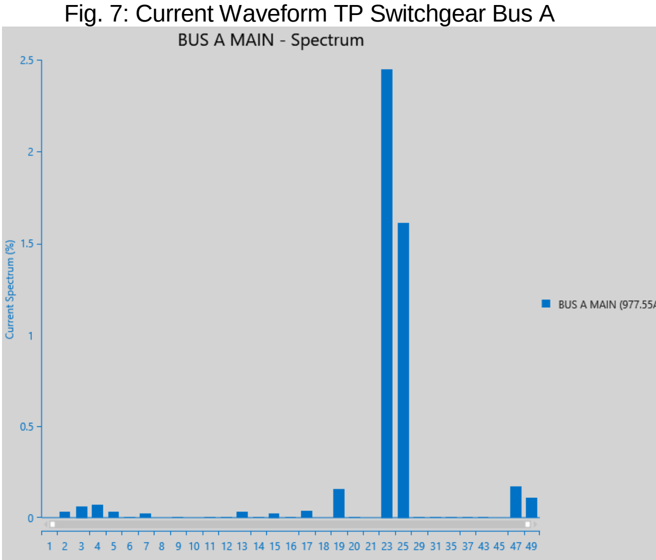

Fig. 8: Current Harmonic Spectrum TP Switchgear Bus A

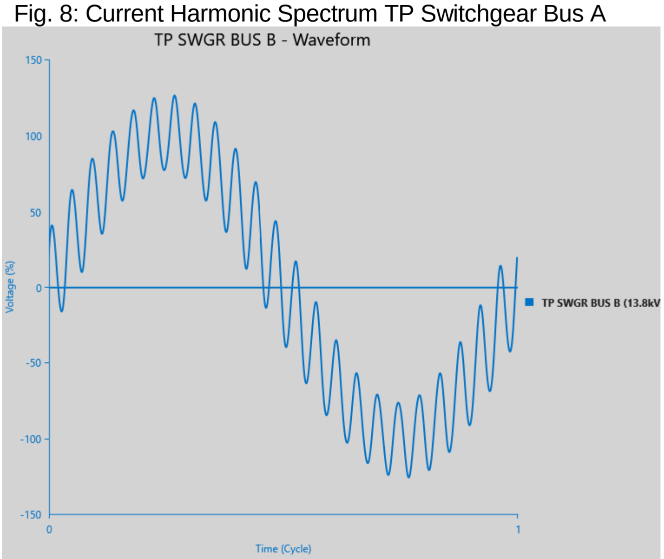

Fig. 9: Voltage waveform- TP Switchgear Bus B

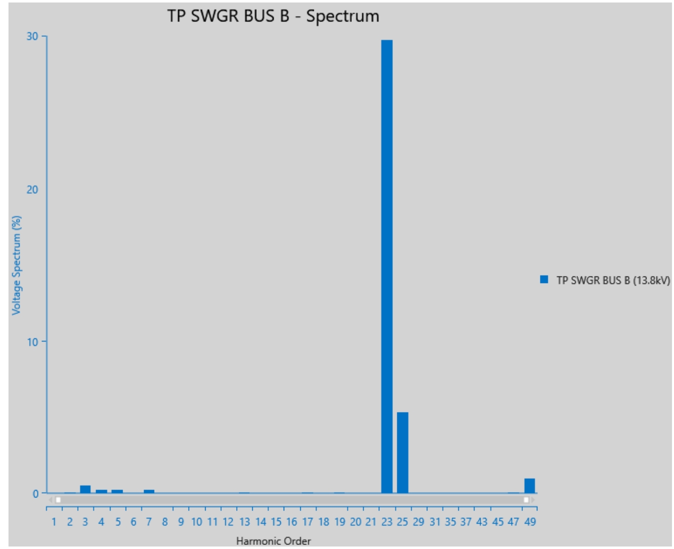

Fig. 10: Voltage Harmonic Spectrum- TP Switchgear Bus B

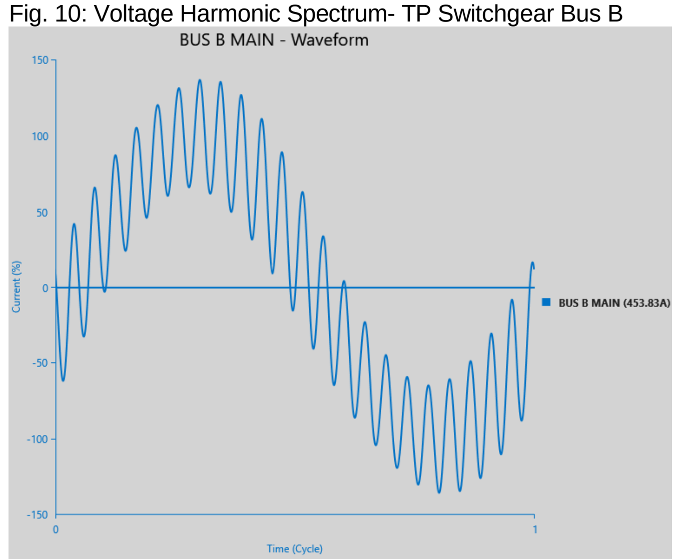

Fig. 11: Current Waveform TP Switchgear Bus B

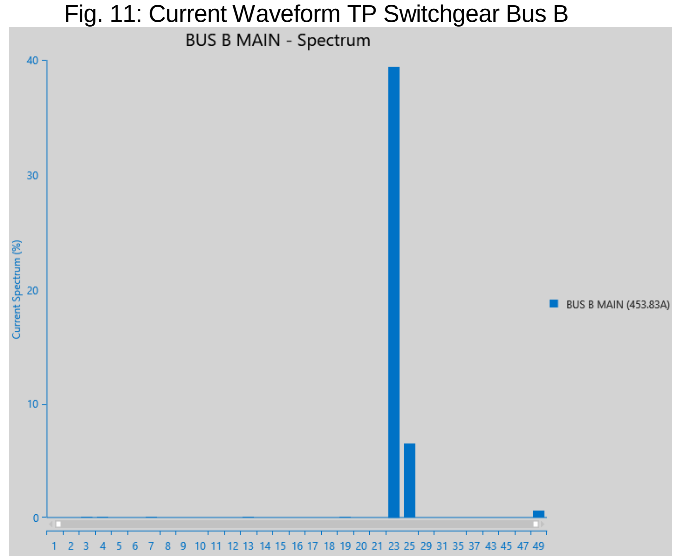

Fig. 12: Current Harmonic Spectrum TP Switchgear Bus B

III. OFFSHORE HARMONIC MITIGATION

The calculated total voltage and current harmonic distortion results are not acceptable and must be mitigated to assure reliable operation. Solutions using active and passive harmonic filters, as well as an alternative solution, will be discussed in the following sections.

A. Active Harmonic Filters

1) *Active Harmonic Filter Description:* One approach to addressing harmonic distortion is to install active harmonic filters near the harmonic-current sources, such as VSDs at LV SWBD1. Active harmonic filters receive input from broad-frequency current transformers measuring the current flowing to the load bus. The active harmonic filter is modeled as a multiple-frequency harmonic current source in series with an inductor [5]. The active harmonic filter output injects current to cancel the harmonic currents flowing to the load bus. Ideally, this would change the noisy current flowing to the bus to a pure fundamental-frequency current.

2) *Active Harmonic Filter Advantages:* The harmonic currents generated by the loads will vary, depending on which individual loads are in service, and the actual load on the individual loads. Active harmonic filters have the ability to adjust their output current to effectively cancel the harmonic currents flowing to the load bus.

3) *Active Filter Limitations:* Active harmonic filters contain significant internal inductance. Since the inductive impedance increases linearly with increasing frequency, the voltage drop across this inductance will increase with increasing frequency. Because the voltage available to the active harmonic filter is the bus voltage, the ability of the active harmonic filter to generate canceling harmonic currents at higher harmonic frequencies is limited by the bus voltage. Therefore, the frequencies of the harmonic currents required must be considered when sizing the active harmonic filter. Active harmonic-filter manufacturers generally rate their filters based on 100% of the harmonic current required is fifth harmonic. Depending on the manufacturer, this generally means that the filter capacity that is consumed by a given harmonic h is h/5 * I_h, where h is the harmonic order and I_h is the current required for the h^{th} harmonic.

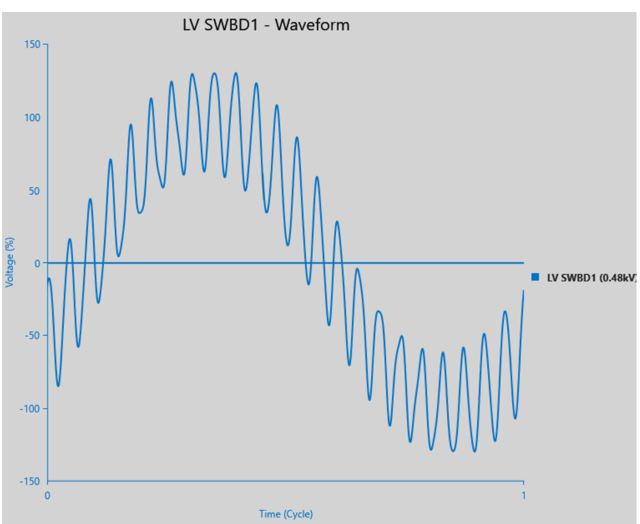

Fig. 13: Voltage waveform- LV SWBD1 Bus

4) *Example:* Fig. 1 shows the one-line diagram for the system considered. The following is an example showing one method of sizing an active harmonic filter connected in parallel to the AFD receiving power from Bus "LV SWBD1".

a) *Step one:* Define the desired current distortion limits. The first step in sizing the active harmonic filter is to define the desired distortion of the current flowing to bus "LV SWBD1". In many cases, the limits recommended in Table I are adequate. However, there may be cases, like the case shown in section II, where additional filtering of certain frequencies is desired. An example of such a case is adding additional filtering for harmonics that are near the system resonant frequency.

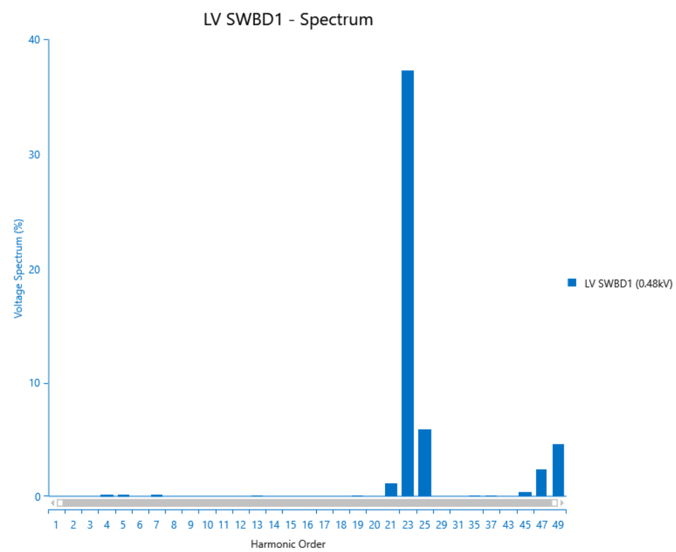

Fig. 14: Voltage Harmonic Spectrum- LV SWBD1 Bus

b) *Step two: Determine the current harmonic spectrum.* The second step is to calculate the harmonic spectrum of the current flowing to the bus. The worst-case harmonic spectrum of the current flowing to Bus "LV-SWBD1" is given in the second column in Table IV. Under these conditions, the fundamental-frequency current IL is 1497.9 A and the maximum short-circuit current ISC is 29 kA. Because of the system resonance near the 23rd harmonic, the filter will be sized to produce the harmonic currents required to eliminate the 21st, 23rd, and 25th harmonics and bring the other harmonic currents within the Table I recommendations.

c) *Step three:* Determine the filter current required. The third step is determining the harmonic current at each harmonic required to bring the current flowing to the load bus within the desired harmonic limits. The results of this step are shown in the third column in Table 1.

TABLE IV
ACTIVE FILTER SIZING

*Harmonic Order**	Current (A)	Filter Current Required (A)	Filtered Current (A)	Filter de-rating	De-rated Filter Current (A)
2	0.5	0.0	0.5	100.0%	0.0
4	1.5	0.0	1.5	100.0%	0.0
5	0.9	0.0	0.9	100.0%	0.0
7	0.6	0.0	0.6	71.4%	0.0
11	0.2	0.0	0.2	45.5%	0.0
13	0.1	0.0	0.1	38.5%	0.0
17	0.2	0.0	0.2	29.4%	0.0
19	0.1	0.0	0.1	26.3%	0.0
21	16.6	16.6	0.0	23.8%	69.7
23	60.7	60.7	0.0	21.7%	279.4
25	29.6	29.6	0.0	20.0%	147.9
29	0.3	0.0	0.3	17.2%	0.0
31	0.2	0.0	0.2	16.1%	0.0
35	0.3	0.0	0.3	14.3%	0.0
37	0.3	0.0	0.3	13.5%	0.0
43	0.1	0.0	0.1	11.6%	0.0
45	2.5	0.0	2.5	11.1%	0.0
47	10.4	5.9	4.5	10.6%	55.9
49	11.0	6.5	4.5	10.2%	63.5
$Total_{RMS}$	71.3	70.1	7.1		334.6

* Note that harmonics with current magnitudes < 0.05 A are not shown.

d) *Step four:* Determine the harmonic spectrum with the filter applied*.* The fourth step is to determine the resulting harmonic spectrum after the filter has been applied. Since the filter will supply current at the required frequency with opposite polarity to the unfiltered harmonic current, this is a simple subtraction. The results of this step are shown in the fifth column.

e) *Step five:* Check to ensure the TDD requirements are met*.* The fifth step is determining whether the Total Demand Distortion meets the requirements. As indicated in Step Two, the fundamental-frequency current I_L for Bus "LV-SWBD1" is 1497.9 A and the maximum short-circuit current I_{SC} is 29 kA. Since $I_{SC}/I_L < 20$, Table I requires the total harmonic current to be a maximum of 5% of I_L, or 74.9 A. Since the filtered harmonic current is only 7.1 A, no further filtering is required to meet the IEEE 519 TDD requirements.

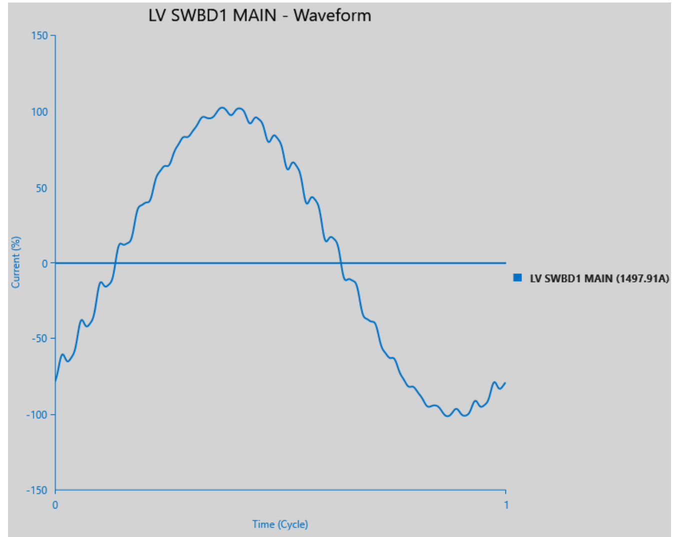

Fig. 15: Current waveform- LV SWBD1 Bus

f) *Step six:* Calculate the active filter rating*.* The sixth step is to calculate the required active filter rating. As mentioned above, active filters cannot supply the same filter current over all frequencies. This sizing example assumes a filter that must be de-rated for higher harmonic orders by a factor of h/5. The derating assumed for each harmonic order is shown in the fifth column of Table I and the resulting de-rated current is shown in the sixth column. The active filter in this example requires a minimum rating of 334.6 A.

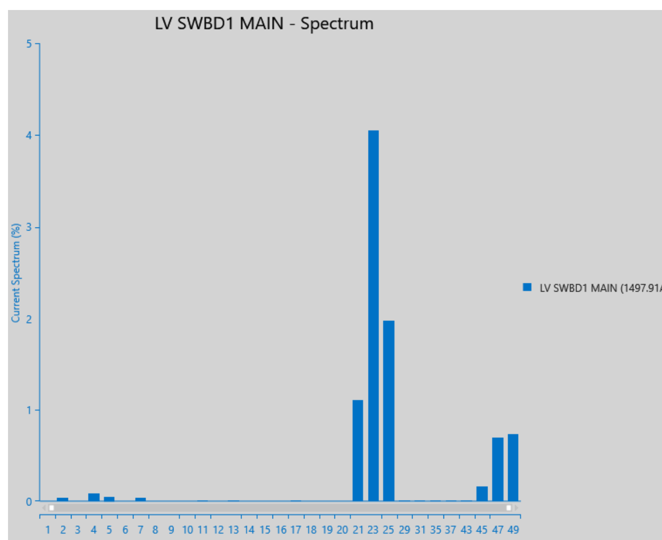

Fig. 16: Current Harmonic Spectrum- LV SWBD1 Bus

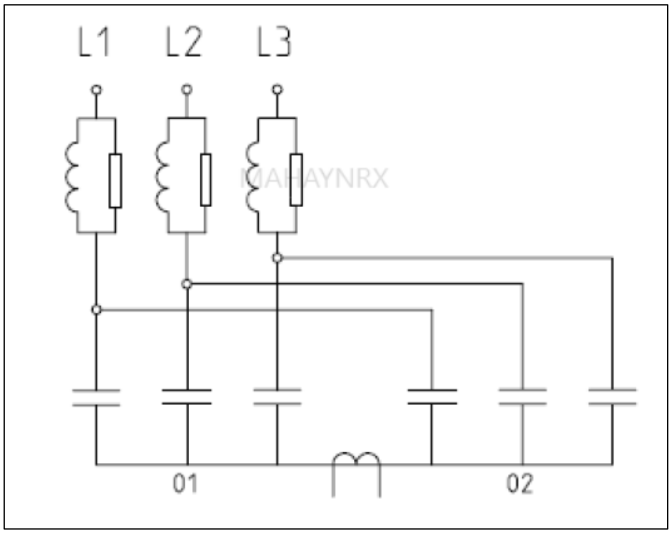

Fig. 17: High Pass Passive Filter

B. High Pass Passive Filter:

A high pass filter consists of C, L, and R elements as shown in Fig. 17 and to be connected at the TP SWGR buses. The larger the bank in terms of MVAR the more effective it becomes in absorbing high order harmonics. However, large banks will result in excessive losses in the resistive element, which provides a dampening effect to parallel resonance peaks and subsequent harmonic amplification. The filter parameters can be calculated from the following equations [6]

$$C = \frac{h^2}{2\pi f h^2} \times \frac{Q}{V^2} \qquad (5)$$

where

C	filter's capacitance in $farads$;
h	harmonic order to be filtered;
V	system voltage in kV;
Q	filter's size in $MVAR$

For 1 MVAR filter size and for the 23rd harmonic order to be filtered, $C = 13.93\ \mu F$

The inductive element L can be calculated as follows:

$$L = \frac{1}{h^2-1} \times \frac{V^2}{2\pi f Q} \qquad (6)$$

Based on the aforementioned parameters, $L = 0.974\ mH$

R can be determined based on the following equations

$$R = Q_f X_{lh} \qquad (7)$$

where

Q_f	Quality factor of the filter;
X_{lh}	inductive reactance at the tuning frequency;

Typically, Q_f values are selected between 0.5 to 5. The higher the value of Q_f, the more effective the filter at the tuning frequency. Therefore, $Q_f = 5$ is selected since the 23rd harmonic is the primary targeted harmonic to be mitigated. This would result in 41.8 ohms for the resistive element of the filter. [7]. It should be noted that the filter is tuned at the 22.8 harmonic to prevent the system from potentially being parallel resonant at the 23rd in case of failure of a few capacitors units. [7] [8]. Maximum harmonic loading should be considered while designing the filter, and results should be shared with the manufacturer for proper equipment design. With the above parameters considered, V_{THD} at the TP SWGR bus B will drop to 2%. Fig. 18 demonstrates how the parallel resonance frequency shifted away from the 23rd order with the application of the high pass damped filter. Figs. 19 and 20 demonstrate the new voltage waveform and harmonic spectrum respectively. As shown in the results, the filter is very effective in reducing harmonics throughout the system. However, the physical space might be a limiting factor in considering high pass filters on offshore platforms. Also, power losses and heat radiation might pose a challenge in indoor installations.

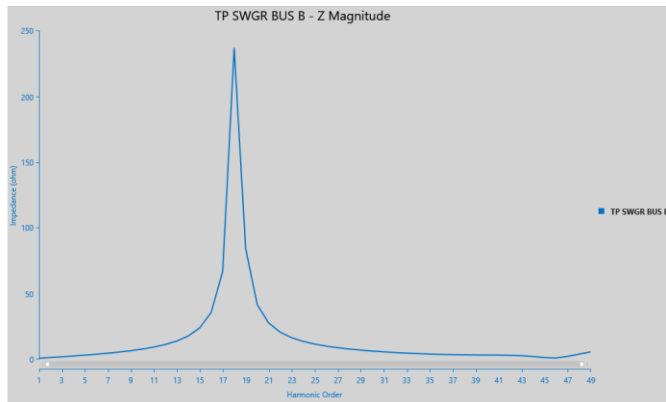

Fig. 18: Frequency Scan- TP SWGR Bus B w/high pass filter

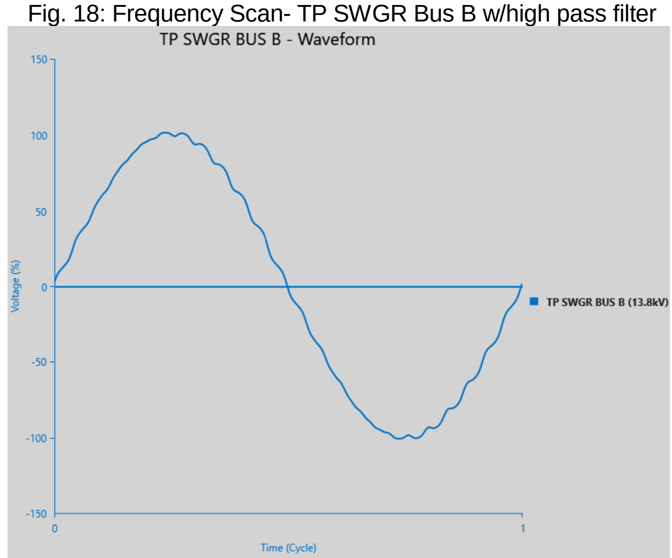

Fig. 19: Voltage waveform, TP SWGR Bus B w/high pass filter

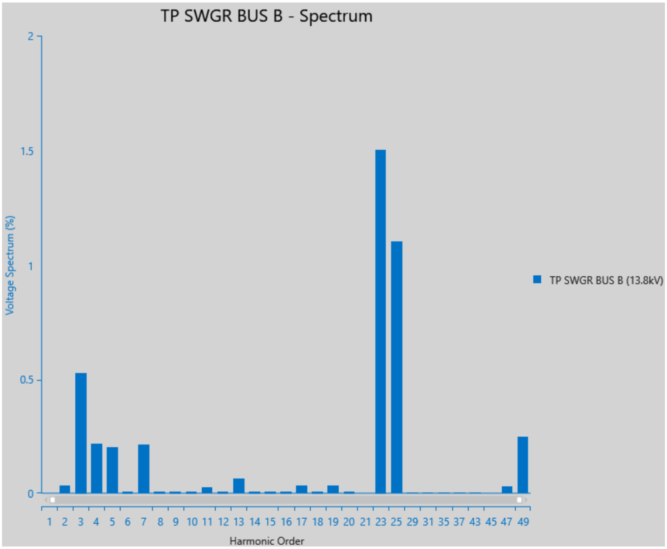

Fig. 20: Voltage Harmonic Spectrum, TP SWGR Bus B w/high pass filter

C. *Alternative Solutions:*

Utilizing active front end (AFE) drives can offer an acceptable alternative since harmonic injection in the system will be minimal. However, care should be exercised since they are more susceptible to system disturbances (i.e. voltage sags and swells) with no isolation transformer at the front end. Phase shifting for the main transformers on the wellhead platforms (i.e. T1 and T2) can also be considered to provide further harmonic cancellation. However, it is still likely for harmonics to be amplified with one of the many possible switching scenarios.

IV. CONCLUSION

Twenty-four (24) pulse VSDs are superior when it comes to harmonic injection in the system with the 23rd and 25th harmonics being the major characteristic ones. Utilizing this technology is becoming common in the artificial lifting industry. However, in offshore application where long submarine cables are present, system resonance can amplify harmonics to unacceptable levels. Solutions including active harmonic filters and high pass passive filters can be implemented to achieve acceptable voltage and current harmonic distortion levels. Active harmonic filters can be installed at the low voltage bus near the VSDs to cancel harmonics. Specific harmonics can be targeted to be eliminated and other harmonics can be partially reduced to meet standard requirements.

High order harmonics pose a challenge since filter capacity has to be de-rated. This might lead to cost escalation considering the size of the required active filter when several ESPs are running at full load at the same bus. High Pass passive filters can be considered to be connected at the medium voltage bus to absorb high order harmonics. However, physical space might be a limitation in offshore installations. In addition, power losses in the resistive element can pose a challenge for indoor installations. Utilizing active front end drives might offer a cost-effective solution from a harmonic mitigation standpoint.

Overall, proper system design and analysis should be conducted in the early stages to identify resonance points, harmonic amplification and specify mitigation solutions.

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