Handling System Harmonic Propagation in a Diesel-Electric Ship with an Active Filter

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***Abstract*—Harmonic distortion is often a challenge in marine vessel power systems due to the presence of large motor drives containing diode or thyristor rectifiers. Governing standards impose requirements on bus voltage Total Harmonic Distortion (THD) which can be demanding to fulfil. An attractive measure to reduce THD is to use 12-pulse rectifiers, as they are known to cancel the 5th and the 7th harmonic. However, the added cost and space of this solution compared with standard 6-pulse rectifiers is significant. This paper proposes to base propulsion motor drives on 6-pulse rectifiers, and mitigate harmonic problems by means of power electronic based active filters. A detailed numeric simulation model is developed for evaluating the performance of the topology. A case study system is defined consisting of two propulsion motor drives and two synchronous generators. The active filter greatly improves the bus voltage THD in all defined simulation cases. The performance is also better than a corresponding system using 12-pulse rectifiers and no active filter.**

I. Introduction

Harmonic distortion is a well-known challenge in all kind of AC-based power systems. The term *harmonics* is commonly used to describe all components of voltages and currents with a frequency different from the fundamental (e.g. 50 Hz). There are many origins for harmonics, and all power systems will contain a certain level of them. Whether this will cause operational problems or not depends on the amount of harmonic distortion, and on the ability of various units to function properly under distorted conditions. Harmonic distortion can lead to problems with different levels of severity. The most severe consequence is malfunctioning units, and this will only occur under strongly distorted voltages. However, even moderate harmonic levels can lead to increased mechanical wear of components, as well as significantly increased power losses.

Generally, small power systems such as those in ships and oil rigs will have more distorted voltages and currents compared to large onshore power grids [1] [2] [3]. This is mainly due to the high percentage of non-linear load units often interfaced through thyristor or diode rectifiers, both of which are known to consume significant amounts of harmonic current. There are several standards for allowed distortion levels [4] [5] [6], and typically the voltage THD must be limited to 5 % or 8 %.

This paper is focusing on the motor drive rectifier loads mentioned above, as this is the main source of harmonic currents in diesel-electric ship propulsion systems. There are several strategies for how to compensate the harmonic currents:

1) Utilize 12-pulse rectifiers (or higher order) to cancel key harmonic components
2) Passive filtering based on combinations of capacitors, inductors and resistors
3) Active filtering based on high-bandwidth switched power converter

Strategy 1 and 3 are explained more in detail in section II and III, respectively. Passive filtering is not evaluated in this paper, see [6] [7] for more information on this topic.

The paper is mainly focusing on active filters and how they can reduce harmonic content in diesel-electric ship propulsion systems. A case study system is defined and a corresponding simulation model is developed in the SimPowerSystems environment of MATLAB/SIMULINK. Section II presents how 6-pulse and 12-pulse diode rectifiers will bring harmonic distortion to a ship power system. Section III focuses on design and control of active filter in the specific case system. Finally, simulation results are presented and discussed in section IV.

II. Harmonic distortion from diode rectifiers

Schematics of the 6-pulse and 12-pulse diode rectifiers are shown in Fig. 1. The 6-pulse rectifier consists of a two-winding transformer and a standard diode bridge, while the 12-pulse uses a three-winding transformer and two diode bridges. The diode bridges can be connected either in parallel or in series on the DC-side, depending on the required voltage and current level for the load. Another option is to let each diode bridge supply one motor as shown in Fig. 1d). However, this option can give higher harmonic content than options b) and c) unless the motors are running at close to equal power level.

The voltages and currents from both topologies are shown in Fig. 2. The corresponding frequency spectrum is shown in Fig. 3, and is obtained from taking the Fast Fourier Transform (FFT) on the data in Fig. 2. The system used to simulate these waveforms is the "case 1" explained in section IV (without active filter connected). The main difference between the two topologies is the removal of 5th and the 7th harmonic in

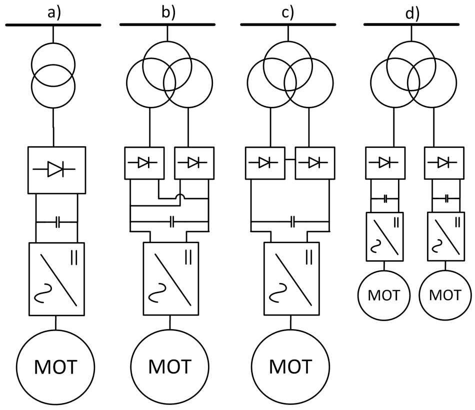

Fig. 1: Various VSD-topologies: a) 6-pulse, b) 12-pulse DC parallel connected, c) 12-pulse DC series connected, d) 12-pulse driving two motors

the 12-pulse rectifier. Additionally, the 17^{th} and the 19^{th} harmonics are also removed. Harmonic cancellation in the 12-pulse rectifier is obtained by letting the secondary windings be connected in delta-wye. With this configuration, the currents seen from the primary will be shifted in phase with 30^o referred to the fundamental frequency. The 5^{th} and 7^{th} harmonics on the other hand, will be shifted with $6{\cdot}30 = 180^o$. They are therefore in opposite phase, and their sum will be zero. Consequently, they will not be visible at the primary winding terminals. The same is valid for all the side-bands of any odd multiple of 6 (17^{th},19^{th},29^{th},31^{th}...).

III. Active filter design and control

An active filter is basically a high bandwidth switched power converter with ability to act as a harmonic current or voltage source [8]. High bandwidth in this context refers to a combination of low measurement sampling time and fast

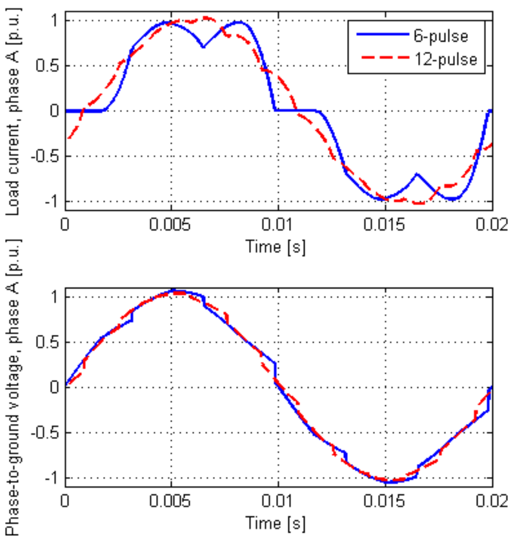

Fig. 2: Comparison of waveforms for 6-pulse (blue) and 12-pulse (red) rectifiers for the "Case 1" topology in Fig. 6

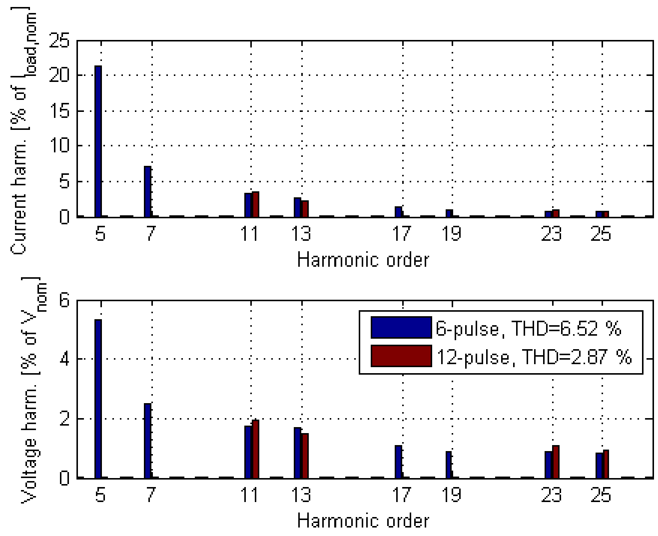

Fig. 3: Comparison of voltage and current harmonics for 6-pulse (blue) and 12-pulse (red) rectifiers for the "Case 1" topology in Fig. 6

response in the closed loop control system. Generally, an active filter can be realized both as a Voltage Source Converter (VSC) and a Current Source Converter (CSC), and be configured as either current controlled or voltage controlled. This paper will consider active filters based on the current controlled VSC-topology. This is the preferred topology in most applications of active filtering.

Active filters can further be divided into two categories: *broadband* [9] [10] [11] or *selective harmonic* filters [12] [13]. Selective harmonic filters are configured to cancel certain harmonics by using individual controllers locked to each frequency. Broadband filters on the other hand, are configured to compensate a wide range of harmonic frequencies, including interharmonics. Their response is limited by some constraints, such as the switching frequency, control system response time and current limit. The presence of fluctuating active power is also a major limiting factor for the capability. This paper has implemented a broadband type of active filter.

A schematic of both the power circuit and the control system of the implemented active filter is included in Fig. 4. The power circuit consists of three main parts:

- The semiconductors, denoted VSC in Fig. 4
- DC-side filter capacitor C_{DC}
- AC-side filter, here assumed to be LCL-type

There are many VSC topologies, e.g. two-level, three level, MMC etc. In this work the standard two-level converter is assumed. The DC-terminals are connected to a filter capacitor, which serves as a short-term energy storage. It is important that the DC voltage fluctuations are kept within a sufficient margin. A filter is also required between the VSC AC-terminals and the connection point. There are many filter topologies suitable for this purpose, here the LCL-type is assumed [14]. The switching voltage ripple is attenuated by the series inductors L_{AF1} and L_{AF2}, while the switching ripple current is consumed by

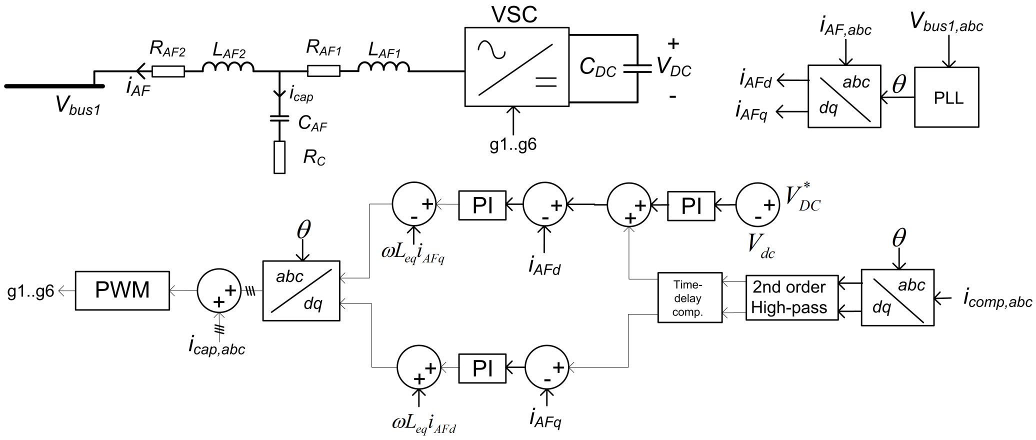

Fig. 4: Active filter power circuit and control system

the shunt capacitor C_{AF}. The shunt resistor R_C is inserted to provide some damping at the filter resonant frequency.

The dq-frame is chosen for implementing active filter control, and the control system block diagram is presented in Fig. 4. The angle used for dq-transformation is obtained from a PLL synchronized to the bus terminals (bus 1). The control system objective is to provide a current i_{AF} that is equal to the compensation current $i_{comp,abc}$. The signal $i_{comp,abc}$ is normally chosen as equal to the harmonic current which the filter seeks to cancel, but it can also be selected in a more sophisticated way [15].

After $i_{comp,abc}$ is converted into the dq-frame, a second order high-pass filter is applied. This will remove the fundamental frequency component since the fundamental frequency is transformed to a DC-quantity in the dq-frame. The cutoff-frequency of the high-pass filter must be selected with care, as unwanted interactions with the DC-voltage controller can occur if parameters are not chosen properly.

The bandwidth of the current controller is restricted by the VSC switching frequency and by the dynamic response of the AC-side filter. The response time of the current controller has a negative effect on filter performance, illustrated in Fig. 5. The figure shows simulation results from case 1b presented in section IV. The fifth harmonic currents are calculated based on FFT-analysis and are presented in complex form. $i_{comp,abc}$ is chosen equal to the load current I_{load1}. However, the active filter current i_{AF} is lagging the load current by $\approx 30^o$. This is related with the current controller response time, which has been estimated to $T_c \approx 0.3$ ms. from a step response simulation. When the fifth harmonic is considered, a time-delay of 0.3 ms. corresponds to $0.3 \cdot \frac{5}{20} \cdot 360 \approx 27^o$. This is close to the phase delay of 30^o in Fig. 5. For higher-order harmonics, the phase delay would increase roughly in proportion to the harmonic order. This simple illustration underlines the importance of designing a filter with as high bandwidth as possible.

For reducing the impact of control system time delays, a block denoted "Time-delay compensation" (TDC) is designed. There are several ways of implementing such feature, see [16] for an overview. A common factor for all methods is that they reduce the transient performance of the active filter, and they must therefore be applied with care. The method applied in this work is based on delaying the sampled values of $i_{comp,dq}$ with a period $T_{delay} = \frac{1}{2 \cdot f_{PLL}} - T_c$, where f_{PLL} is the fundamental frequency calculated by the PLL, and T_c is the control system closed loop response time defined in the previous paragraph. The method is further presented and discussed in [16].

The inner current controller is configured in a standard way, including the feed-forward term for minimizing the cross-coupling between the d- and q-axes during transients or dynamic changes. After the reference signals are transferred back to abc-frame, the filter capacitor current $i_{cap,abc}$ is added as a feed-forward term. This will improve the controller response when the grid current i_{AF} is used in the feedback loop [9] [10]. The gate signals $g1...g6$ are obtained from a standard Pulse-Width-Modulation (PWM), but other techniques (e.g. hysteresis) could have been applied as well.

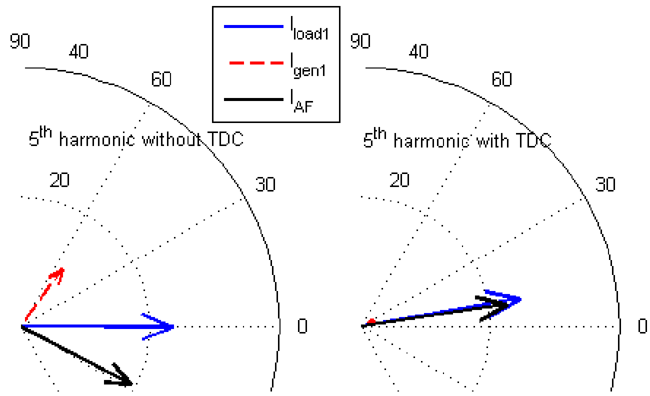

Fig. 5: Complex representation of 5^{th} load 1 current harmonic with (left) and without (right) time-delay compensation (TDC) added. Values in % of $I_{load1,nom}$.

IV. Case study simulations

A. System description

The case study presented in this paper is based on a simplified equivalent of a vessel power system where only the propulsion loads are included. The simplification is justified from the fact that these loads typically are responsible for the dominant part of power consumption and of the harmonic distortions. An overview of the case study topologies is shown in Fig. 6. "Case 1" is the simplified topology mainly used for illustration purposes, while "case 2" is the full system. The vessel contains two generators, each connected to respective buses, *bus1* and *bus2*. One propulsion motor is connected to each bus, supplied through Variable Speed Drives (VSD). The VSDs contain six-pulse diode rectifiers and voltage source inverters. A transformer is included as well for providing galvanic insulation. A transmission series impedance is included between the two buses. Finally, the active filter is connected to bus 1 as seen in the figure.

Seven simulation cases are compared in the analysis, see Table I. Three are based on the case 1 topology, while four are based on the case 2 topology. The other difference between them is the choice of active filter current reference (i_{comp}). Note that the simulation of 12-pulse rectifier from section II is also included in the comparison. The parameter values used in all simulations are given in Table II. Both loads are operated at nominal power consumption in all simulation cases.

TABLE I: Simulation case overview

Case name	Description	AF reference (i_{comp})
Case 1a	1 generator + 1 load	$i_{comp} = 0$
Case 1b	1 generator + 1 load	$i_{comp} = i_{load1}$
Case 2a	2 generators + 2 loads	$i_{comp} = 0$
Case 2b	2 generators + 2 loads	$i_{comp} = i_{load1}$
Case 2c	2 generators + 2 loads	$i_{comp} = i_{load2}$
Case 2d	2 generators + 2 loads	$i_{comp} = i_{load1} + i_{load2}$
12-pulse (case 1)	See section II	$i_{comp} = 0$

TABLE II: Parameter values applied to case simulations

Parameter	Value
Rated voltage (LL RMS)	690 V
Generator rated power	1000 kVA
Nominal frequency	50 Hz
Load 1 rated power	500 kW
Load 2 rated power	500 kW
Generator inductance	0.1 p.u. / 151 μH
Generator resistance	0.01 p.u./ 4.8 mΩ
Load transformer series inductance	0.07 p.u./ 212 μH
Load transformer series resistance	0.01 p.u./ 9.5 mΩ
Impedance between bus 1 and 2 (Z_b)	0.005 + $j \cdot$ 0.05 p.u.
Active filter switching frequency	10 kHz
Active filter DC-voltage	2000 V_{DC}
Active filter HP cut-off	20 Hz
L_{AF1}	202 μH
R_{AF1}	7.1 $m\Omega$
L_{AF2}	101 μH
R_{AF2}	7.1 $m\Omega$
C_{AF}	167 μF
R_C	224 $m\Omega$

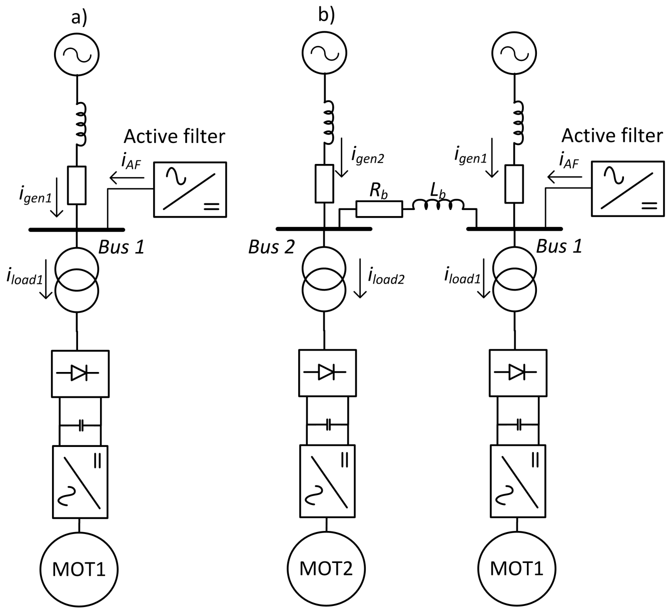

Fig. 6: Case study systems: a) Case 1 - one motor and one load, b) Case 2 - two motors and two loads

B. Case 1 results

Results from the case 1 simulations are presented in Fig. 7 and Fig. 8. Only the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics are presented as they constitute the dominant part of the system harmonic content. Before the filter is connected (case 1a), harmonics are equal on both buses, and the voltage THD is relatively high (6.53 %). The 5^{th} harmonic is clearly dominant, and contributes with 5 % to the voltage THD. When the filter is connected (case 1b), all harmonics are significantly reduced. There are small residual 5^{th} and 11^{th} harmonics, while the 7^{th} and the 13^{th} are close to eliminated. In principle it should be possible to completely cancel all harmonics for the case 1 topology, but the non-ideal current controller discussed in section III will always cause a certain level of residual harmonics. The resulting THD in case 1b of 0.93 % is considered to be a very good filter performance under the given conditions.

An interesting observation is how the load 1 harmonic current magnitudes are affected by the active filter being enabled. All the magnitudes increase in case 1b compared with case 1a. This illustrates an important challenge in active filtering of rectifier loads. When the filter starts to improve the waveform of the bus voltage, the load is able to draw more harmonic current. This can be explained by considering the equivalent harmonic impedance seen from the load. When the filter is enabled, the harmonic impedance is reduced, and hence the harmonic current increases. The harmonic phase angles are also shifted, this can be seen in Fig. 5 for the 5^{th} harmonic.

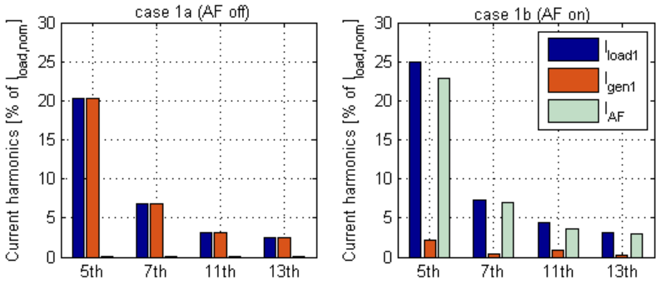

Fig. 7: Case 1 current harmonics comparison. Left: case 1a (filter disconnected), right: case 1b (filter connected)

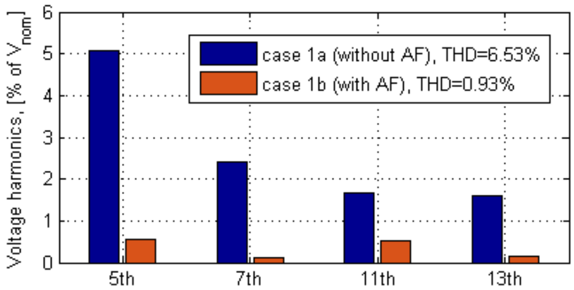

Fig. 8: Case 1 voltage harmonics comparison

C. Case 2 results

As presented in Table I, several choices for active filter current reference i_{comp} has been tested. The standard approach in active filtering is to place the filter as close as possible to a load (here: load 1), and to only consider this load current for generation of the reference current i_{comp}. This corresponds to case 2b where $i_{comp} = i_{load1}$. However, in a system with dispersed loads and generators, the harmonic content can be further reduced if some kind of global optimisation is applied to the current reference. Optimisation for generating the active filter reference currents is discussed in [15] for the same topology as case 2 through applying Model Predictive Control (MPC). Case 2c and case 2d represent an initial attempt to optimise current references based on measurements from multiple loads. Intuitively, voltage THD should approach zero at both buses if the filter is able to inject the current $i_{load1} + i_{load2}$. However, the challenging factor here is the impedance $Z_b = R_b + jL_b$ between bus 1 and bus 2. The harmonic current flowing through Z_b will give a harmonic voltage difference between the buses, and hence imposing a theoretical minimum limit for the THD. This limit is roughly proportional to the magnitude of Z_b.

Fig. 9 shows one fundamental period of the currents and voltages in the system for case 2d. The load current waveforms are similar to Fig. 2. However, the generator currents are close to sinusoidal due to good performance of the active filter. The bus voltages appears close to sinusoidal, but note that waveforms with THD in the 1-3% range will always appear close to sinusoidal.

A comparison of bus voltage THD in all seven simulation

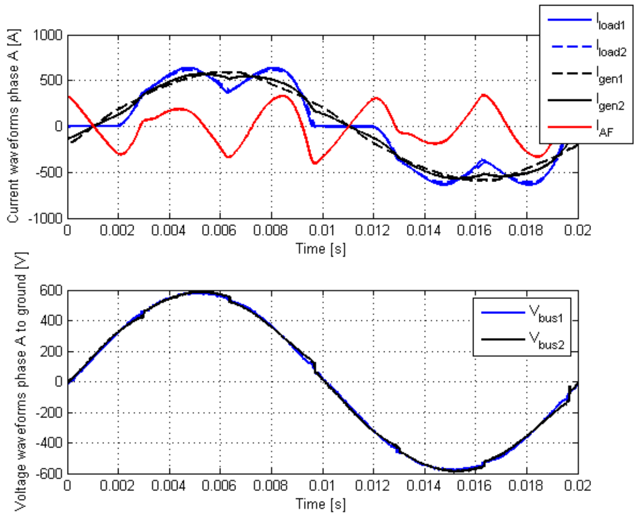

Fig. 9: One fundamental period of voltages and currents in case 2d

cases is presented in Fig. 10. The two cases with active filter disabled (1a and 2a) have equal THD of 6.53%. Case 1b performs well with THD of 0.93%. Case 2b and 2c performs close to identical, this can be explained by the fact that both loads are operating at the same power level. Hence, the load current harmonics will be close to equal in both magnitude and phase. Case 2d performs well with THD equal to 0.92 % at bus 1 and 2.38% at bus 2. The impedance Z_b is causing the higher THD at bus 2 as explained before. Finally, it is interesting to compare these results with the performance of the ideal 12-pulse rectifier. The 12-pulse gives a voltage THD of 2.87% without any additional filter installed. This is better than case 2b and case 2c, but worse than case 2d. However, the differences are not that significant, and other factors such as cost, size and reliability must be given most weight when comparing the solutions. It must also be kept in mind that the real harmonic profiles will be worse than those obtained from numeric simulations due to non-ideal components. This is valid both for the 12-pulse rectifier and for the active filter solution.

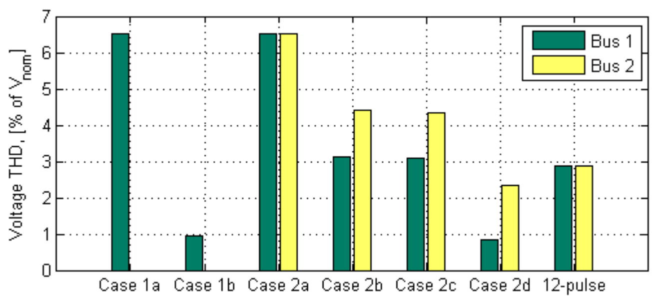

Fig. 10: Voltage THD comparison between all cases

A final comparison is made in Table III regarding sizing of the active filter. A simplified estimate of size is to divide the peak active filter current with the peak fundamental load 1 current. Case 1b, 2b and 2c has similar values in the range of 35-40% of the load current. Similar size is expected here since the active filter in all three cases is configured to compensate fully the harmonic current from one load. The difference between the cases is too small to draw any further conclusions. On the other hand, the current in case 2d is significantly higher since the filter is configured to compensate both load currents. The current of 69% is slightly less than the sum of currents in case 2b and 2c, but the difference is too small to draw any conclusion regarding sizing. However, a general conclusion is that an active filter needs to be rated fairly large in the case of compensating six-pulse rectifiers in ship propulsion power systems. By considering the THD-values it seems reasonable that an active filter rated $\approx 55\%$ will bring similar THD-performance as the 12-pulse case. However, the cost, size and reliability are important factors that needs to be evaluated in further work. It is important to remark that the objective to comply with the harmonic standards (e.g. [4]) in the most cost-efficient manner. For this purpose, optimisation methods can be applied both during design and operation phases as described in [15].

TABLE III: Simplified active filter size comparison

Case name	AF peak current % of $I_{load1,nom}$	Bus 1 THD	Bus 2 THD
Case 1b	35 %	0.93 %	N/A
Case 2b	38 %	3.20 %	4.40 %
Case 2c	41 %	3.15 %	4.35 %
Case 2d	69 %	0.93 %	2.45 %
12-pulse	0 %	2.87 %	2.87 %

V. Conclusion

This paper has investigated how active filters can reduce harmonic content in diesel-electric ship power systems. It is proposed to replace motor drive 12-pulse rectifiers with 6-pulse rectifiers, and to utilize an active filter for limiting the harmonic distortion. The selected active filter topology is a shunt-connected VSC-based filter with dq-frame control system. In the case of one generator and one load, the active filter is able to reduce the bus voltage THD from 6.53 % to 0.93 %. However, the performance is deteriorated in the case with two loads separated by an impedance. A single active filter cannot eliminate all harmonics in a system with multiple buses and harmonic loads. The minimum level of THD depends on the system impedances, loading of units and on the harmonic distortion characteristics. The results are finally compared with the 12-pulse rectifier case, and the active filter performs better when it is not constrained by its current rating. Further work should evaluate the cost, weight, size and reliability of the two solutions before it can be concluded whether or not the proposed topology is the better choice. Another topic for additional studies is dimensioning of active filters using system-level optimisation.

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