More in-depth analytical investigations of two Effective Harmonics Filters for More Electric Marine Vessel Applications

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Abstract— **In the last decades, due to the substantial evolution of shipboard power systems (SPSs) towards all-electric ships, power quality (PQ) issues onboard ships have become a serious challenge. To deal with this problem, using active filters may not be very practical because they have limited rated powers, high implementation cost, and other deficiencies particularly for medium-voltage SPSa. Some cost-effective solutions such as passive power filters (PPFs) and fixed capacitor-thyristor controlled reactors (FC-TCR) might be a reliable solution for medium voltage SPSs due to their capability to operate in medium and high voltage applications, low cost and easy maintenance. The contribution of this paper is to provide more in-depth analysis and mathematical development to evaluate and compare the performance of these solutions. Moreover, developed mathematical formulas are suggested to enhance the FC-TCR capability in terms of harmonic filtering. Through intensive simulation studies of a practical shipboard power system, which are carried out in MATLAB/Simulink environment, it is demonstrated that the FC-TCR can enhance the power quality and voltage stability of SPSs better than traditional PPFs filters.**

Index Terms—**Fixed capacitor-thyristor controlled reactor (FC-TCR), Harmonics filtering, Power factor (PF) compensation, passive power filters (PPFs), Shipboard power systems, Voltage stability.**

I. Introduction

Over recent years, the electric power evolution onboard SPSs has contributed to enhancing their performance, efficiency, and reliability by substituting the mechanical propulsion system with an electrical one based on power electronic converters (PECs) [1], [2]. However, through the utilization of PECs, harmonic propagation has found its way to SPSs, and offshore installations [1], [2], [3]. Ensuring a good power quality onboard SPSs has become a hot topic not only to avoid serious damage to the electric power system (EPS) but also to improve the safety of the ship passengers and/or crew, and reduce the specific emissions and fuel consumption [4]. The common advanced solutions for PQ issues are constrained either by the implementation cost or by the application criterion. For example, shunt passive power filters (PPFs) can reduce the most dominant harmonics and compensate for a degree of power factor (PF) [5], [6]. Nonetheless, these filters cannot be an ideal solution for SPSs due to several disadvantages such as large size, heavy weight, fixed tuning, fixed reactive power compensation, and the risk of resonance. The active power filters (APFs) can overcome the weaknesses of the SPPF [7], [8]. Nevertheless, the power rating and switching frequency are inversely proportional due to losses, which implies that the APFs are not desirable for medium/high power systems. The high cost and complex maintenance further limit their applications in SPSs. The PPFs can be combined with the APFs to decrease a bit the stress of power of the APF; hence, offer slightly decreased cost in a topology known as a hybrid APF [9]. However, this solution comes at the cost of the bulkiness and complexity of the system. Therefore, the SPPFs are still widely used for medium voltage SPSs. To overcome the drawbacks of the solutions mentioned above, a cost-effective solution based on a fixed capacitor–thyristor-controlled reactor (FC-TCR) is proposed in [11]. The capacitor compensates the inductive reactive power and causes a leading PF, while the TCR adjusts the leading PF towards unity. Although, this solution seems to be effective for medium voltage SPSs as the switching frequency of the TCR is very low compared to APFs (only two pulses per cycle), and it uses only one variable filter. It; however, did not attract much attention for SPSs.

This paper proposes a comparison of the PPFs and FC-TCR based on more in-depth analytical investigations to present the weaknesses of the traditional PPFs such as the parallel/series resonance and fixed selectivity. Then, via the proposed mathematical development and the enhanced control algorithm, it demonstrates how the FC-TCR can act as a low-pass filter; and thus, suppresses the low- and high-order harmonics, as well as ensuring the voltage stability. Based on the intensive simulation studies of a practical shipboard power system, which are carried out in MATLAB/Simulink environment, it has been demonstrated that both technqiues can enhance the power quality of the

SPS, but the FC-TCR offers more advantages over its counterpart in harmonics rejection and voltage stability enhancement.

The rest of the paper is organized as follows. In section II, an overview of the electrical power system of the modeled ship and analytical investigations of the PPF are addressed. In section III, the analytical investigations of the FC-TCR are presented. Section IV presents the numerical results and discussions, and Section V, concludes this article.

II. ANALYTICAL INVESTIGATION OF THE PASSIVE POWER FILTERS

The EPS of the SPS consists of the production (synchronous generators (SGs)), transmission, and distribution systems. Fig. 1 shows the single-line diagram of a typical electric power system of all-electric ships. It consists of two or more than two fixed-speed diesel generators connected to the main switchboard, two steam tunnel thrusters, two propulsions, two main converters to vary the speed of the propellers and results in drawing a large number of harmonics. A set of PPFs and the FC-TCR compensator, which will be presented in the next section are added and connected in parallel with the main switchboard. Other components such as ballasting pumps, and harbor generators, are not modeled since they cause neglected power quality issues comparing to the propellers.

There are several classification societies and international regulations that have imposed limits on power harmonics for ships such as ABS 2008 [10] and PRS/25/9/2006 [11] that are similar to the norms for industrial power systems like IEEE 45:2002 [12] and IEC 60092-101:2002 [13]. The implementation of PPFs is a practical solution in industries to mitigate the most dominant harmonics and compensates a degree of the power factor [14], [6]. The PPFs are distinguished by the ease of implementation and maintenance since they do not require any complicated control algorithms and voltage/current sensors. Moreover, their cost is much lower comparing to the APF, which makes their application more attractive and feasible in ships [20]–[22]. However, the PPFs still struggle from several deficiencies, the main one is the possible stimulation of the resonance phenomenon. This latter is divided into two categories, series resonance, and parallel resonance. In order to analyze the resonance phenomenon of the PPFs, the simplified single line diagram basic principle of Fig. 1 is presented in Fig. (2), considering that the FC-TCR is disconnected and only one set of tuned PPFs is connected to the main switchboard of the EPS. Fig. 2 (a) is the fundamental equivalent circuit on a per-phase base for Fig. 1, where V_S can be the voltage source of one synchronous generator or more than one feeder connected in parallel. X_{Ls} and R_s are respectively the reactance and the resistance of the main impedance. R_{lo} and X_{lo} are the parameters of the combination of linear and non-linear loads (propulsions, bow tunnel thrusters, etc.). V_{lo} is the load voltage. X_{Cf} and X_{lf} are respectively the reactances of the capacitors and the coil of the PPF, and R_f is the resistance of the PPF. Fig. 2 (b) shows the equivalent harmonic circuit
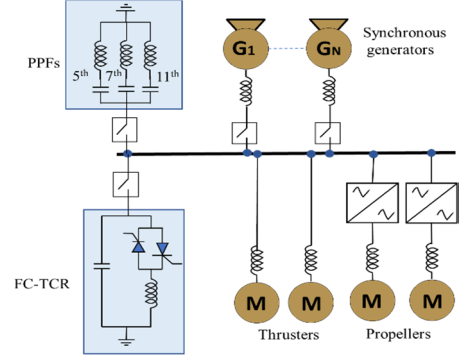

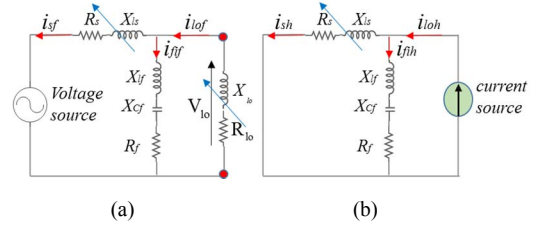Fig.1. Single line diagram of a typical electrical power system for all-electric ships

(a)   (b)

Fig.2. Single line diagram of the basic principle of a single tunned PPF connected to the electrical power system of the ship. (a) Fundamental equivalent circuit (b) Harmonics equivalent circuit

of Fig. 1, which simplifies the concept of harmonic filtering using a single tunned PPF. When studying the harmonic filtering, the fundamental components are neglected; therefore, the voltage source is considered short-circuited, and the fundamental load is considered open-circuited.

a. Case study 1: series resonance

The interaction of the series resonance can occur between the PPF impedance and the main impedance. The main impedance of the EPS of the ship is the sub-transient reactance of the generators plus the line impedance of the wires. If we consider that the load is disconnected then, the transfer function of the system can be expressed as:

$$G_s^H = \frac{V_{lo}}{V_s} = \frac{Z_{Fi}}{Z_s + Z_{Fi}} \qquad (1)$$

where $Z_{Fi} = R_f + j(X_{lf} - X_{lc})$, and $Z_s = R_s + jX_s$. $X_{lf} = 2\cdot\pi\cdot f\cdot h\cdot L_f$, and $X_s = 2\cdot\pi\cdot f\cdot h\cdot L_s$. f is the nominal frequency, h is the harmonic order.

Substituting $j\cdot 2\cdot\pi\cdot f$ by s, then the transfer function in the s domain becomes:

$$G_s^H(s) = \frac{R_f + L_f\cdot s + 1/C_f\cdot s}{L_s\cdot s + R_s + R_f + L_f\cdot s + 1/C_f\cdot s}$$

$$= \frac{R_f + L_f\cdot s + 1/C_f\cdot s}{(L_s + L_f)\cdot s + (1/C_f\cdot s) + R_s + R_f} \qquad (2)$$

The EPS of the ship is distinguished by the redundancy of the SGs, which means that the energy management system decides the number of connected and disconnected generators under different modes. Hence, the main impedance Z_s keeps changing during sailing. According to (2), the insertion of the main impedance in the transfer function of the PPF deviates its tuning frequency. Fig. 3 presents the behavior of the tuning
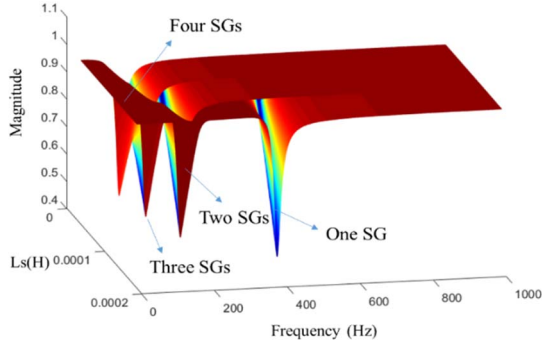
Fig.3. Series resonance of the PPF with the main impedance under different operating modes

Fig.4. Parallel resonance of the PPF with the main impedance under different operating modes

frequency of the PPF that is connected in series with the main impedance. It is noteworthy that the variation of L_s due to the connecting and disconnecting of the SGs deviates the whole system's tuning frequency. If the tuning frequency meets with the fundamental one, a severe series resonance occurs, which can lead to catastrophic consequences.

b. Case study 2: parallel resonance

The parallel resonance can occur when the inductance of the load, which is connected in parallel with the PPF (see Fig. 2(a)) varies, thus affects the total impedance of the system.

According to Fig. 2 (a), if we consider that the load is connected. Then, the transfer function of the system becomes:

$$G_s^H(s) = \frac{\dfrac{Z_{Fi}Z_{lo}}{Z_{Fi}+Z_{lo}}}{\dfrac{Z_{Fi}Z_{lo}}{Z_{Fi}+Z_{lo}}+Z_s} = \frac{A}{A+Z_s} \quad (3)$$

where $Z_{lo} = R_{lo} + jX_{lo}$, and $X_{lo} = 2 \cdot \pi \cdot f \cdot h \cdot L$.

$$A = \frac{Z_{Fi}Z_{lo}}{Z_{Fi}+Z_{lo}} = \frac{(R_f + L_f s + 1/C_f s)(L_{lo}s + R_{lo})}{(R_f + L_f s + 1/C_f s) + (L_{lo}s + R_{lo})}$$

$$= \frac{L_{lo}L_f s^2 + (L_{lo}R_f + L_f R_{lo})s + R_{lo}/C_f s + L_{lo}/C_f + R_s R_{lo}}{1/C_f s + (L_{lo}+L_f)s + R_{lo} + R_f} \quad (4)$$

Substituting (4) in (3) results in:

$$G_s^H(s) =$$

$$\frac{\dfrac{L_{lo}L_f s^2 + (L_{lo}R_f + L_f R_{lo})s + R_{lo}/C_f s + L_{lo}/C_f + R_f R_{lo}}{1/C_f s + (L_{lo}+L_f)s + R_{lo} + R_f}}{\dfrac{L_{lo}L_f s^2 + (L_{lo}R_f + L_f R_{lo})s + R_{lo}/C_f s + L_{lo}/C_f + R_f R_{lo}}{1/C_f s + (L_{lo}+L_f)s + R_{lo} + R_f} + L_s s + R_s}$$

$$(5)$$

After some mathematical development, the formulas (6), which is presented at the head of the next page is obtained. Based on (6), the total impedance of the system can be presented in terms of the load variation as shown in Fig.4. If we suppose that the active power of the load is very small compared to the reactive power, then this implies that R_{lo} is small compared to L_{lo}, it indicates that the variation of L_{lo} deviates the tuning frequency of the total impedance. If the tuning frequency tends towards the nominal one, it results in
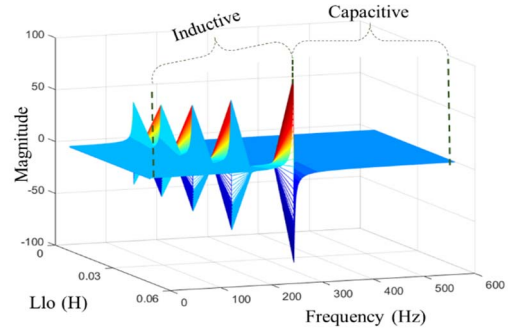
a severe parallel resonance, which can increase the line's current significantly, and thus causes catastrophic consequences.

III. ANALYTICAL INVESTIGATION OF THE FIXED CAPACITOR-THYRISTOR CONTROLLED REACTOR

The classical TCR basic structure contains a very sophisticated valve, which can be controlled effectively to compensate for the PF. These valves comprise a pair of anti-parallel connected thyristors in series with a reactor as shown in Fig.1 [15]. Fig. 5 presents a single line diagram of the basic principle of FC- TCR connected to the main switchboard of the EPS of the ship (considering that the PPFs are disconnected). Fig. 5(a) is the equivalent circuit on a per - phase base for Fig. 1, where X_{CFi} is the impedance of the switched capacitors and X_{LFi} is the variable inductance controlled by the TCR. Fig. 5(b) is a simplified version of Fig.5(a), where $i_{Fh5} \dots i_{FhN}$ denote the harmonics generated by the TCR and $i_{loh5} \dots i_{lohN}$ denote the harmonics generated by the non-linear loads. Fig. 5(c) and (d) are, respectively, the equivalent harmonic and fundamental circuits for Fig. 5(b) that enable the study of harmonic filtering, PF compensation, and voltage stability. Fig. 5 (c) shows the harmonic equivalent circuit of Fig. 1, which simplifies the concept of harmonic filtering using the FC-TCR. i_h is the sum of harmonics of both TCR and non-linear loads. The frequencies of X_{CFi}, X_{LFi} and X_{Ls} are calculated at the most dominant harmonic. What distinguishes the FC-TCR from the PPFs and APF is the ability to act as a low pass filter that can reject
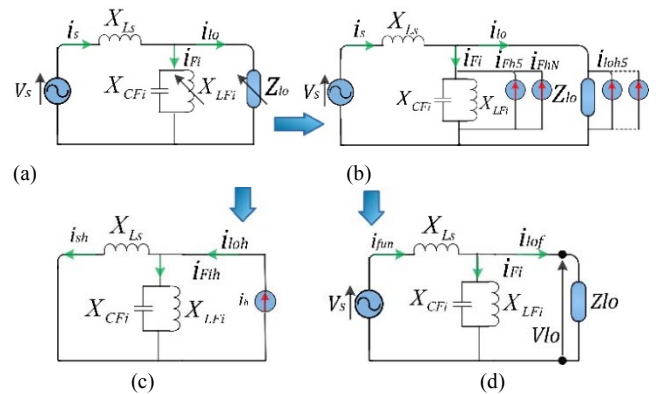

Fig.5. Single line diagram of the basic principle of FC- TCR connected to the electrical power system of the ship. (a) The equivalent circuit on a per-phase base for Fig. 1. (b) Simplified circuit of Fig. 2(a). (c) Harmonics equivalent circuit. (d) Fundamental equivalent circuit

$$G_s^H(s) = \cfrac{L_{lo}L_f s^2 + (L_{lo}R_f + L_f R_{lo})s + \cfrac{R_{lo}}{C_f s} + \cfrac{L_{lo}}{C_f} + R_f R_{lo}}{L_{lo}L_f + L_s(L_{lo} + L_f)s^2 + ((L_{lo}R_f + L_f R_{lo}) + L_s(R_f + R_{lo}) + R_s(L_f + L_{lo}))s + (\cfrac{R_{lo}}{C_f} + \cfrac{R_s}{C_f})\cfrac{1}{s} + \cfrac{L_{lo}}{C_f} + R_f R_{lo} + \cfrac{L_s}{C_f} + R_s(R_f + R_{lo})} \quad (6)$$

low- and high-order harmonics. The harmonic current i_{loh} that is split in both the source impedance and the filter is expressed as:

$$\partial = \frac{I_{sh}}{I_{loh}} = \frac{\left| \cfrac{X_{LFi} \cdot X_{CFi}}{X_{LFi} + X_{CFi}} \right|}{\left| \cfrac{X_{LFi} \cdot X_{CFi}}{X_{LFi} + X_{CFi}} + X_{Ls} \right|} \cdot 100 \quad (\%) \qquad (7)$$

where ∂ is a harmonic attenuation factor, which defines the filtering capability of the HF. The smaller ∂ is, the higher the performance of the HF. The main impedance is responsible for transmitting the harmonic currents into the voltage. The implementation of the HF, however, reverses the functionality of the main impedance and makes it the key instrument, which forces the harmonic currents to flow through X_{CFi} instead of jumping into the voltage. Fig. 6(a) illustrates the variation of ∂ in terms of the main impedance and X_{LFi}. Suppose that the PF of the EPS can go down to 0.6, then the capacitance of the HF C_{FI} can be fixed to 400 μF to overcompensate the PF (from lagging PF into leading PF), after that the variation of the TCR inductance L_{FI} adjusts the leading PF towards the optimal value. According to Fig. 6(a), it is obvious that when the main impedance (X_{Ls}) is very small, ∂ tends towards unity, this means that all harmonics flow into the power supply. The increase of X_{Ls}, however, decreases ∂ significantly which indicates that the HF performance is optimized. Whereas the variation of X_{LFi}

(a)

(b)

Fig.6. Filtering performance of the FC-TCR HF. (a)The effect of the main impedance on improving the filtering capability of the HF. (b) The effect of the HF impedance on filtering capability.

has a negligible effect (variation of 1%) on the HF performance when adjusting the PF. The second essential factor of decreasing ∂ and improving the performance of the FC-TCR HF is the value of X_{CFi}. The impedance of this latter decreases proportionally to the increase of the harmonic order h ($X_{CFi} = \cfrac{1}{2 \cdot \pi \cdot f \cdot C \cdot h}$). Fig. 6(b) shows the variation of X_{CFi} and X_{LFi} in terms of ∂ where X_{Ls} is set to 7 Ω (estimated value of the main impedance) at the fifth harmonic. It is evident that the decrease of ∂ is correlated to the decrease of X_{CFi}, while the variation of X_{LFi}, which adjusts the PF does not affect the filtering capability. From Fig. 6 one can conclude that in order to guarantee a high filtering performance of the FC-TCR HF the main impedance should be at least 6 times or larger than the impedance of the TCR at the most dominant harmonic as formulated below:

$$X_{Ls} \geq 6 \cdot \frac{X_{LFi} \cdot X_{CFi}}{X_{LFi} + X_{CFi}} \qquad (8)$$

Since the value of X_{Ls} increases proportionally to the harmonic order ($X_{Ls} = 2 \cdot \pi \cdot f \cdot L_s \cdot h$), it implies that the voltage is always prone to high-order harmonics. However, according to Fig. 5(d), the proposed FC-TCR HF acts as a low-pass filter, which prevents the high order harmonics providing the following transfer function:

$$G_{FI}^H = \frac{V_{lo}}{V_s} = \frac{Z_{Fi}}{s \cdot L_s + Z_{Fi}} \qquad (9)$$

where L_S is the inductance of X_{Ls}, Z_{Fi} is the impedance of the filter and expressed as:

$$Z_{Fi} = \frac{s \cdot L_{Fi} \cdot \cfrac{1}{C_{Fi} \cdot s}}{s \cdot L_{Fi} + \cfrac{1}{C_{Fi} \cdot s}} = \frac{s \cdot L_{Fi}}{1 + s^2 \cdot C_{Fi} \cdot L_{Fi}} \qquad (10)$$

where C_{FI} and L_{FI} are, respectively, the capacitance and inductance of the FC-TCR HF. After some mathematical manipulations, (10) becomes:

$$G_{FI}^H = \frac{\cfrac{s \cdot L_{Fi}}{1 + s^2 \cdot C_{Fi} \cdot L_{Fi}}}{\cfrac{s \cdot L_{Fi}}{1 + s^2 \cdot C_{Fi} \cdot L_{Fi}} + s \cdot L_s} = \frac{1}{\cfrac{L_s}{L_{Fi}} + L_s \cdot C_{Fi} \cdot s^2 + 1} \qquad (11)$$

Fig. 7 depicts the Bode diagram of G_{FI}^H. According to Fig. 7(a), the HF provides a low impedance path for the fundamental and low-order harmonics. After the cut-off frequency, the output phase of the high-order harmonics changes dramatically, and the gain decreases to create a high impedance. It is noteworthy that the resonance which occurs at the cut-off frequency is far from the fundamental frequency. Even when the TCR provides a high variation of
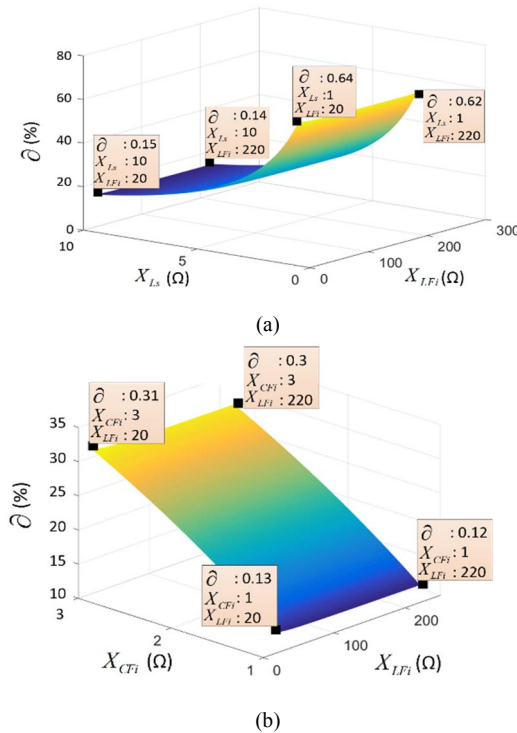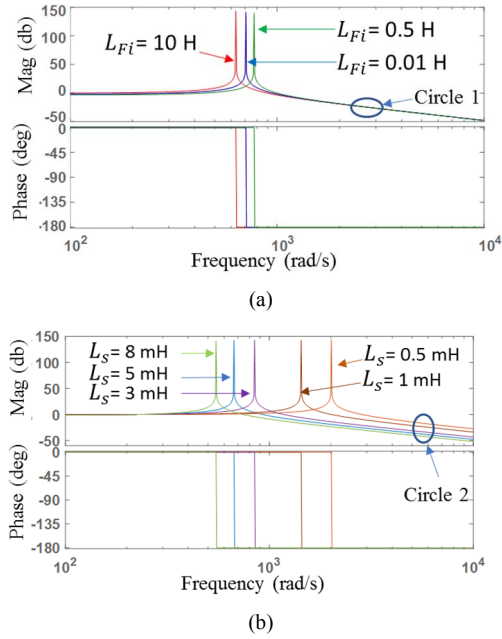
Fig.7. Filtering performance of the FC-TCR HF. (a)The effect of the main impedance on improving the filtering capability of the HF. (b) The effect of the HF impedance on the filtering capability

L_{FI} to adjust the PF, the cut-off frequency changes slightly and remains far from the fundamental frequency. Moreover, circle 1 illustrates that the variation of L_{FI} does not affect the filtering performance and keeps providing almost the same impedance at the high-order harmonics. Fig. 4(b) shows the performance of the filter in terms of L_S. As shown in circle 2, the increase of L_S decreases the gain at the higher-order harmonics. This demonstrates that the increase of L_S is proportional to the capability of the filtering. The cut-off frequency, however, is exposed to a large variation. Therefore, when designing the FC-TCR HF, it is mandatory to take into account the impedance of each SGs and make sure that the cut-off frequency is far from the fundamental range to prevent the series resonance.

IV. TEST RESULTS AND DISCUSSIONS

Simulation results of a practical shipboard power system are carried out under the MATLAB/Simulink environment. The system is modeled in accordance with the schematic

TABLE I. System Parameters

Synchronous generators	**Nominal voltage**	**V=6.6 kV (+6%, -10%)**
	Electric Power Apparent power Baserotational peed	**P=6980 ekW, S=8725 kVA, Ω=720 rpm.**
propellers	Rated power	P=4000 kW
thrusters	Rated power	P=1750 kW
Shifted Transformers	Transformed voltage	V=6.6 kV/715V
Non-linear loads	Rated power	P=700 kW
FC-TCR HF	Inductance capacitance	L=0.006 mH C=500 µF
PPFs	5th harmonic filter	L5=0.002 H, C= 202.642 µF
	7th harmonic filter	L5=0.002 H, C= 103.389 µF

depicted in Fig. 1, and the parameters of the system are summarized in Table I. According to Fig. 8 (a), in the time interval of 0 to 0.12s, both voltage and current waveforms are harmonically contaminated with THDs of respectively 21.43% and 19.74% as depicted in the harmonic spectrum of Fig. 9(a). The connection of the switched capacitor of the FC-TCR in the instance 0.2s acts as a low-pass filter as demonstrated in Fig. 6 and 7; hence, filtering both voltage and current by decreasing their THDs respectively to around 5% and 4.3%, which respects the aforementioned norms. However, the fixed capacitor causes a leading power factor by generating a large amount of capacitive reactive power, which causes an overvoltage. In the instance 0.16s, the TCR is connected. It is obvious that the TCR controls the overvoltage to follow the reference voltage. Thus, it ensures the stability of the voltage. It is worthy to note that even after connecting the TCR, the waveform of both voltage and
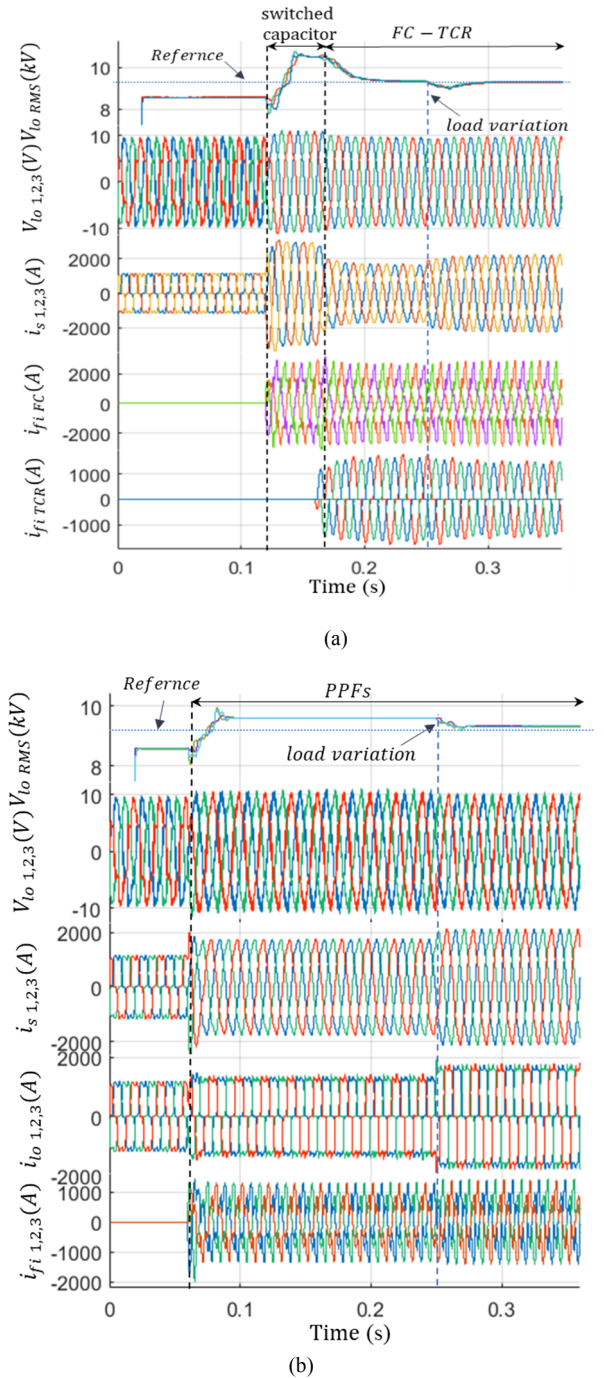

(a)

(b)

Fig.8. Harmonic mitigation and voltage drop enhancement of an SPS using: (a) FC-TCR compensator. (b) PPFs.
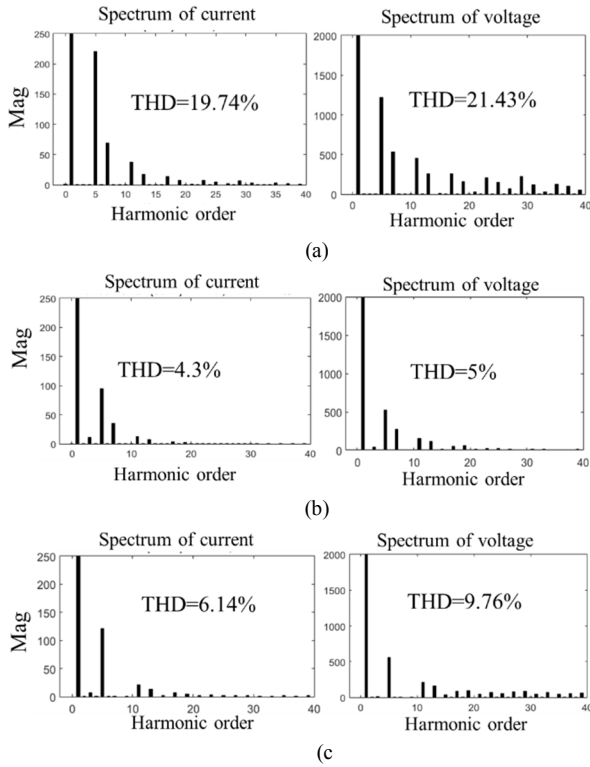
Fig.9. Harmonic spectrum of the EPS of the analyzed ship. (a) before the connection of filters. (b) using the FC-TCR HF. (c) using the PPFs.

current remains close to the sinusoidal form. This assertion is confirmed in the harmonic spectrums that are plotted in Fig. 9 (b). in the instance 0.25s, a variation of load occurs. It is clear that the FC-TCR is flexible during the load variation by forcing the voltage to follow the reference with a fast transient response. According to Fig. 8 (b), it shows that the implementation of the PPFs only mitigates the harmonics of the voltage and current with a THDs of respectively 9.6% and 6.1% that do not respect the norms (see Fig. 9(c)). Moreover, the over/drop voltage caused by the load variation cannot be adapted by the PPFs due to their fixed behavior characteristic.

V. CONCLUSION

More in-depth analytical investigations of the PPFs and the FC-TCR compensator were addressed in this paper. The purpose of this study is to analyze the filtering behavior of these compensators in improving the power quality issues of a medium-voltage SPS; and hence, compare their performance. Then, these analyses are validated via intensive simulation scenarios of a practical shipboard power system, which are carried out under MATLAB/Simulink environment. Based on the obtained results, it has been proven that the FC-TCR has more advantages than the conventional PPFs such as:

1. Better filtering capability: with the appropriate design of the tradeoff between the main impedance and the filter impedance using the proposed equations, the FC-TCR filter can act as a low-pass filter; thus, reduce both voltage and current THDs to standardized values. While the traditional PPFs failed to provide an efficient performance under the same conditions.

2. Less sensitivity to the resonance: in contradiction with the PPFs that have a fixed impedance, which can stimulate the resonance under the variation of the line impedance under different operating modes of the

ship. The FC-TCR can adapt its impedance according to the novel operating mode; hence, avoid the risk of the resonance.

3. Flexibility under load variation: in opposition to the PPFs that have fixed impedance, which only compensates a degree of reactive power, the FC-TCR can be adapted under load variation, and consequently injects the right amount of capacitive reactive power that compensates for the voltage drops; hence, ensures the voltage stability.

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