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Harmonics Rejection Capability Enhancement of Passive Power Filters for All-Electric-Shipboard Micro-Grids

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***Abstract* – In recent years, the significant revolution of shipboard micro-grids (SMs) towards all-electric ships offered several advantages such as high efficiency, better maneuverability, and controllability. However, the application of power electronics onboard SMs, particularly for DC and hybrid ships leads to serious power quality issues. The application of passive power filters (PPFs) has been largely used to solve some of the power quality issues, such as harmonics contamination, power factor compensation, and voltage drop enhancement. However, analyzing some crucial factors such as the harmonic attenuation factor (HAF) and filters sensitivity factor (FSF) of these filters have not been attracted much attention. In this paper, a more in-depth mathematical analysis of the HAF and FSF of these filters is conducted with details. Moreover, some developed solutions to improve these factors are suggested. Based on intensive simulation studies of a practical hybrid ferry, which are carried out under MATLAB/Simulink environment, it has been demonstrated that the conducted analysis and proposed solutions can enhance the filtering performance of the PPFs.**

Index Terms* – Filters sensitivity factor (FSF), Harmonic attenuation factor (HAF), Harmonics, Power factor, Passive power filters (PPFs), Shipboard micro-grids (SMs).

I. INTRODUCTION

In the last decades, a considerable revolution of SMs towards all-electric based on the power electronic converters (PECs) have been growing to provide enhanced maneuverability, controllability, and efficiency [1]. However, the dark side of this advancement lies in drawing a considerable amount of harmonics [2]. Particularly for DC and hybrid ships that implement rectifiers to convert the AC power into DC [3]. The risk of the harmonics circulation does not only affect the electrical power system, but it also threats the lives of the crew and passengers [4]. The application of active power filters (APFs) can reduce the harmonics, and compensate for the power factor [5]. However, the high cost, the control and maintenance complexity degrade their application.

The PPFs have been widely used to reduce the harmonics and compensate the power factor [6], [7]. In contradiction with the APFs, the PPFs are featured by the low cost, easy installation and maintenance, they do not require any complicated control algorithms, and they can be implemented for low, medium, and high power applications. Hence, their implementation for SMs does not only reduce the harmonics and improve the power factor but it can also contribute to enhance the energy efficiency, reduce the fuel consumption and decreases emissions [8].

Accurate tuning of the PPFs at the aimed frequencies does not mean high harmonics rejection capability. The performance of the PPFs depends strongly on analyzing the *HAF* in terms of harmonic filtering. However, improving and studying the *HAF* and improving it did not take much attention in the literature. Moreover, seeking to improve the *HAF* can increase the *FSF* if the filters are not well designed, and consequently can deteriorate the system stability, particularly during the frequency variations, which is a common issue for SMs. In this regard, in this paper a more in-depth harmonic analysis of the *HAF* is addressed, then propose some solutions to improve it. Moreover, improving the *HAF* can increase the *FSF*, thus the theoretical and analytical investigation of this issue is detailed. Furthermore, new configurations of the PPFs are proposed to improve the tradeoff between decreasing the *HAF* and the *FSF*. Through intensive simulation studies of modeling a practical hybrid electric ferry named Ferry Happiness that is carried out under MATLAB/Simulink environment, it has been proved that the conducted analysis and proposed solutions can enhance the filtering performance of the PPFs.

The rest of the paper is organized as follows. In section II, the problem statement of the harmonics rejecting capability of PPFs is detailed. In section III, solutions to improve the *HAF* and *FSF* are suggested. Section IV presents the numerical results and discussions, and Section V, concludes this paper.

II. PROBLEM STATEMENT OF THE HARMONICS REJECTING CAPABILITY OF THE PPFS

The PPFs are one of the most used solutions in industries. There exists two categories of PPFs, low-pass filters (single tuned filters), and high-pass filters, where each category comprises different structure [11]. The most used type of PPFs is the single tuned filter due to their simplicity and ability to rejecting the most dominant harmonics. The single tuned PPFs consists of an inductor (L) connected in series

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with a capacitor (C) to create a resonant frequency at the aimed harmonic, hence, the total impedance of the filter Z_{tot} is expressed as:

$$Z_{tot} = R_f + j(X_{Lh} - X_{Ch}) \tag{1}$$

where $X_{Lh} = 2\cdot\pi\cdot f\cdot h\cdot L$; $X_{Ch} = 1/2\cdot\pi\cdot f\cdot h\cdot C$; R_f is the intern resistor of the filter; h is the harmonic order. Fig. 1 (a) presents a single line diagram of the electrical power system of the selected hybrid ship, which constitutes of two diesel generators connected in parallel, two propellers, energy storage system, and hotel loads. The power manager decides the number of generators that are turned on/off based on the operation mode. The energy storage system is integrated to support diesel generators, hence, reduces fuel consumption and emissions. The PPFs that are tuned at the 5th and 7th harmonics are connected in parallel to the AC switchboard. In order to enable the PPF to filter the aimed harmonic and compensate for the power factor simultaneously, the following equations need to be fulfilled:

$$X_{Lh} = X_{Ch} \Rightarrow \omega_n = \frac{1}{\sqrt{LC}} \tag{2}$$

$$X_f = \frac{V_{Lo}^2}{Q_C} \tag{3}$$

where ω_n is the tuning frequency. V_{Lo} is the load voltage. X_f and Q_C are respectively the equivalent impedance of the filter at the fundamental frequency and the reactive power generated by the filter that is expressed as:

$$Q_C = V_{Lo}\cdot i_{Lo}\cdot \sin(\phi) \tag{4}$$

If the equation (2) is fulfilled, it implies that the harmonic voltage (V_{hL}) of the aimed frequency at the terminals of the coil of the PPF equals to the harmonic voltage (V_{hC}) at the terminals of the capacitor. As these voltages have a phase shift of 180°, their summation results in:

$$V_{hfi} = V_{hL} + V_{hC} \simeq 0 \tag{5}$$

where

$$V_{hL} = X_{Lh}\cdot i_{hn} \tag{6}$$

$$V_{hC} = X_{Ch}\cdot i_{hn} \tag{7}$$

However, tunning the filter at the aimed frequency does not mean high harmonic rejecting capability. Therefore, this paper focuses on the *HAF*, which is crucial to improve the harmonic rejecting capability of the PPF. Fig. 1 (b) presents the simplified single line diagram of the electrical power system of the hybrid ship, where V_s presents the voltage source of one generator.

X_{Ls} , R_s , X_{Ch} , X_{Lh} are respectively the inductive reactance and resistance of the main impedance, the capacitive reactance and the inductive reactance of the filter. Z_{lo} is the non-linear load, which is modelled as a linear load plus a source of harmonic currents. The equivalent harmonic model, which exhibits the mechanism of the harmonic mitigation of the filter, is presented in Fig. 1(c), where the voltage is considered short-circuited and the linear load is open-circuited. Hence, the *HAF* can be expressed as:

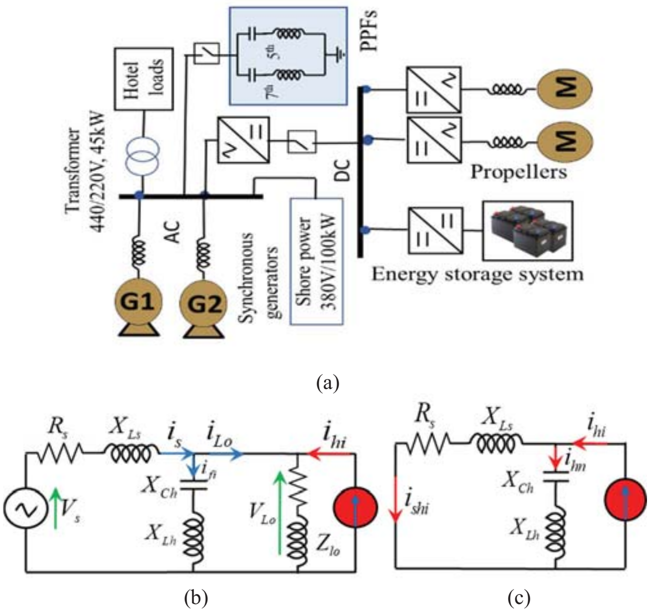


Fig.1. Single line diagram of the PPF connected to the main switchboard of the hybrid ferry. (a) single line diagram of the electrical power system of the hybrid ferry. (b) the equivalent circuit of the PPF for Fig. 1(a) on a per-phase base form. (c) single-line schematic of equivalent harmonic circuit basic principle of Fig. (b).

$$\partial = \frac{I_{shi}}{I_{hi}} = \frac{|X_{Lh} - X_{Ch} + R_{fi}|}{|X_{Lh} - X_{Ch} + X_{Ls} + R_{fi} + R_s|} \tag{8}$$

After some mathematical manipulations, (8) becomes as presented in (9) and (10) at the top of the next page. Fig 2 (a) and (b) presents respectively the behavior of the *HAF* (∂) in terms of X_{Ls} with X_{Ch} and X_{Ls} with X_{Lh} at the tunned frequency. It is obvious that the increase of X_{Lh} and X_{Ch} require higher values of the main impedance to decrease the *HAF*. However, since the line impedance value is uncontrollable, it can significantly affect the filtering performance if the value of X_{Ls} is small. Fig. 2 (c) and (d) presents respectively the behavior of the *HAF* in terms of X_{Ls} with X_{Ch} and X_{Ls} with X_{Lh} at the tunned frequency taking into consideration higher values of the line impedance and PPF resistors. It is noteworthy that the behavior of the *HAF* is similar to Fig. 2(a) and (b). However, the increase of R_f and R_s from $0.1\,\Omega$ to $1\,\Omega$ limits the tuning sharpness of

$$\partial = \frac{|(2\cdot\pi\cdot f\cdot h\cdot L - 1/(2\cdot\pi\cdot f\cdot h\cdot C))j + R_{fi}|}{|(2\cdot\pi\cdot f\cdot h\cdot L - 1/(2\cdot\pi\cdot f\cdot h\cdot C) + 2\cdot\pi\cdot f\cdot h\cdot L_s)j + R_{fi} + R_s|} \tag{9}$$

$$\partial = \frac{|2\cdot\pi\cdot f\cdot h\cdot j(L - 1/((2\cdot\pi\cdot f\cdot h)^2 C)) + R_{fi}|}{|(2\cdot\pi\cdot f\cdot h\cdot j(L + L_s - 1/((2\cdot\pi\cdot f\cdot h)^2 C)) + R_{fi} + R_s|} \tag{10}$$

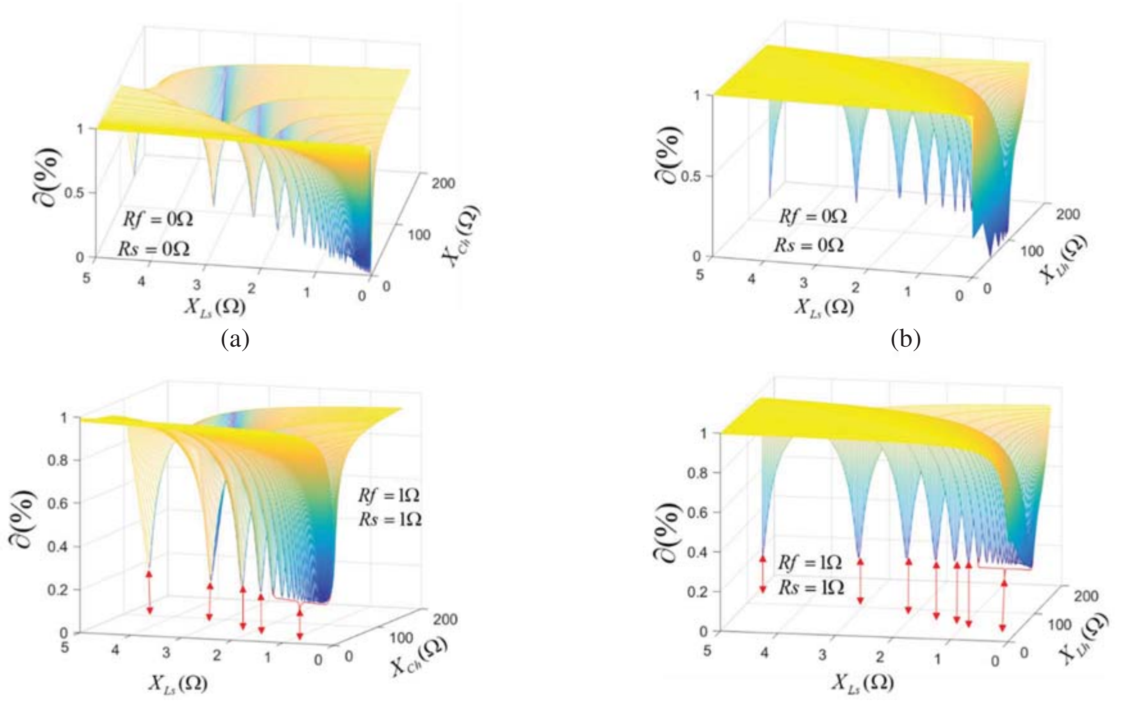


Fig.2. Harmonics attenuation factor of the PPFS. (a) *HAF* of the PPF in terms of the variation of the reactance of the main impedance and the filter capacitive reactance. (b) *HAF* of the PPF in terms of of the variation of the reactance of the main impedance and the filter inductive reactance. (c) *HAF* of the PPF in terms of the variation of the inductive reactance of the main impedance and the filter capacitive reactance with R_f=R_s=1 Ω. (d) *HAF* of the PPF in terms of the variation of the inductive reactance of the main impedance and the filter inductive reactance with R_f=R_s=1 Ω.

the PPF. Therefore, the quality factor Q_f that will be detailed in the next section should be selected appropriately to improve the *HAF*.

III. Solutions to Improve the Harmonics Rejecting Capability of the PPFs

As it has been demonstrated in the previous section that decreasing the values of the capacitive and inductive reactances of the PPFs with respect to the tunning frequency leads to improve the *HAF*. However, this solution results in decreasing the total impedance of the filter at the fundamental frequency. Hence, leads to an increase in the injection of the capacitive reactive power, which deteriorates the power factor and decreases the efficiency of the system. Especially for DC and hybrid ships, which generally do not need a high compensation of the PF due to the dominant DC loads. In order to overcome this deficiency, the installation of a supporter coil ($L_{\sup}$) in parallel with the PPFs as presented in Fig. 3 enables the compensation of the surplus capacitive reactive power caused by the decrease of X_{Ch} and X_{Lh} at the fundamental frequency. The decrease of X_{Lh} and X_{Ch} while insuring the equation (2), thus equation (3) becomes:

$$X_f = \frac{V_{Lo}^2}{Q_C + Q_{su}} \tag{11}$$

where Q_{su} is the inductive reactive power generated by $L_{\sup}$. It is noteworthy to mention that the summation $Q_C + Q_{su}$ should compensate for the reactive power of the system as:

$$Q_C + Q_{su} = V_{Lo} \cdot i_{Lo} \cdot \sin(\phi) \tag{12}$$

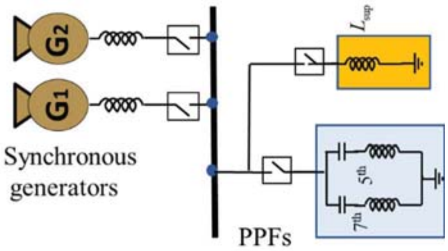


Fig. 3. Single line diagram of the PPF with a supporter coil connected to each synchronous generator of the hybrid ship.

In case the system does not require reactive power, then $Q_C \simeq Q_{su}$. It is crucial to mention that Q_C should not be equal to Q_{su} to avoid resonance. Although the schematic presented in Fig. 3 can significantly decrease the *HAF*, it, however, can lead to rising the *FSF*, which is expressed as:

$$FSF_L = \frac{M}{2 \cdot \pi \cdot f \cdot h \cdot L} \tag{13}$$

$$FSF_C = D \cdot 2 \cdot \pi \cdot f \cdot h \cdot C \tag{14}$$

where FSF_L and FSF_C are the filter sensitivity factors of respectively the inductance and capacitance of the PPF, M and D are respectively the numbers of the paralleled inductors and capacitors.

The transfer function of the single tuned PPF is expressed as

$$Z_{tot}(s) = \frac{s}{\omega_n^2} + \frac{1}{\omega_n \cdot Q_f} + \frac{1}{s} \tag{15}$$

where Q_f is the quality factor of the PPF and formulated as (16) below.

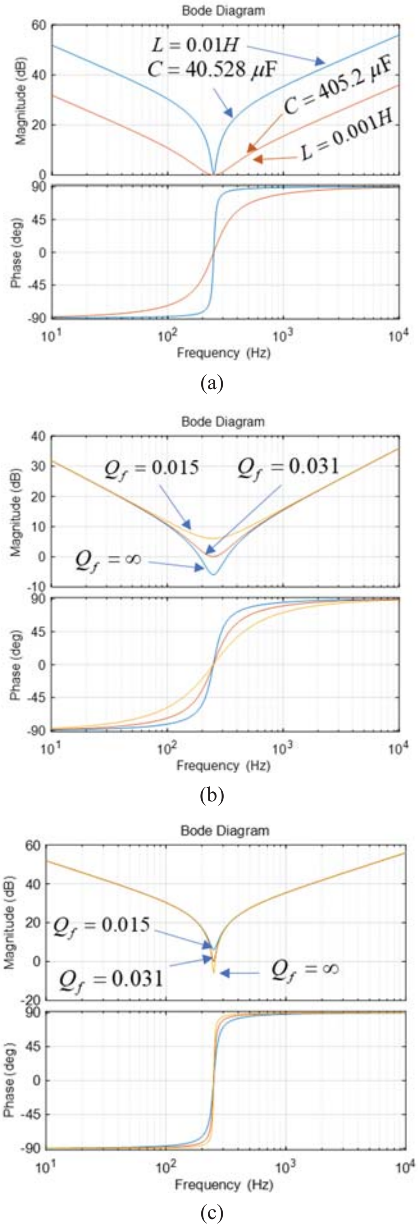


Fig. 4. Bode diagram of a single tunned PPF. (a) bode diagram of a PPF turned at the 5th harmonic with large and small values of L and C . (b) influence of the quality factor on the PPF tunning with large values of L and C. (c) influence of the quality factor on the PPF tunning with small values of L and C.

$$Q_f = \frac{1}{R_f}\sqrt{\frac{L}{C}} \tag{16}$$

Fig. 4(a) presents the Bode diagram of a PPF tunned at the 5th harmonic with different values of L and C (*L=0.01, L=0.001* and *C=405 μF, C=40.5μF*). It is evident that tunning the filter with small values of L and C provide high harmonic rejection capability for the tunned harmonic and the adjacent frequencies. However, its bandwidth is even larger at the fundamental frequency, which consequently increases the reactive power that is injected by the filter, and thus affects the *FSF*. Fig. 4 (b) and (c) demonstrates the influence of the quality factor on the rejection capability of the PPF. It is obvious that the smaller Q_f is, the better harmonic rejection capability of the PPF. However, a very small Q_f results in a long transients caused by the PPF. Therefore, it is necessary to define the appropriate value of Q_f , which provide a good compromise. Generally R_f is selected small during the design to provide an acceptable Q_f ranged between 30 and 60 [11] .

A better visualization of the *FSF* is depicted in Fig. 5 taking into account the fundamental component and the most dominant harmonics. Fig. 5 (a) presents the behaviour of the FSF_C in terms of the PPF capacitance and the frequency variation. Although the increase of *C* results in the decrease of X_{Ch} , which decreases the *HAF* and improves the rejection capability of the PPF, it however, leads to increase the FSF_C . Consequently, the increase of the FSF_C can lead to the instability of the system. Moreover, the increase of the harmonic order makes the system stability more sensitive. Fig. 5 (b) presents the behaviour of the FSF_L in terms of the PPF capacitance and the frequency variation. It is very obvious that the decrease of the filter inductance results in decreasing X_{Lh} , hence, leads to increase FSF_L , which consequently makes the stability of the system more sensitive and can lead to disastrous consequences. Fig. 5 (c) is added to demonstrate that when the filters' parameters are modified to optimize the *HAF*, the total filter impedance Z_{tot} remains almost fixed if the equation (2) is insured. However, the sensitivity of each component of the PPF have different *FSF*.

In order to achieve a low *HAF* with a low *FSF*, two main solutions can be used. The first one is the increase X_{Ls} . However, this solution is not practical since the line impedance of the system is fixed. Adding extra impedances in series with the system to enhance the *HAF* and *FSF* leads to the voltage drop. Therefore, the authors propose the solution of paralleling the PPFs components as depicted in Fig. 6. It means that instead of decreasing the filter components, it would be wise to parallel the components. Hence, the reactance of each component remains fixed. Consequently, the *FSF* will not increase. On the other hand, the *HAF* of the total system becomes:

$$\partial_2 = \frac{I_{shi}}{I_{hi}} = \frac{\left|\frac{X_{Lh}\cdot X_{Lh}}{X_{Lh}+X_{Lh}} - \frac{X_{Ch}\cdot X_{Ch}}{X_{Ch}+X_{Ch}} + \frac{R_{fi}\cdot R_{fi}}{R_{fi}+R_{fi}}\right|}{\left|\frac{X_{Lh}\cdot X_{Lh}}{X_{Lh}+X_{Lh}} - \frac{X_{Ch}\cdot X_{Ch}}{X_{Ch}+X_{Ch}} + \frac{R_{fi}\cdot R_{fi}}{R_{fi}+R_{fi}} + X_{Ls} + R_s\right|}$$

(17)

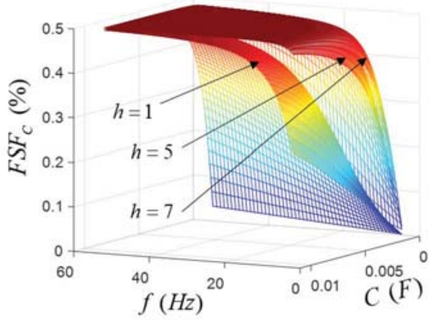
After some mathematical manipulations (14) becomes:

$$\partial_2 = \frac{\left|\frac{1}{2}X_{Lh} - \frac{1}{2}X_{Ch} + \frac{1}{2}R_{fi}\right|}{\left|\frac{1}{2}X_{Lh} - \frac{1}{2}X_{Ch} + X_{Ls} + \frac{1}{2}R_{fi} + R_s\right|} \tag{18}$$

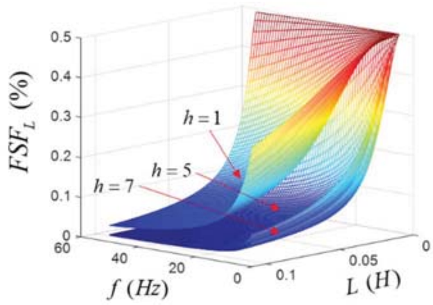
From (18) one can conclude that the solution, which is proposed in Fig. 6 does not affect the *FSF*, but the *HAF* is decreased to the half.

IV. Numerical Validation and Discussion

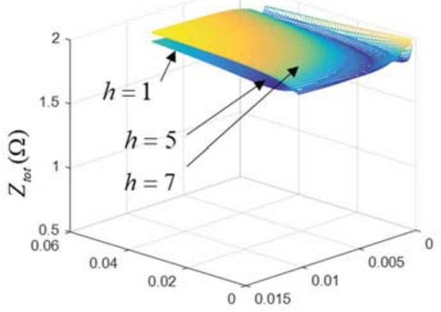
The numerical results of a modelled practical hybrid electric ferry named Ferry Happiness, which is newly launched as a passenger ferry serves in Cijin Island in



(a)



(b)



(c)

Fig. 5. Filters sensitivity factor. (a) *FSF* in terms if the PPF inductance and frequency variation. (b) *FSF* in terms of the PPF capacitance and frequency variation. (c) the total impedance of the PPF in terms of its capacitance and inductance.

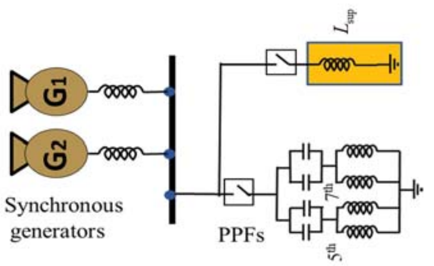


Fig. 6. Single line diagram of paralleled components of the PPF with a supporter coil connected to the main switchboard of the hybrid ship

Kaohsiung are carried out under the MATLAB/Simulink environment. Fig. 7 presents the photo of the ferry and its electrical power system. The main system parameters are summarized in Table I.

Fig. 8 presents the performance of the PPFs in reducing the harmonics of the hybrid ferry. The first subplot presents the contaminated voltage V_{Lo}. The second subplot presents the contaminated load current i_{lo}. The third subplot depicts the filtered source current i_s. The fourth subplot shows the filter's current, and the last subplot illustrates the total harmonic distortion (THD) of i_s and i_{lo}. It is clear that in the instant 0.06s the connection of the PPFs results in improving the waveform of i_s by reducing the THD from 26% to 17%. However, since the *HAF* is not taking into consideration, the amount of THD is not reduced much.

Fig. 9 presents the performance of the PPF in minimizing the harmonics of the hybrid ferry, taking into account the proposed analysis of the *HAF* and the *FSF*. The subplots arrangement is similar to that of Fig. 8. Based on the proposed methods that are presented in Fig. 6 and Fig 3, it is obvious that when installing the PPFs in the instant 0.06s, the THD of i_s is decreased from 26% to 12%. It is worthy to mention that the THD can be reduced more if more extract PPFs are installed for other low order harmonics. The obtained THD can be achieved using one of the schematics in Fig. 3 and 6. However, as it has been demonstrated in the previous section. Using the schematic of Fig. 3 results in increasing the *FSF*. Hence, the best choice is to use the schematic presented in Fig. 6.

Fig. 10 depicts the harmonics spectrum of i_s. It is obvious that the proposed more in-depth analysis and configuration enhance the filtering capability of the PPFs more when the HAF and the FSF are optimized.

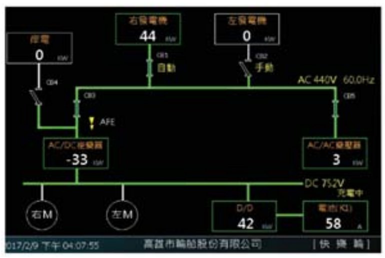


Fig. 7. Picture of the selected hybrid ferry and its electrical power system.

TABLE I. SYSTEM PARAMETERS

Category	Parameters	Values
Synchronous generators	RMS voltage	V=450V
	Electric Power	P= 2x88 ekW
propellers	Rated power	2x112kW/1620rpm
Hotel loads	Nominal power	P=35 ekW
PPFs	5th harmonic filter	$L=0.006/0.016H$ $C=67.54/25.3302\ \mu F$
	7th harmonic filter	$L=0.006/0.016H$ $C=34.46/12.92\ \mu F$
	Supporter inductance	$L_{sup}=0.06H\quad R=2\Omega$

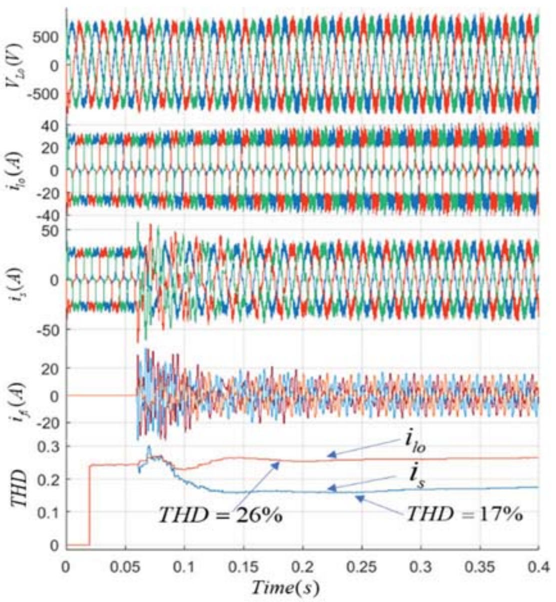


Fig. 8. Performance of the PPF with high *HAF* and low *FSF*.

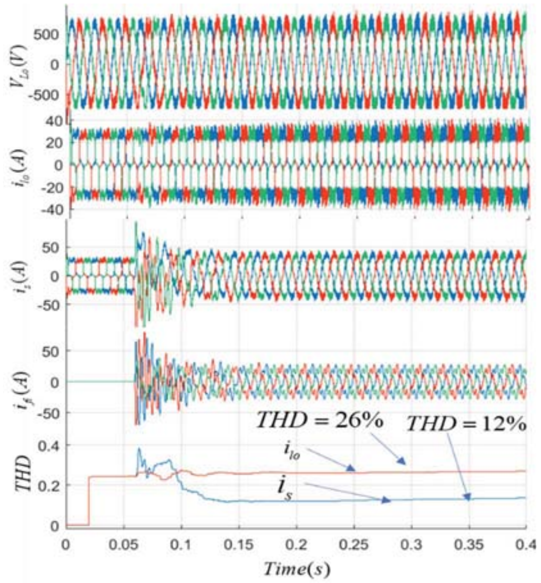


Fig. 9. Performance of the PPF with low *HAF* and low /high *FSF*.

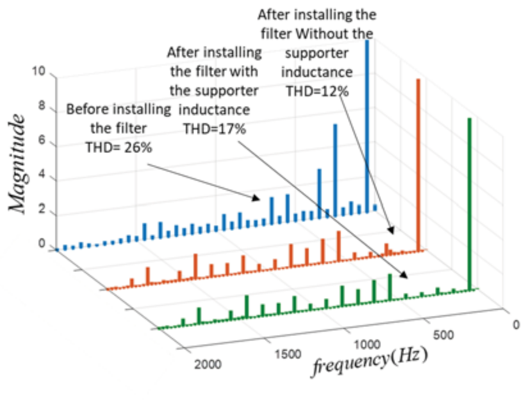


Fig. 10. Harmonics spectrum of the source current before and after installing the proposed filters.

V. Conclusion

In this paper, a more in-depth theoretical analysis of the *HAF* and the *FSF* of PPFs were proposed to enhance the power quality of SMs. Moreover, novel configurations of PPFs for enhancing the *HAF* and *FSF* have been conducted. The validation of the proposed analysis is achieved via modeling a practical hybrid electric ferry named Ferry Happiness, which newly launched as a passenger ferry serves in Cijin Island in Kaohsiung. Based on the conducted work, it has been confirmed that the proposed more-in depth analysis and configurations can enhance the *HAF* and *FSF*; hence, improves the harmonic rejection capability of the PPFs resulting in the following remarks:

- Accurate tuning of the PPF at the aimed harmonic frequency does not mean high harmonics rejection capability of the filter.
- The only way to improve the harmonic rejection capability of the PPF is by analyzing and decreasing the *HAF*.
- Decreasing the *HAF* to improve the *FSF* can affect the stability of the system and becomes more sensitive, mainly if the system struggle from the frequency drifts such as the SMs. Therefore, it is necessary to make a compromise between the *HAF* and the *FSF* during the optimization.

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