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Aspects regarding the use of passive filters for harmonic mitigation in power rectifiers

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Abstract. The power rectifiers, along with other types of static converters are present in the power generation systems of naval vessels, whose powers reach the order of hundreds of MW. This fact, inevitably leads to the appearance of harmonics with very high weights.

As a solution for the problem of harmonics mitigation, the authors conceived several simulation in Matlab Simulink relating to the efficiency of different type of passive filter. These simulations took into account the characteristics of the main types of passive filters used on board ships, highlighting at the same time, the steps for calculating the constructive elements.

Keywords: non-linear power, quality factor

1. Introduction

Most of the ships generate a.c. electricity by diesel generators. It is essential to use power conversion devices în line with separation transformations to convert a.c. to d.c. energy for equipment that are driven by d.c. power. Usually the a.c. to d.c power conversion is made by rectifiers witch use in generally IGBT semiconductors.

Rectifiers are very harmful for energy sources, it represents among the largest producers of harmonic distortions. Maintaining the THD (Total Harmonic Distortion) in proper reduced parameters represents a good mark of power quality în electricity. THD affects: phase shift between voltage and current, distorted power and total power coefficient. Therefore, the reduction of harmonics for power sources that feed nonlinear consumers represents an economic problems of high interest.

As the first measure for limiting harmonics, high-performance rectifier equipment such as 12-pulse or 24-rectifiers can be used, to the detriment of 6-pulse rectifiers, transformers or harmonic filters. The harmonic filters play an essential role in limiting the harmonics, therefore get into the discussion a proper parameterization, an inadequate parameterization entails a low efficiency of system.

In case of using a d.c. power system on board ship (figure 1), we need to pay more attention about harmonics, because it is involved a lot of converted energy.



Figure 1. On board DC grid – Multi drive power system scheme [1]

2. Theoretical fundamentals regarding to passive filters criteria

The passive filters used to diminish the distortion level are classified as follows:

- series filter, thus increasing the impedance value for desired harmonics orders path;
- shunt filters, thus decreasing the impedance value for desired harmonics orders path.

Single tuned passive filter - This type is tuned to suppress a single frequency, is designed according to this characteristics:

- harmonic current order that requires blocking;
- capacitive reactive power necessary to compensate non-linear power of system;
- quality factor;
- voltage level;
- fundamental frequency given by the system.

The apparent power (S) of three phase a.c. system is given as [2]:

$$S^2 = P^2 + Q_X^2 + D^2 \tag{1}$$

where: *P*-active power, Q_X -reactive power, *D*- distorted power.

Filter power necessary to compensate non-linear power of system (*G*) on fundamental frequency, is given as; [2]:

$$G^2 = (Q^2 + D^2) = S^2 - P^2 \to G = \sqrt{S^2 - P^2}$$
 (2)

where: G-non-linear power of system.

Then the capacitance filter value is given as [2]:

$$C = \frac{G}{(V^2 \cdot 2\pi f)} \tag{3}$$

$$G = \frac{V}{X_c} \tag{4}$$

where: V-nominal voltage, f-fundamental frequency, X_c -capacitive reactance on f.

Impedance for resonant frequency is given as [3]:

$$Z_n = R + j \left(2\pi f_n L - \frac{1}{2\pi f_n C} \right) \tag{5}$$

where: Z_n -filter impedance on resonant frequency, *R*-filter resistance, f_n - resonant frequency (harmonic order), *L*-inductance, *C*-capacitance.

A passive filter tuned to the resonant frequency will have very low impedance only for the harmonic frequency that is to be eliminated. For an ideal filter, the inductive and capacitive reactance will be equal for tuned frequency, as in following equation [3]:

$$X_{Ln} = X_{Cn} \to 2\pi f_n L = \frac{1}{2\pi f_n C} \tag{6}$$

$$\omega_n = n\omega_0 = \frac{1}{\sqrt{LC}} \tag{7}$$

$$Z_n = R \tag{8}$$

where: ω_n -pulsation on resonant frequency, ω_0 -pulsation on fundamental frequency, X_{Ln} and X_{Cn} inductive and capacitive reactance on resonant frequency, *n*-harmonic order [4].

With equation (3) can be calculated the inductance (L) as in following equation:

$$L = \frac{1}{[(2\pi f_n)^2 * C]}$$
(9)

The quality factor (Q) (the adjustment of tuning accuracy and, consequently the bandwidth) can be set by changing the resistor value. High Q of filters are designed to eliminate only specific harmonics (narrow band). On the other hand, if the filter has a low Q, the harmonic components close to the tuning frequency can be attenuated.

The inductive and capacitive reactance of the filter at the tuning frequency are equal (ideal case) so, Q can be defined as the ratio between the capacitive reactance and the resistance of the filter. The Q coefficient can be obtained from the following equations [4]:

$$\begin{cases} Q = \frac{X_{Ln}}{R} = \frac{X_{Cn}}{R} = \frac{\sqrt{\frac{L}{c}}}{R} \\ X_0 = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{c}} \end{cases}$$
(10)
$$Q = \frac{X_0}{R} \to R = \frac{\sqrt{\frac{L}{c}}}{Q}$$
(11)

where: X_0 -inductive or capacitive reactance

From equation (7), resonant frequency (L and C for f_n) is given as [2]:

$$f_n = \frac{1}{2\pi\sqrt{LC}} \tag{12}$$

The band pass (BP) filter on figure 2, is delimited below by the frequency to witch the impedance is equal to resistance and the amplitude is $\sqrt{2R}$. The relationship between the quality factor and the bandwidth can be expressed as follows [5]:

$$Q = \frac{\omega_n}{BT} \tag{13}$$



Figure 2. The effect of impedance on the frequency band [5]

Double tuned passive filter. (Figure 3) are the equivalent of two single tuned filters connected in parallel. These filters uses series and parallel resonance circuits, which makes them complex. The electronic components with index 1 correspond to the first tuned frequency, while the elements with index 2 correspond to the secondary tuned frequency.



Figure 3. Double tuned passive filter [6]

For double tuned filter, all the parameters needed $(L_1, C_1, R_1, L_2, C_2, R_2)$ can be calculated from single tuned filters parallel connected [7]

High pass passive filters - The high pass filters (figure 4) are provided with damping resistance, which reduces the quality factor of the filter. The low quality factor increases the bandwidth of the filter and makes it suitable for a range of harmonic frequencies greater than the cutting frequency. These filters allow only the frequencies above the cut-off frequency to be passed - to infinity, blocking the frequencies below the cut-off frequency f_c .



Figure 4. High pass filter operation (a)-Second Order, (b)-Third order, (c)-C-Type [8], [9]

For all high pass passive filter from figure 4, the quality factor is given as [10]:

$$Q = \frac{R}{\omega_f L} \tag{14}$$

is defined as the ratio of resistance to reactance of the parallel RL circuit at the tuned frequency; decides the bandwidth that determines the sharpness at the tuning frequency.

3. THD in power factor

To determine the power factor with the effect of the THD content, three separate measurements are needed [11]:

- determining the content of *THD*_{current};
- calculation of the distortion factor;
- determining the phase shift between the fundamental waveforms of the current and the voltage.

The power factor as an effect of the phase shift between voltage and current, without involving the *THD* effect is given as:

Power factor =
$$\cos(\theta_v - \theta_i) = \cos(\varphi)$$
 (15)

where: θ_{v} -voltage phase, θ_{i} -current phase, φ -phase shift between voltage and current.

Distortion factor =
$$\sqrt{\frac{1}{1 + THD_{curent}^2}}$$
 (16)

From (15) and (16) \rightarrow the power factor having the *THD*_{current} involvement, is given as:

Power factor^{*} = cos(
$$\varphi$$
) $\sqrt{\frac{1}{1 + THD_{curent}^{2}}}$ (16)

(In the equation of *power factor*^{*}, the unit value of THD is used, not the percentage value)

4. Simulations

An a.c. energy source is simulated in Matlab-Simulink. ($U_l = 500$ kV, 60Hz) feeding a rectifier (12 pulses, thyristors, 6-phase input, $U_l=200$ kV) in line through a transformer (three-phase primary $U_l=500$ kV/6-phases secondary $U_l=200$ kV, S = 1200MVA). The simulations were retrieved and modified from [12].

The purpose of these simulations is to observe the amount of harmonic distortions injected in power source by the a.c.-d.c. quadrant of the electric converter. Also, it can be observed the parameters differences of source electrical energy quality, according to the passive filters variables.



4.1. Running the application without filters (simulation 1)

Figure 5. Running the application without filters, (simulation 1)

Table 1. Fundamental voltage/current, Phase angle, Phase shift $\varphi(^{\circ})$, (Simulation 1)

	Fundamental Voltage	Fundamental Current	Phase shift $\varphi(^{\circ})$
	60 Hz (Fnd): 100.00% 207.4°	60 Hz (Fnd): 100.00% 179.0°	28.4°
P	ower $factor_1 = \cos(28.4^\circ) \sqrt{\frac{1}{1+TH_2}}$	= 0.879 * 0.9972 = 0.877	



Figure 6. Voltage waveform, *THD*_{voltage}, simulation 1



Figure 7. Current waveform, *THD_{current}*, simulation 1

 Table 2.Main voltage and current harmonic ranks, amplitude in % of fundamental, "relative" phase angle, simulation 1

Voltage harmonic rank	Current harmonic rank
660 Hz (h11): 12.12% 58.3°	660 Hz (h11): 6.02% 137.4°
780 Hz (h13): 9.93% 51.8°	780 Hz (h13): 4.11% 128.7°
1380 Hz (h23): 3.96% 227.7°	1380 Hz (h23): 0.89% -68.2°
1500 Hz (h25): 3.85% 215.9°	1500 Hz (h25): 0.77% -82.0°
2100 Hz (h35): 1.30% 172.7°	2100 Hz (h35): 0.22% 229.1°

4.2 Running the application with Single tuned filters - $Q=2 Q_{filter}=3*200MVAR$ for harmonic ranks: 11^{th} , 13^{th} , 23^{th} (simulation 2)



Figure 8. Running the application, simulation 2

Table 3. Fundamental voltage/current, Phase angle, Phase shift $\varphi(^{\circ})$, simulation 2



Figure 9. Voltage waveform, THD_{voltage}, simulation 2



Figure 10. Current waveform, THD_{current}, simulation 2

4.3. Running the application with: C-type High-Pass Q=100 3th, Double-Tuned Q=100 11th and 13th, High-Pass 24th Q=100, $Q_{filter}=3*100MVAR$ (simulation 3)



Figure 11. Running the application, simulation 3

Table 4. Fur	ndamental voltage	e/current. Phase	angle. Phase	shift $o(^{\circ})$.	simulation 3
Lable	iaumonium vonus	courrent, r muse	ungio, i muse	$\sin \psi$, onnunution o



Figure 12. Voltage waveform, *THD*_{voltage}, simulation 3



Figure 13. Current waveform, *THD_{current}*, simulation 3

4.4. Running the application with C-type High-Pass Q=50 3th, Double-Tuned Q=50 11th and 13th, High-Pass 24th Q=50, Q=3*200Mvar, (simulation 4)

Table 5. Fundamental voltage and current, Phase angle, Phase shift $\varphi(^{\circ})$, simulation 4





Figure 15. Current waveform, *THD*_{current}, simulation 4

4.5. Running the application with C-type High-Pass Q=50 3th, Double-Tuned Q=50 11th and 13th, High-Pass 24th Q=50, Q=3*100MVAR (simulation 5)



Table 6. Fundamental voltage and current, Phase angle, Phase shift $\varphi(^{\circ})$, simulation 5

Figure 16. Voltage waveform, *THD*_{voltage}, simulation 5



Figure 17. Current waveform, *THD_{current}*, simulation 5

4.6. Running the application with: C-type High-Pass Q=2 3th, Double-Tuned Q=20 11th and 13th, High-Pass 24th Q=7, Q=3*200Mvar (simulation 6)

Table 7. Fundamental voltage and current, Phase angle, Phase shift $\varphi(^{\circ})$, simulation 6

Fundamental Voltage	Fundamental Current	Phase shift $\varphi(^{\circ})$
60 Hz (Fnd): 100.00% 206.3°	60 Hz (Fnd): 100.00% 207.9°	-1.6°

$$Power \ factor_5 = \cos(-1.6^\circ) \sqrt{\frac{1}{1 + THD_{curent}^2}} = 0.9996 \sqrt{\frac{1}{1 + 0.0045_{current}^2}} = 0.9995$$



Figure 18. Voltage waveform, THD_{voltage}, simulation 6



Figure 19. Current waveform, *THD*_{current}, simulation 6

5. Conclusions

From the presented simulations we can conclude that the values of the harmonic distortions has a major impact on the power factor, by modifying the phase shift between voltage and current and by increasing the distortion factor. A proper solution for the THD reduction is represented by connecting passive filters on power grid.

To achieve a high power factor of sources, we have to pay close attention to passive filters parameters. Achieving a low quality factor of C-type High-Pass, Double-Tuned, High-Pass filters and a proper reactive power compensation, the power factor increases from 0.8771 for no filters connected to 0.9995 for the most efficient configuration of passive filters, simulated in this paper.

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