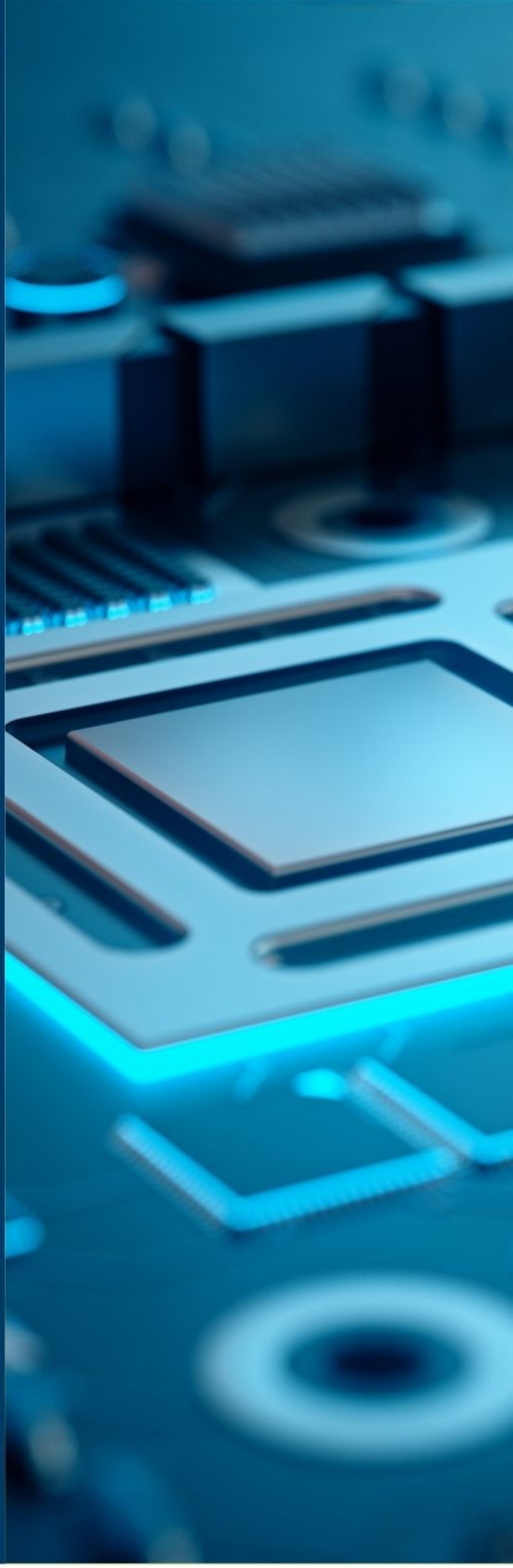

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Effective and low-cost passive compensator system to improve the power quality of two electric generators

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Abstract: To suppress the most dominant harmonic currents and compensate for the power factor (PF) of electric generators (EGs), a technique based on passive power filters (PPFs) is presented here. The key feature of the proposed method is the implementation of only a set of PPFs for compensating the power-quality issues of two EGs. This characteristic makes the suggested approach highly cost-effective and considerably reduces the required space for placing PPFs. The performance of the proposed technique is demonstrated using simulation studies under MATLAB/Simulink environment and validated experimentally.

1 Introduction

The widespread application of electronic equipment based on semiconductors in both domestic and industrial utilisation has caused serious quality issues in power systems. Among these issues, the most serious one is perhaps increasing the harmonic pollution in the grid voltage. The international standard (e.g. IEEE 519–1992 and the IEC 61000-3-6), however, has imposed strict limits on the level of harmonics in the power systems as they cause serious problems such as increasing losses in the power systems, reducing the lifetime of equipment, generating audible noise, causing interference with communication systems etc. [1, 2]. The aforementioned harmonic problems are particularly noticeable in DC power systems such as DC grids and microgrids, and DC shipboard power systems since their application require DC power converters [3–5]. To deal with the problems caused by harmonics, different approaches have been proposed in the literature. The implementation of active, passive, and hybrid passive/active filters are the most common solutions [6–11]. The active power filters (APFs) consist of two-level or three-level inverters, which generate the same harmonics of the grid, but opposite in phase to suppress them [7, 8]. Moreover, the APFs can also compensate for the power factor (PF). Nevertheless, this solution suffers from a number of drawbacks, mainly the high cost, the maintenance complexity, and the big amount of losses [9, 12]. The mixed topologies, which associate the PPFs to the APFs, have attracted the researchers in a so-called hybrid topologies [13]. The hybrid APFs can offer an acceptable harmonic rejection with a lower power rating of the DC link of the converter, and thus reduce the cost of the filter. However, the hybrid topologies present some issues such as the flow of the compensating currents of the PPFs in the APFs [11]. Since the real problem of the harmonics is caused by their low frequencies (3rd, 5th, and 7th), the use of PPFs still a promising solutions due to their simple structure, easy maintenance, higher efficiency, the ability of correcting the PF, and the low cost [14–17].

In several applications of DC shipboard power systems and DC microgrids, the sources of power consist of diesel engines or gas turbines with AC power EGs. The AC power is converted into DC power via power converters and shunted with each other to satisfy the heavy load requirements. During the conversion of power from AC to DC, the power converters generate an unacceptable amount of harmonics, which threaten the EGs. Since the EGs are not connected before the conversion of power from AC into DC, they can be controlled to be shifted by 60° or 180°. Based on this idea, a technique to suppress the harmonics and improve the power quality of two EGs using a set of PPFs is proposed in [1]. The application of this work, however, is limited to single-phase applications. It implies that it may not be applicable to most electric power systems, such as DC microgrids and DC ships, as they are most often based on three-phase generators. To deal with this limitation, extending the idea proposed in [1] to the three-phase systems is presented here.

The rest of this work is organised as follows. Section 2 presents the concept of harmonic movement in an electric power system. Section 3 introduces the conception and calculation of passive power filters (PPFs). Section 4 discusses the obtained simulation results. Section 5 provides the experimental validation. Finally, Section 6 concludes this paper.

2 Concept of harmonic movement in an electric power system

A sinusoidal voltage supply generates a sinusoidal current. However, when the load is non-linear such as rectifiers, it generates harmonic currents in the power system. In a single-phase system, according to Fourier definition, the signal of each harmonic frequency is alternative. It means that from 0 to π, the phase generates this harmonic while the neutral absorbs it, and from π to 2π the phase absorbs it, while the neutral generates it [Fig. 1*a*]. However, for a balanced three-phase system, the harmonics of the order $6\ h\ \pm 1$ (h denotes harmonic order) are delivered and absorbed simultaneously between phases with a shift of (2/3) as shown in Fig. 1*b*. These harmonics must be generated and absorbed so that the rectifier works properly; however, this process is operated through the power supply, which deteriorates the waveform of the voltage. One of the most used solutions that can prevent the circulation of these harmonics in the power supply is the installation of the PPFs. The role of PPFs is to generate the aimed harmonic current to the system to counter its similar harmonic in the power supply. However, since the PPFs are subjected to a sinusoidal voltage supply, they will surely generate only a fundamental current that corrects the PF. If in addition to correcting the PF, generating the targeted harmonic components is intended, the PPF should be subjected to the same harmonic

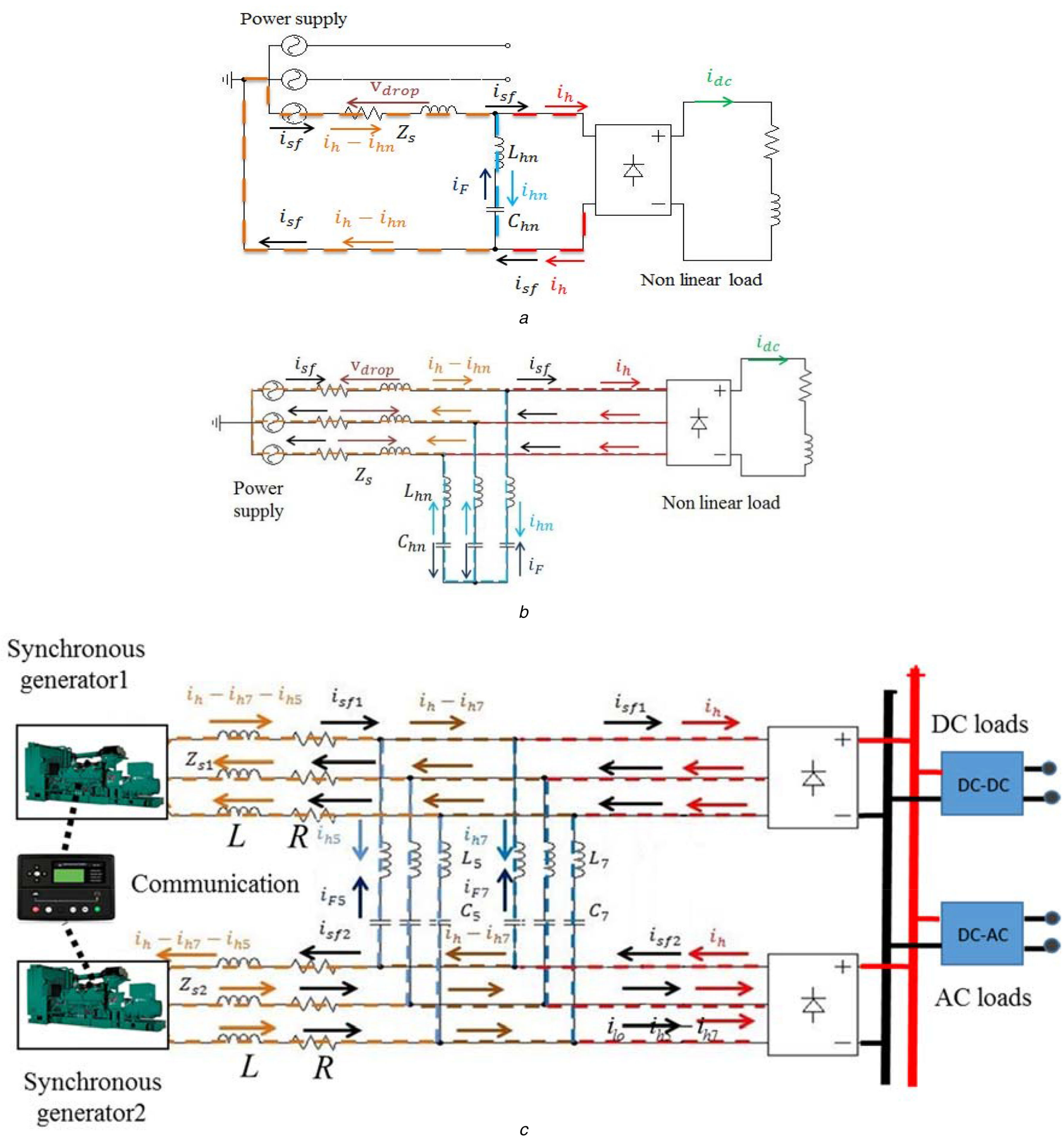

Fig. 1 *Principle of harmonic movement in the power supplies and PPF*
(a) Single phase system case, ***(b)*** Three phase system case, ***(c)*** Three phase system of two diesel generators filtered by a one set of PPF

voltages. This demonstrates the major role of the source impedance Z_s, which acts as a voltage harmonic supply for the filters to enable them to generate the aimed harmonic currents. Notice that the passage of the distorted source current i_s in Z_s increases the distortion in voltage. Considering this fact, the voltage across to the non-linear load can be expressed as:

$$v_{\text{lo}} = v_s - v_{\text{drop}} \tag{1}$$

where v_s is the power supply voltage, v_{drop} is the total voltage drop caused by Z_s, and v_{lo} is the voltage across the non-linear load.

Assuming that the source current i_s contains a fundamental component i_{sf} and harmonic components i_h ($h = 1, 2, \ldots, n$) flow through Z_s, the resulted voltage drop can be expressed as:

$$v_{\text{drop}} = Z_s \times \left(i_{\text{sf}} + \sum_{h=2}^{n} i_h \right) \tag{2}$$

This equation demonstrates that either the increase of harmonics or the augmentation of Z_s can distort the waveform of v_{drop}. The substitution of (1) in (2) shows how the distortion of harmonic currents affects v_{lo}. Observe that in (1), v_{drop} has a negative sign (–) which means that when installing the PPF, as v_{drop} is the harmonic supply of PPF, the harmonic generated by the PPF i_{hn} will be opposite to the similar one of the power supply. The movement of i_{hn} in the tuned filter creates a harmonic voltage composed of two components: v_{Lhn} in the harmonic reactance of the coil X_{Lhn} shifted by $\frac{\pi}{2}$, and v_{Chn} in the harmonic reactance of the capacitor X_{Chn} shifted by $\left(-\frac{\pi}{2}\right)$ as formulated in (3) and (4).

$$v_{\text{Lhn}} = X_{\text{Lhn}} \times i_{\text{hn}} \tag{3}$$

$$v_{\text{chn}} = X_{\text{chn}} \times i_{\text{hn}} \tag{4}$$

So the shift between v_{Lh} and v_{ch} is π, the impedance of the filter for each harmonic h is expressed as:

$$Z_{\text{fhn}} = R_f + j \times (X_{\text{Lhn}} - X_{\text{chn}}) \tag{5}$$

where R_f is the intern resistor of the filter. A large value of R_f results in deviating the filter from the tuning frequency.

Mostly for single-tuned filters, R_f comprises a small value, which leads the quality factor Q_u to be high and sufficient (usually ranged from 30 to 60) [18].

$$Q_u = \frac{X_{\rm Lhn}}{R_f} = \frac{X_{\rm chn}}{R_f} = \frac{1}{R_f}\sqrt{\frac{L}{C}} \quad (6)$$

For the sake of simplicity, R_f is considered disregarded during the design of the filter due to its small value compared to the reactance, thus the tuning of the filter at certain harmonic h is obtained as:

$$X_{\rm Lhn} = X_{\rm chn} \quad (7)$$

According to (3), (4), and (5), $V_{\rm Lhn}$ and $V_{\rm chn}$ will be equal in the amplitude but opposite in phase. This implies that the total harmonic voltage of the filter $V_{\rm hnf}$ can be expressed as:

$$V_{\rm hnf} = V_{\rm Lhn} + V_{\rm chn} \simeq 0 \quad (8)$$

The formula (8) indicates that the impedance of the filter at the resonance frequency is very low which makes it generates the maximum amplitude of the aimed harmonic current $i_{\rm hn}$.

For single-phase system [Fig. 1*a*] when i_s flows through Z_s, it creates $v_{\rm drop}$ that is full of harmonics. Consequently, the contaminated voltage generates $i_{\rm hn}$ with the blue colour in the tuned filters shifted by π. As a result, $i_{\rm hn}$ of the source supply and $i_{\rm hn}$ of the filters will be equal in amplitudes and shifted by π, which implies that the sum of them is tended towards zero. Consequently, these harmonics are rejected from the source currents, and thus improve the THD*i*% of i_s. Moreover, the movement of $i_{\rm hn}$ of the filters in Z_s creates another harmonic voltage drop of the aimed harmonic, which is opposite in phase. This implies that the sum of them tends towards zero. Consequently, the voltage THD*v*% decreases, and the total harmonic currents i_h of the load with the red colour remains fixed. As long as the shift between the harmonic currents of the phase and the neutral is π, it implies that the harmonic current of the PPF that is shifted by π is sufficient for both of them to reject each other. However, for three-phase systems, the shift is 2/3; therefore, the PPF generates the harmonic current between the phases without the need of the neutral. Note that in Fig. 1*b*, if the output of the filters of the first and the second phases are connected to each other, while the output of third filter is disconnected from them and connected to the neutral, it results in suppressing the third-phase aimed harmonic; whereas, the harmonics of the other phases are only reduced. This remark is observed due to the different shifts between the filters. For the third filter, the shift between neutral and phase is π, which makes it function as a single-phase system. This means that every point of the signal in the phase has the opposite point in the neutral, and thereby the sum of them becomes 0. However, in three-phase systems, the sum of the same points of the three phases that is shifted by 2/3 produces zero. Since there are only two wires that are connected, it implies that the sum of them does not provide 0. Therefore, the need of the harmonics for the third wire is insured starting from the power supply.

The comprehension of phase shifting in PPFs and the movement of harmonics provide them another advantage, which is the ability to work with two lines as shown in Fig. 1*c*. This figure introduces an example of two electric power systems, which convert the AC power into DC, then supply heavy loads. Such applications are found in all DC ships, DC microgrids, and DC networks [3, 5]. The power management system, which is responsible for running and controlling the EGs, can adapt the EGs to be shifted by π. This shift ensures the absorption and delivering of harmonics between two electric generators (EGs). In Fig. 1*c*, only the filters of the harmonics 5th and 7th are used to validate the idea. When the first EG starts generating the power from 0 to π, it delivers i_s to the first non-linear load, which contains the fundamental current $i_{\rm sf}$, and the harmonic currents i_h. Simultaneously, the second EG, which starts from π to 2π, generates and absorbs the power similar to that of the first EG, but with π radian phase shift. When installing the PPFs between two systems, they generate the aimed harmonic currents i_{h5} and i_{h7} to both power supplies. The harmonic currents in the input of the filter are shifted by π to the ones of the output. Consequently, the filter harmonic currents counter the aimed harmonics of both EGs simultaneously, and the sum of the fundamental currents of the filters i_{F5} and i_{F7} provides the total fundamental filters current i_F that compensates the PF. While the rest of the harmonic currents $i_h - i_{\rm hn}$ pass through the power supply. What is remarkable in this topology is that the systems are three-phase, but when connecting the filters between them and making the required shift, they function as a single-phase system to improve the power quality. It is noteworthy to mention that this topology works with any type of passive filters. Moreover, it can work even with the batteries of compensating the PF.

3 Conception and calculation of passive power filters

There are two categories of PPFs: tuned filters, and high-pass filters. Each category contains different types [18]. In the proposed topology, only tuned filters are used to validate the idea due to their simple structure.

In order to design a PPF, the following steps have to be satisfied:

3.1 Harmonic rejection capability of PPFs

As indicated in the previous section, the PPFs cannot reject the aimed harmonics without the aid of main impedance; therefore, there is always a trade-off between the impedance of the PPF, which is tuned at the aimed harmonic and the main impedance. Fig. 2 depicts a single-line diagram of the basic principle of PPF, which facilitates the analysis of harmonic rejection capability. Fig. 2*a* presents the fundamental equivalent circuit, which enables the analysis of the resonance phenomenon and PF compensation. Fig. 2*b* portrays the harmonic equivalent circuit, which facilitates the design of the PPF in terms of harmonic rejection capability. According to Fig. 2*b*, the non-linear load can be modelled as a harmonic source, while the supply source acts as a short circuit. The harmonic current, which is split into the PPF and the supply, can be expressed as:

$$\partial = \frac{i_{\rm sh}}{i_{\rm loh}} = \frac{|Z_f|}{|Z_f + Z_s|} = \frac{|X_{\rm lf} + X_{\rm cf} + R_f|}{|X_{\rm lf} + X_{\rm cf} + X_s + R_f + R_s|} \quad (9)$$

where ∂ is known as the harmonic attenuation factor. The smaller ∂ is, the higher harmonic rejection capability of the PPF. Fig. 3 presents the behaviour of the main impedance reactor and the filter resistor in terms of ∂ at the 5th tuning frequency. It is obvious that the increase of X_{ls} results in decreasing ∂, which means that the increase of $X_{\rm ls}$ forces more amount of the aimed harmonic to flow into the PPF. Whereas, the increase of R_f affects the filtering capability of the PPF. Therefore, adjusting the compromise between $X_{\rm ls}$ and R_f is mandatory during the design of the PPFs to make sure that ∂ is very small. Moreover, in real applications the values of the PPF inductor and capacitor can slightly vary with time, which creates a small impedance that results in affecting the harmonic rejection capability; therefore, based on (13), $X_{\rm cf}$ and $X_{\rm lf}$ should not be accurately equal during the optimisation of the tradeoff between $X_{\rm ls}$ and the PPF impedance.

Fig. 3*b* presents the influence of the main impedance resistor R_s on the harmonic filtering capability. It is obvious that the increase of R_s creates a larger path for the harmonics to flow into the supply voltage and thus forces them to flow into PPF, which consequently results in decreasing ∂. However, the increase of R_s results in increasing Z_s, which leads to increases $v_{\rm drop}$, and thereby deteriorates the voltage waveform. In order to choose the suitable value of the source impedance without affecting the supply voltage, the drop voltage caused by this impedance must be less than 10% of the supply voltage as formulated below:

$$v_{\text{drop}} = Z_s \times i_s \le \frac{v_s}{10} \quad (10)$$

The existence of the inductor in Z_s is to act as an augmenting harmonic voltage supply with the augmentation of harmonic frequencies, whereas, the resistor acts as a fixed harmonic voltage supply with all frequencies.

3.2 Adapting the power factor

The principle is presented for the single-phase system and it can be generalised for the three-phase system. The PPF proved their ability in optimising the PF while suppressing harmonics [18]. The PF of the system before installing the filters is calculated as [19]:

$$\text{PF} = \cos(\vartheta) = \cos(\varphi) \times \cos(\gamma) = \frac{P}{s} \quad (11)$$

where $\cos(\varphi)$ is the displacement factor, $\cos(\gamma)$ is the distortion factor, P is the active power, S is the apparent power.

The inductive reactive power, which is caused by the coils and affects the PF in the system, is expressed as:

$$Q_L = 3 \times V_s \times i_{\text{lo}} \times \sin(\varphi) \quad (12)$$

where V_s and i_{lo} are, respectively, the *RMS* voltage and current of the load.

Note that before connecting the filters i_{lo} and i are identical. When installing one PPF, it produces a capacitive reactive power that is expressed in (13) [19].

$$Q_c = 3\frac{V_{\text{lo}}^2}{X_f} \quad (13)$$

where X_f is the total reactance of the filter at the fundamental frequency.

To tend the PF as possible as near to unity, the following equations should be verified.

$$Q_L = Q_C \quad (14)$$

$$X_f = -3\frac{V_{\text{lo}}^2}{Q_L} \quad (15)$$

$$X_f = |X_{\text{Cf}} - X_{\text{Lf}}| = \frac{1}{2 \times \pi \times f \times C_f} \quad (16)$$

where: C_f is the capacitance of the total reactance X_f. X_{Cf} and X_{Lf} are, respectively, the inductive and capacitive reactances at the fundamental frequency.

It is noteworthy to observe that the reactance X_f of the filter has a capacitive impact due to the risen value of the capacitor comparing to the inductance at the fundamental frequency, and the minus indicates the negative capacitive effect. Equation (15) is used in case of installing one tuned PPF, in case of installing more than one PPF for the three-phase system, the (15) becomes:

$$X_{\text{ftot}} = \sum X_f = -3\frac{V_{\text{lo}}^2}{Q_L} \quad (17)$$

where: X_{ftot} is the equivalent reactance of all filters that are combined in parallel with each other and give the required compensating reactive power**.**

3.3 Resonance of the tuned and fundamental frequencies

There are two types of resonance caused by the PPFs, the first one is the resonance at the aimed frequency. The second one is the resonance at the fundamental frequency, which its existence is severe. The determination of the aimed resonant frequency of PPFs must be very accurate so that the filter mitigates the maximum

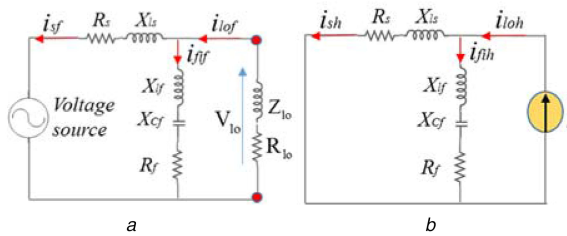

Fig. 2 *Single line diagram of the basic principle of PPF connected to the grid*

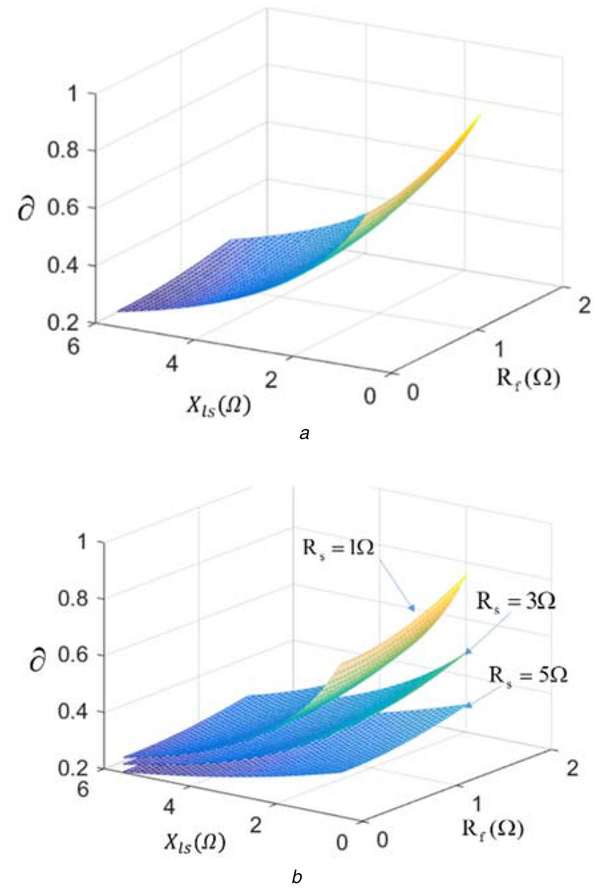

Fig. 3 *Harmonic rejection capability of PPF*
(a) Influence of the main impedance and PPF impedance in terms of ∂, ***(b)*** Influence of the main impedance resistor on the filtering behaviour of the PPF

amplitude of the aimed harmonic. The deviation from this frequency disrupts the filtering process. In addition, a large increase of the intern resistor of the filter results in decreasing the quality factor, which consequently affects the filtering accuracy as demonstrated in Fig. 4*a*. The formula that ensures the resonant at the aimed frequency can be expressed as [15]:

$$X_C = h^2 \times X_L \quad (18)$$

It is obvious that the reactance of the capacitor is bigger than the one of the inductor by the square of harmonic order, which confirms that the filters generate a capacitive reactive power at the fundamental frequency. Therefore, during the design of the filter, it is mandatory to verify that the total reactance of the PPF at the fundamental frequency is not equal to the main impedance reactance so that to avoid falling in the fundamental resonance. For a three-phase system, in order to design the PPF, the total impedance of the system should be determined. However, the difficulty that faces this step in most applications lies in the unidentified parameters of the load. Since the severe resonance occurs only at the fundamental frequency, the total impedance of the system Z_{tot} including source impedance Z_s, filter's impedance Z_f and non-linear impedance Z_{lo} cannot be determined for the

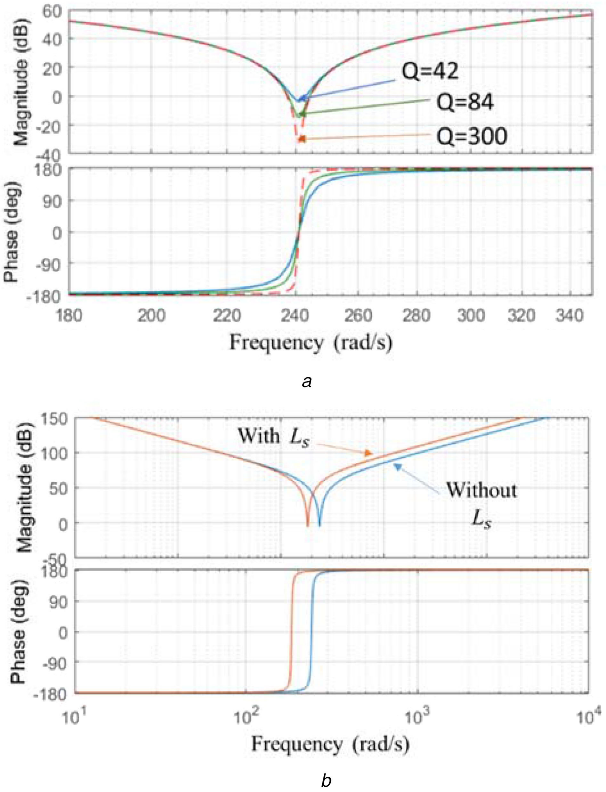

Fig. 4 *Bode diagram of a single tuned PPF*
(a) Effect of the quality factor on the filtering capability, ***(b)*** Influence of the main impedance on the resonant frequency

fundamental frequency without a prior information about the non-linear load. Therefore, we propose the following equivalent impedance, which provide an approximated linearisation of the non-linear load impedance at the fundamental frequency as formulated in (19).

$$Z_{\text{lo}} = 3 \times \frac{v_s}{i_{\text{lof}}} \tag{19}$$

where i_{lof} is the fundamental current of the non-linear load before installing the filters. Then we introduce Z_{tot} as

$$Z_{\text{tot}} = Z_S + Z_f // Z_{\text{lo}} = \frac{Z_f \times (Z_{\text{lo}}/3)}{Z_f + (Z_{\text{lo}}/3)} + Z_S \tag{20}$$

After some mathematical manipulations, Z_{tot} becomes:

$$Z_{\text{tot}} = \frac{(R_f - jX_f) + 3 \times \left(\frac{(R_s + jX_s) \times (R_f - jX_f)}{(R_{\text{lo}} + jX_{\text{lo}})} \right) + (R_s + jX_s)}{1 + 3 \times \left(\frac{(R_f - jX_f)}{(R_{\text{lo}} + jX_{\text{lo}})} \right)} \tag{21}$$

where X_{lo} and R_{lo} are, respectively, the reactance and resistor of the equivalent non-linear load.

$$X_{\text{lo}} = |Z_{\text{lo}}| \sin(\Upsilon) \tag{22}$$

$$R_{\text{lo}} = |Z_{\text{lo}}| \cos(\Upsilon) \tag{23}$$

The addition of 3 in Z_{tot} is due to the subjection of the real impedance of the DC part to line-to-line voltage, while the filters subject to line-to-neutral voltage. Since the inductive effect in the DC part of the three-phase system is small, it is recommended to disregard X_{lo} for the sake of simplicity, and only consider R_{lo} for simplifying the calculation.

The fundamental current generated by the power supply is:

$$i_{\text{sf}} = \frac{V_s}{Z_{\text{tot}}} \tag{24}$$

According to the (24), three steps lead to fall in the resonance. First, the diminution in the values of both filters and sources resistors, thus the (28) becomes:

$$Z_{\text{tot}} = \frac{-jX_f + 3 \times \left(-j\frac{X_s \times X_f}{Z_{\text{lo}}} \right) + jX_s}{1 + 3 \times \left(\frac{-jX_f}{Z_{\text{lo}}} \right)} \tag{25}$$

The second step is to verify the equality between X_s and X_f, if their values are equal at the fundamental frequency, the (25) becomes:

$$Z_{\text{tot}} = \frac{3 \times \left(-j\frac{X_s \times X_f}{Z_{\text{lo}}} \right)}{1 + 3 \times \left(\frac{-jX_f}{Z_{\text{lo}}} \right)} \tag{26}$$

The last step is the augmentation of Z_{lo} or R_{lo} rather. From (26) it is clear that the augmentation of Z_{lo} decreases the value of Z_{tot} towards zero, which drives i_{sf} in (26) to infinity, this intense augmentation is called the resonance and causes disastrous consequences.

Another case study of the resonance is the disconnecting of the load and unsuitable choice of the PPF parameters in terms of the main impedance parameters. The best example of this issue is depicted in Fig. 2*a*. In this case, the equivalent impedance of the system based on the Laplace domain can be expressed as:

$$Z(s) = \frac{\frac{1}{s \times c_f} + L_f \times s + R_f}{\frac{1}{s \times c_f} + (L_f + L_s) \times s + R_f + R_s} \tag{27}$$

Fig. 4*b* is depicted to demonstrate the influence of the main impedance on the resonant frequency of a PPF tuned at 5th harmonic. Based on (27), it is clear that the increase of the main impedance inductor X_{ls} pushes the tuning frequency towards the fundamental. Therefore, in order to avoid falling in the danger of the resonance, the value of X_{ls} and X_f must be chosen carefully different during the design.

4 Numerical analysis and discussion

The simulation studies are performed under MATLAB/ Simulink environment; the *RMS* values of the source voltage are 56 V for both EGs with 50 Hz as a fundamental frequency. Other simulation parameters are resumed in Table 1. For the simulation procedure, two EGs are modelled to supply the power, the second EG is shifted with π from the first one. Fig. 5 synthesises the obtained results. The subplots depict, respectively, the supply voltages v_{s1} and v_{s2}, which are shifted by π and equal in the amplitude. The currents of load i_{load1} and i_{load2} that have the same amplitude and shifted by π. The source currents i_{s1} and i_{s2} after installing the filters, where the filtering quality is satisfactorily seen the improved shapes. The total current of the filter i_{fil}. The DC currents i_{dc1} and i_{dc2}. Figs. 5*b* and *c* are added to demonstrate the filters capability in damping the 5th and 7th harmonic currents of i_{s1} and i_{s2}.

The amplitudes of these harmonic currents before applying the filters were important for both systems (see Fig. 5*b*), and then they considerably diminished after connecting the filters. The spectrums are obtained using the FFT analysis. The THDs have decreased

Table 1 Simulation and practical PPFs parameters of the proposed topology (see Fig. 1c)

Components		Simulation	Practical
filter of the 5th harmonic	L (H)	1.3409	1.3
	C (F)	3.02248292 e^{-7}	3.1175e^{-7}
filter of the 7th harmonic	L (H)	0.6704	0.6
	C (F)	3.08439627 e^{-7}	3.4462e^{-7}
source impedance	L (H)	0.07	0.12
	R(Ω)	15	20
load	L (H)	3	3
	R(Ω)	1130	1130

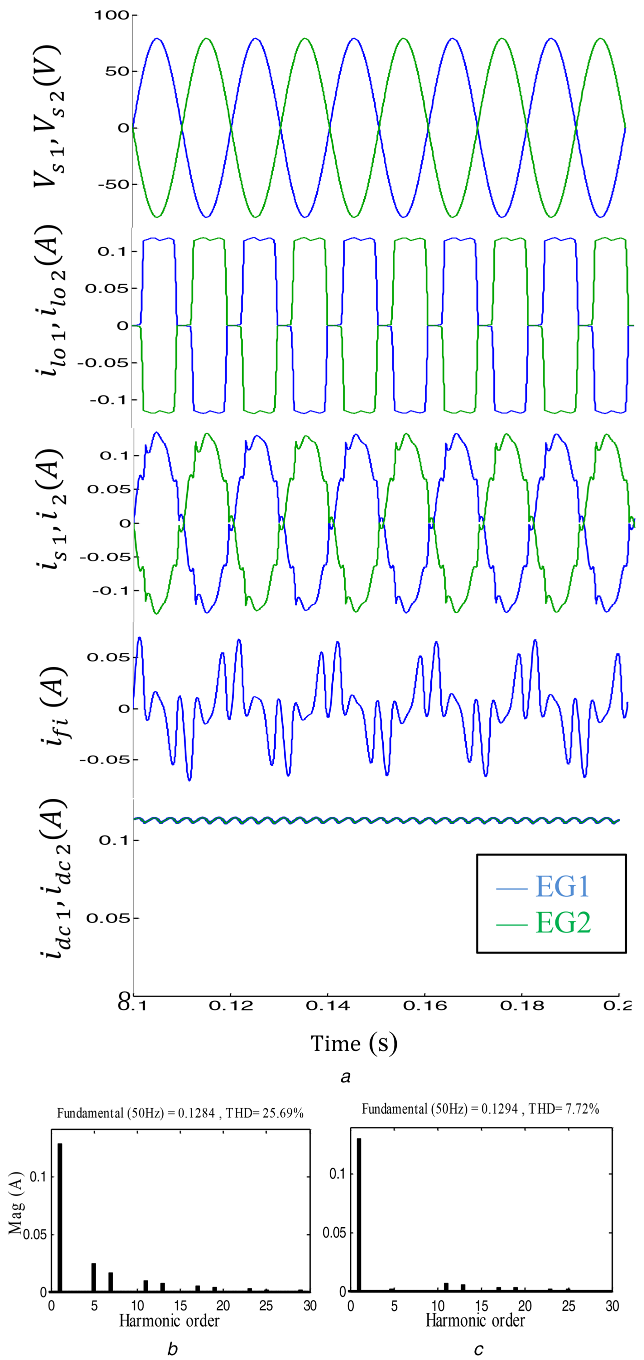

Fig. 5 *Simulation results of applying a single passive filter to damp harmonics of two identical three-phase power supplies*
(a) Signals waveform, ***(b)*** Harmonic spectrum and respective THDs of the load currents of both EGs, ***(c)*** Harmonic spectrum and respective THDs of the source currents of both EGs

from 25.6% to around 7% as shown in Figs. 5*b* and *c*. The obtained THDs in the supply currents are not conform to the norms since only low-order harmonic filters (inferior to11) are installed. They can be more decreased after installing the high-order filters. Note that the objective of this study is to verify the applicability of the proposed approach. Furthermore, based on formula (11), the filters have compensated the PF near to unity (PF = 0.98).

4.1 study case: simulation of the severe resonance phenomenon

The risk of resonance occurs when the equations explained in Section 3C are not verified, Table 2 resumes the parameters that lead to falling in this resonance in case of a three-phase system equipped with 5th and 7th filters. Since the steps that are explained in Section 3 for calculating the PPFs are validated either for one EG filtered by one set of PPFs or for two EGs, the parameters of Table 2 are also validated for both of them to fall in the resonance. The simulation procedure is done under MATLAB/Simulink, where the supply *RMS* voltage is $V = 220$ V and the frequency is 50 Hz. The non-linear load is a variable resistor, disregarding the inductance due to its small effect in the DC part. Three values of the load resistor R_{lo} are verified based on (21) to validate the augmentation of i_s caused by the resonance, as illustrated in Fig. 6. Before installing the filters, the increase of R_{lo} decreases i_s; however, when installing the filters, if the designed parameters of the filters fall in the resonance with the source impedance, the increase of R_{lo} will result in increasing i_s as demonstrated in (24) and (25). In Fig. 6, the red colour depicts the current i_s when $R_{lo} = R_{lo1}$ [see Table 2], the *rms* value of i_s increases from 3.28 to 38 A, which implies that the augmentation of i_s is considerable. When $R_{lo} = R_{lo2}$, i_s rises from 0.349 to 334.3 A. The amplification becomes more significant as depicted with the green colour. Finally, when $R_{lo} = R_{lo3}$, the *rms* value of i_s, which is plotted with the blue colour increases severely from 0.051 to reach 1316 A. This enormous augmentation will certainly burn the system if there is no reliable protection. Note that, in Fig. 6, before the stabilisation of i_s, the transient state amplitude in the three cases of R_{lo} is long. Moreover, in the case where R_{lo} is smaller than R_{lo1}, if a sudden shutdown happens, according to (24), an enormous increase happens in i_{sf} more than the increase of the transient state. This study demonstrates the important consideration of the resonance during the design of the PPFs.

5 Experimental results

The experimental prototype is established using two synchronous generators (SGs) driven by two DC motors, where the excitation of one of the SGs is inversed to make the required shift of π as depicted in Fig. 7. The parameters of the voltage and frequency are identical to the simulation ones. The other parameters are summarised in Table 1. Experimental results are portrayed in Fig. 8. According to Fig. 8*a*, it is obvious that the experimental results almost resemble those of simulation. The slight difference in the current THD of the experimental is due to two reasons: the vibration of DC motors and SGs that are illustrated in Fig. 7, and the excitation current of SGs which is not completely DC.

This perturbation appears in the curve of i_{fil} that is a slightly different from the one of the simulation results. The solution to avoid these issues in practice is by increasing the values of the sources impedances; this increase should not make a considerable voltage drop as explained in Section 3. Besides, this augmentation of sources impedances decreases the high frequency harmonics in practice comparing with simulation as seen the spectrums of Fig. 8*c*. Note that in the simulation work, each spectrum presents the results of both systems since they are identical. However, in experiment, each spectrum depicts the results of each SG. It is obvious that the results of the first SG are almost similar to those of the second one, which validates the effectiveness of the proposed technique. Furthermore, this latter has improved the PF of both power systems, as the suitable parameters of the filters are not available in practice, the resulted PF was less than the one of

Table 2 Simulation parameters that derives to fall in the resonance, which is depicted in Fig. 6

source impedance	R (Ω)	0.001
	L(H)	0.07
filter of the 5th harmonic	L (H)	0.0058
	C (F)	0.000069477
	R (Ω)	0.1
filter of the 7th harmonic	L (H)	0.0029
	C (F)	0.000070895
	R (Ω)	0.1
load	R_{lo1} (Ω)	10,000
	R_{lo2} (Ω)	1000
	R_{lo3} (Ω)	100

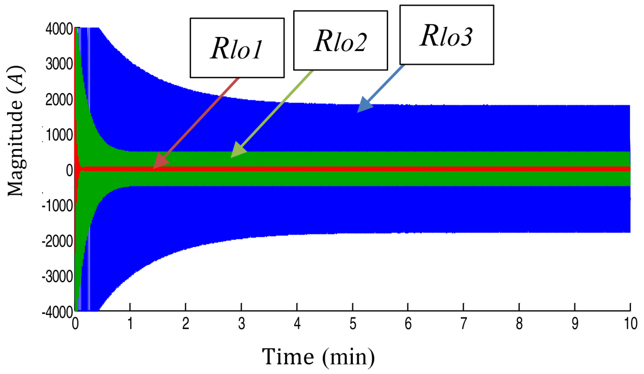

Fig. 6 *Simulation of the resonance phenomenon in the case of a three-phase system with three different values of R_{lo}*

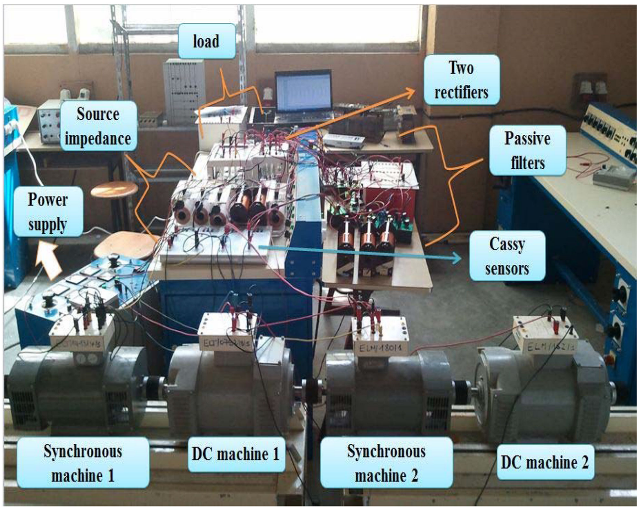

Fig. 7 *Experimental workbench for applying one PPF to two electric networks*

simulation (PF = 0.93), which leads to increase the currents of source as presented in Fig. 8*a*. However, this decrease of PF remains in the limits that respect the norms. Moreover, the practical curves of i_{fil} and the currents of the DC part i_{c1} and i_{c2} are not taken in the same moment with the other curves due to the lack of measurement devices

6 Conclusion

Here, a cost-effective technique based on implementing only one set of PPFs for two EGs was proposed. To this end, the mechanism of the movement of the harmonic current in three-phase EG was first elucidated. This principle was then extended to two EGs. Design aspects of a single PPF to simultaneously compensate dominant harmonic components of two EGs were then explained. Simulation and experimental results were finally presented to verify the effectiveness of the proposed idea. The results demonstrate that using only one set of PPFs can reject the aimed harmonics and compensate for the PF of two EGs if they are shifted with 60° or 180°.

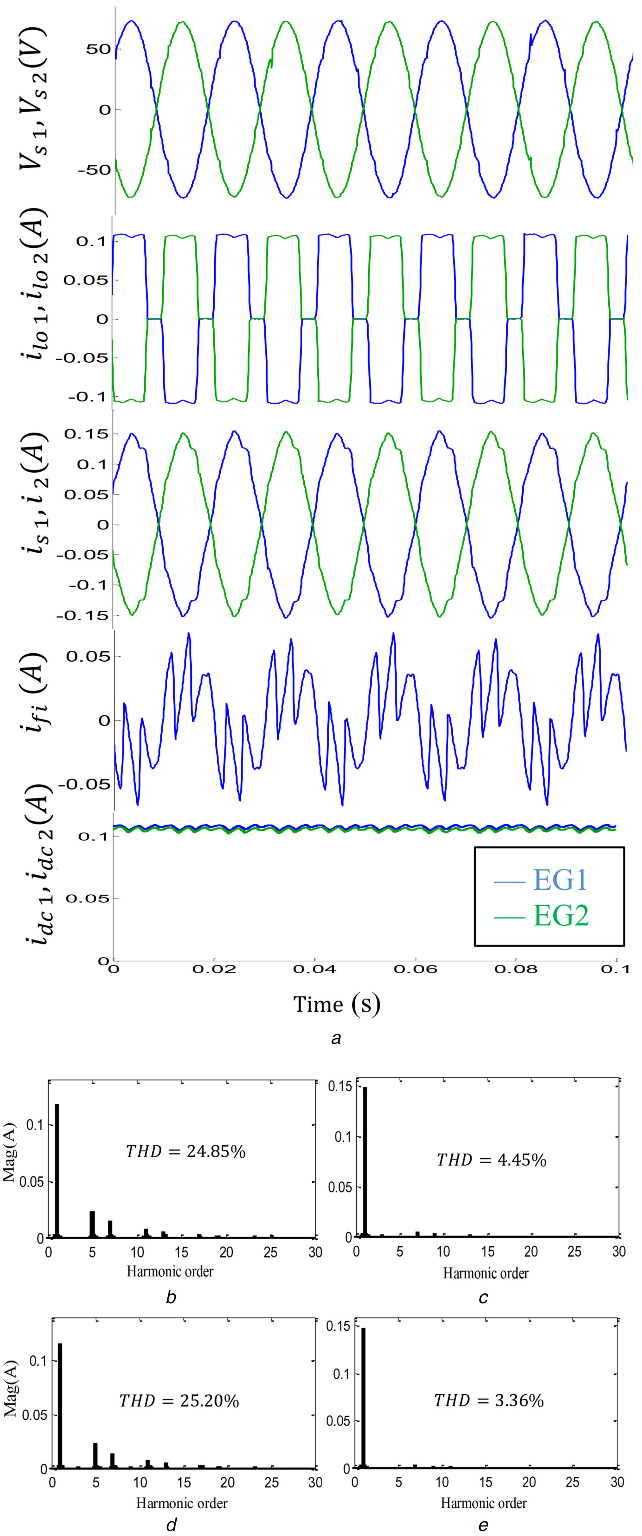

Fig. 8 *Experimental results of applying a single passive filter to reduce harmonics of two identical three-phase power supplies*
(a) Signals waveform, ***(b)*** Harmonic spectrum and respective THD of the load current of SG 1, ***(c)*** Harmonic spectrum and respective THD of the source current of SG 1, ***(d)*** Harmonic spectrum and respective THD of the load current of SG 2, ***(e)*** Harmonic spectrum and respective THD of the source current of SG 2

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