A SOGI Based Band Stop Filter Approach for a Single-Phase Shunt Active Power Filter

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***Abstract*— Control of shunt active power filter (SAPF) requires a cascaded control structure as inner current closed loop followed by outer voltage control loop. The inner current control loop is responsible for tracking of a reference current while the outer voltage loop regulates DC bus voltage to a fixed value. Dynamic performance of the DC bus voltage regulation suffers from the adverse effects such that harmonic currents produced by SAPFs lead to fluctuations in DC bus voltage at certain harmonic frequencies. This causes SAPF to produce additional harmonic components, since the outer voltage loop deals with only fundamental waves where the fluctuations should not appear. This study proposes a DC bus voltage regulation methodology based on a Second Order Generalized Integrator (SOGI) acting as a band-stop filter with the aim of increasing the voltage regulation performance in the steady state. The proposed filter does not affect the transient response thanks to that it only suppresses the harmonic-induced fluctuations in DC bus voltage. Through a simulation study, the proposed methodology is validated, and the results prove the performance and feasibility of the proposed filter.**

Keywords—harmonics, single phase shunt active power filter, Second Order Generalized Integrator (SOGI)

I. INTRODUCTION

Increasing utilization of non-linear loads brings about some power quality problems, such as, low power factor, and high total harmonic distortion, etc., since they draw non-sinusoidal currents and reactive power from the grid. In order to solve the aforementioned problems, passive power filters are extensively used. However, concerns about harmonic profiles of the non-linear loads requires the active power filters, indeed instead of passive ones [1, 2].

In order to make the grid current sinusoidal, each different harmonic of load currents is injected to the grid in the corresponding opposing phase by the active power filter. Like other current source inverters, active power filters include two cascaded control loops. The outer loop, voltage loop, regulates DC bus voltage, while the inner loop, current loop, aims to produce harmonic current components having same amplitudes as the load current harmonics in opposing phases. Not only active power filters eliminate load current harmonics, but also they causes the fluctuations in the DC bus voltage of inverter at certain harmonic frequencies. Unfortunately, these fluctuations constitute a disturbance to the voltage loop; furthermore, they reflect to the output of the DC bus voltage controller. In the literature, there are some efforts to overcome this problem. For example, a low pass filter (LPF) is proposed in [3, 4], and selecting a low voltage controller bandwidth is addressed in [5]. However, these methods affect the transient response of the voltage loop.

In this study, firstly, the unmeant effects of the harmonics currents produced by an active power filter are explored after an introduction covering active power filters. Next, a band stop filter method based on SOGI is proposed to get rid of these effects. This method does not affect the dynamic performance unlike the methods proposed before. The proposed method is examined deeply, and verified by Bode plots, and validated in a simulation environment.

II. SINGLE PHASE SHUNT ACTIVE POWER FILTER

Fig. 1 shows the general structure of a SAPF. As seen from the figure, a SAPF is connected to the load in parallel to eliminate harmonic currents; in other words, it aims to make the grid current pure sinusoidal in a way of doing reactive power compensation, which basically means to make the power factor 1,0. SAPF is controlled through a well-known control method called indirect control method (ICM) in the literature.

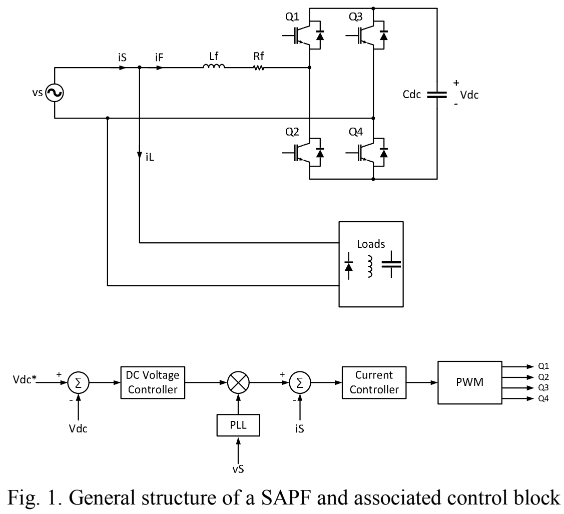

Fig. 1. General structure of a SAPF and associated control block diagram.

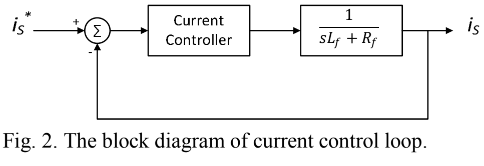

Fig. 2. The block diagram of current control loop.

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ICM is fundamentally based on the measurements of dc bus voltage, source voltage, and source current [6]; it consists of two control loops which are the inner loop and the outer loop. The block diagram of the inner loop is given in Fig. 2. The inner loop uses the reference current (i_S*) provided by the outer loop. In this study, the current controller composes of a proportional resonant (PR) controller as given in (1), where K_{p_I} is proportional gain, ω_0 resonant frequency, K_{r_I} resonant gain and ω_{c_I} cut-off frequency. Since this study does not focus on the current loop, a further consideration about the design procedure regarding the inner loop is kept out of scope here.

DC Bus Voltage Control

The operational principle of a SAPF is to generate currents having same amplitudes with harmonic currents drawn by a load in opposite phases. Harmonic currents created by SAPF itself give rise to small-magnitude fluctuations at certain harmonic frequencies in the DC bus voltage in which the fundamental wave should be handled; these fluctuations essentially mean disturbances for the DC bus voltage control. Fig. 3 shows the block diagram for the outer control loop in case of harmonic currents and reactive power compensation. Due to the fact that the DC bus reference voltage is constant and the measured DC bus voltage has a fluctuating waveform because of load harmonics, PI controller in DC bus voltage loop amplifies these fluctuations. In Fig. 4, PI controller output is examined via Bode analysis in which three different proportional-gain values are considered.

According to Fig. 4, increasing the proportional-gain (K_p) of the PI controller increases the disturbance effect at the output. It can be asserted that lowering the proportional gain helps to improve SAPF's harmonic elimination performance; on the other hand, it unfortunately makes the dynamic response of outer loop worsen. Since these signals are references for the current loops, SAPF generates harmonic currents with higher amplitudes than the required ones. So as to overcome this, there are two common approaches in the literature. The first one utilizes a LPF that filters the measured DC bus voltage whereas the second one suggests to choose a low proportional gain. Both methods results in a deteriorated dynamic response.

This study proposes a method that can overcome aforementioned problems. The proposed method is illustrated in Fig. 5. In this method, a SOGI based band pass filter (BPF) [7], whose transfer function is given in (2), is connected to PI controller in the voltage loop in parallel. The block diagram of SOGI is given Fig. 6. According to this figure, the input is DC bus voltage error (ε) which includes both the reactive and harmonic currents created by SAPF. SOGI creates two orthogonal sinusoidal signals (ε_d and ε_q) at the frequency of ω_0. The amplitude of these signals are same as the one that creates ε at the frequency of ω_0. ε_d is in phase with the input while ε_q lags the input by 90°. Transfer functions given in (2) and (3) are BPF and LPF, respectively. Bandwidth of these filters are determined by the factor k. Moreover, the filter formed by SOGI along with DC bus voltage loop is basically a band stop filter (BSF).

$$G_{PR\_I}(s) = K_{p\_I} + \sum_{h=1}^{1,3,5...} K_{r\_I}\frac{2\omega_{c\_I}s}{s^2 + 2\omega_{c\_I}s + (h\omega_0)} \qquad (1)$$

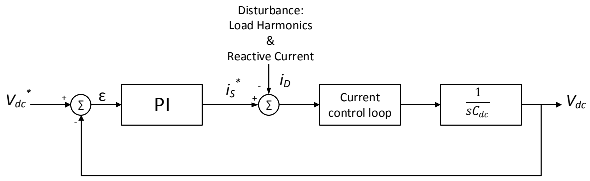


Fig. 3: The block diagram for the outer control loop.

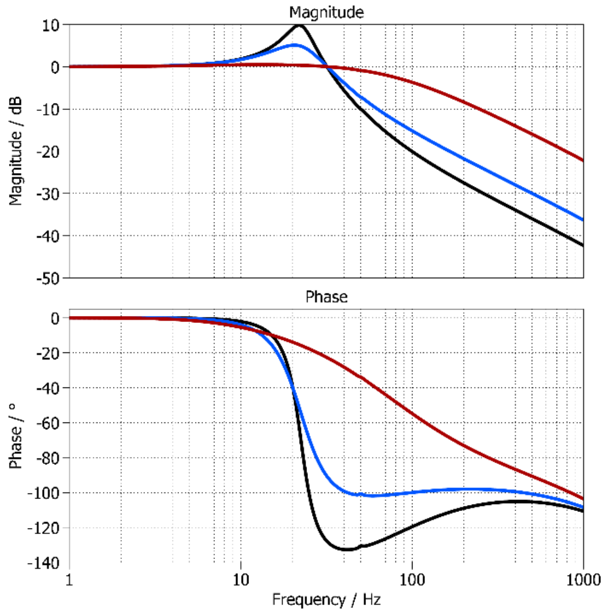


Fig. 4: iS*(s)/iD(s) Bode diagram for the conventional method.

$$\frac{\varepsilon_d}{\varepsilon}(s) = \frac{k\omega_0 s}{s^2 + k\omega_0 s + (\omega_0)^2} \qquad (2)$$

$$\frac{\varepsilon_q}{\varepsilon}(s) = \frac{k\omega_0}{s^2 + k\omega_0 s + (\omega_0)^2} \qquad (3)$$

The SOGI based BPF in Fig.5 passes the signals at the frequency it is set to, w_0; however, i_S*/ε transfer function exhibits a behavior alike the one of a BSF. Fig. 7 shows BSF Bode diagram.

Consequently, the harmonic component of the reference for the current control loop are eliminated at the frequency of w_0 as demonstrated in Fig. 7. It is clear that, when the SOGI is also used for other harmonic frequencies, the effects of load harmonics on i_S* are relaxed. Therefore, SAPF no longer generates additional harmonic currents due to the fluctuating DC bus voltage. Thanks to the proposed method, the performance of SAPF in terms of eliminating harmonics is greatly enhanced. In order to evaluate the performance of the proposed method one can examine the Fig. 8. Here, when K_p is set to 0.1, 4th harmonic is suppressed by -19.89db through the conventional method while it is suppressed by -51.92db through the proposed one.

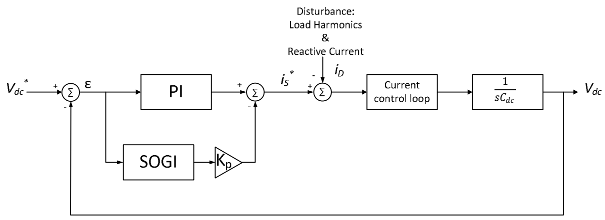


Fig. 5. The block diagram for the proposed method.

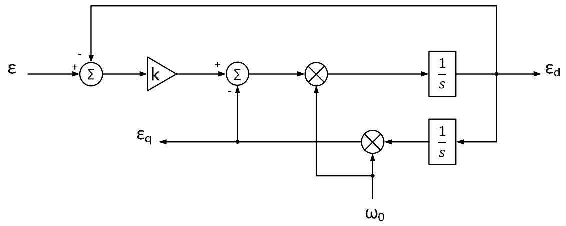


Fig. 6. Blok diagram of SOGI structure.

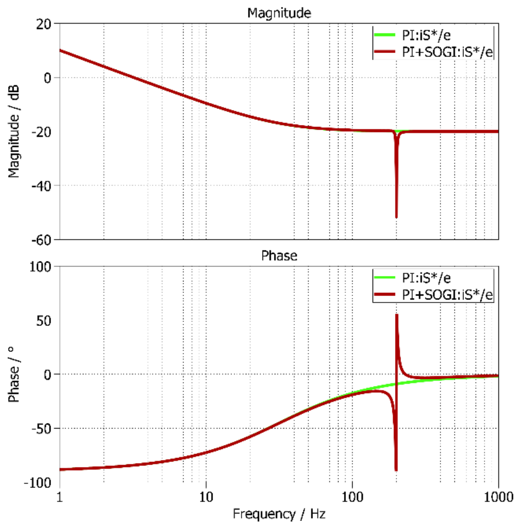


Fig. 7. PI and PI plus SOGI based band stop filter Bode diagrams.

SIMULATION RESULTS

In order to validate the proposed method, a simulation study is conducted by using the PLECS software based on the parameters given in Table 1. In this study, SOGI designs are realized for 2^{nd}, 4^{th}, and 6^{th} harmonics in the DC bus voltage; and 3 different K_p values are used for the sake of comparison. Total harmonic distortion (THD) value of the load current is measured as %106.16 in all cases. Furthermore, in order to benchmark the dynamic performances, the load resistor values in all cases are changed from 30 Ω to15 Ω at1 s.

In the first case, K_p is set to 0.05. According to Fig. 9(a), in this case, THD values are calculated as %4.44 and %3.72 for the conventional and proposed method, respectively. In addition, Fig. 9(b) clearly indicates that dynamic responses of both systems are same as expected. According the harmonic spectrum given in Fig. 9(c), 3^{rd}, 5^{th} and 7^{th} harmonics are decreased substantially by the proposed system.

In the second case, Kp is 0.1. As can be seen from Fig. 10(a), THD values are now %6.63 and %3.75 for the conventional and proposed method, respectively. This observation indicates that THD for the proposed method changes little with respect to the first case even though K_p is doubled. From Fig. 10(b), one can see that transient responses are improved equally for both methods when comparing the first case Again, 3^{rd}, 5^{th} and 7^{th} harmonics for the proposed method are insignificant in comparison to ones for the conventional method.

In the third case, K_p is set to 0.5. As illustrated in Fig. 11(a), THD values in this case are computed as %29.15 and %4.55 for the conventional and proposed methods, respectively. From this results, one can easily see the superior performance of the proposed method over the conventional one in terms of harmonic suppression performance. As can be anticipated, increased K_p results in further equal improvements in the transient responses for both methods as shown in Fig. 11(b). According to the harmonic spectrum given in Fig.11(c), the conventional method fails to suppress 3th, 5^{th} and 7^{th} harmonics while the proposed method shows a really good performance. As a result, it can be commented that the proposed SOGI based band stop filter method prevents i_S* from being affected negatively by the fluctuations in DC bus while it does not deteriorate the transient response of the system.

Table 1. Single Phase Active Power Filter

Parameteres	Values	Parameteres	Values
Switching frequency, f_{sw}	16kHz	Grid voltage, Vg	230V
Sampling frequency, f_{sm}	16kHz	Grid frequency, ωg	2π50 rad/s
DC bus voltage, V_{da}	400V	L_L	1.2mH
DC bus capacitor, C_{da}	1100μF	R_L	0.05Ω
R_F	0.05Ω	C_{L_DC}	500μF
L_F	1mH	R_{L_DC}	30Ω - 15Ω

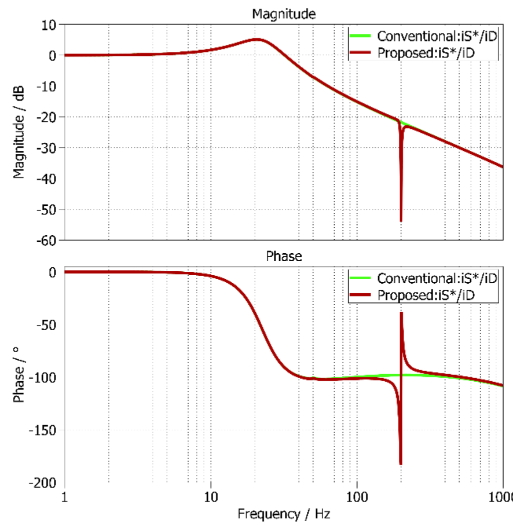
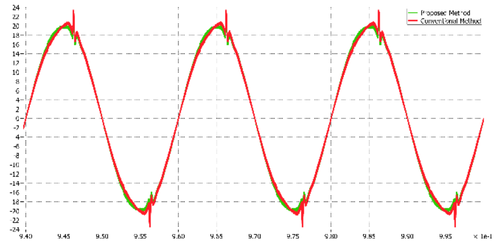


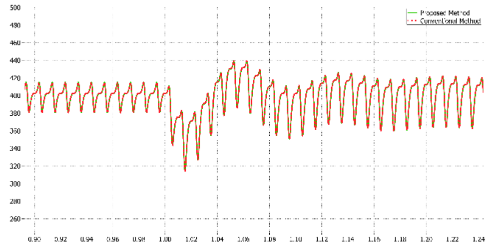
Fig. 8: iS*(s)/iD(s) Bode diagrams for the conventional and proposed method for parameters given in Table 1 when Kp=0.1.

CONCLUSIONS

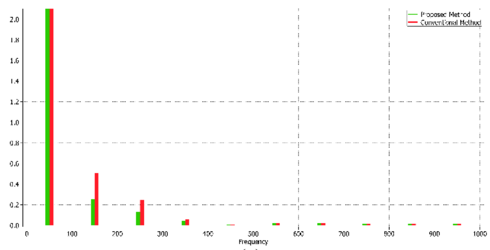
In this study, a DC bus voltage regulation methodology for a shunt active power filter has been proposed. In order to get over the poor voltage regulation performance of the classical control structure, the proposed method takes the advantage of a Second Order Generalized Integrator acting as a band-stop filter. After an introduction and a frequency domain analysis, a simulation study has clearly revealed the improved harmonic suppression performance thanks to the proposed method. Moreover, it has been shown that the transient response of the system is not affected since only the harmonic-induced fluctuations in DC bus voltage are suppressed.



(a)

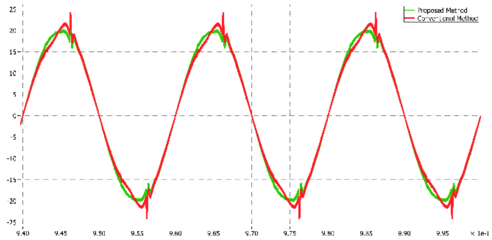


(b)

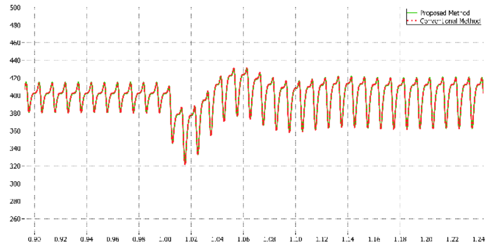


(c)

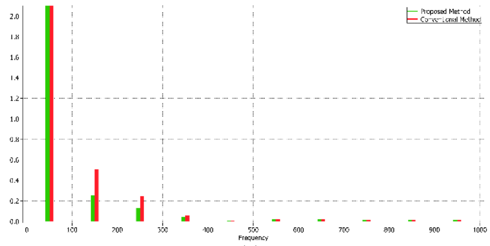
Fig. 9 Simulation results for the conventional and proposed method when Kp=0.05: a) source currents, b) DC bus voltage, c) harmonic spectrums of source currents.



(a)

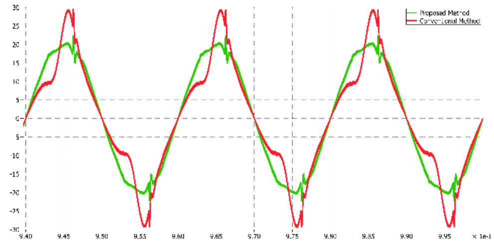


(b)

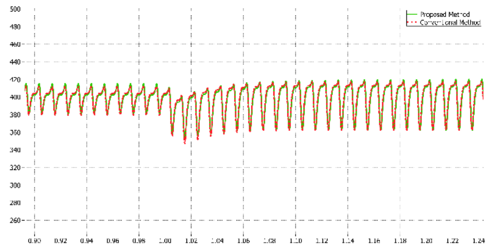


(c)

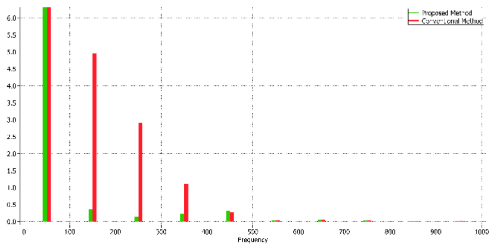
Fig. 10 Simulation results for the conventional and proposed method when Kp=0.1: a) source currents, b) DC bus voltage, c) harmonic spectrums of source currents.



(a)



(b)



(c)

Fig. 11 Simulation results for the conventional and proposed method when Kp=0.5: a) source currents, b) DC bus voltage, c) harmonic spectrums of source currents.

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