A Wavelet–based Shunt Active Power Filter to Integrate a Photovoltaic System to Power Grid

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***Abstract*— This paper improves a cost–effective compensation method for three–phase four–wire shunt active power filter (SAPF). For this purpose, first the online discrete wavelet transform (DWT) along wide inverse DWT is applied to separate the positive component of the non–ideal load voltage in fundamental sequence. Afterwards, using the second–order generalized integrator (SOGI), the total harmonic distortion (THD) of the source–side current is improved. The proposed method is applied to a SAPF which connects a photovoltaic (PV) system to power grid. The improved method is cost-effective, excluding the source current sensor from the calculating process of the desired reference signal. Matlab/Simulink simulations confirm the full compensation of the load current and sinusoidal injection of PV power into grid lines (with THD=1.21%) even under load–terminal voltage harmonics and distortions.**

Keywords—Wavelet transform, non–ideal load voltage, Shunt active power filter, Second–order generalized integrator, Cost–effective, Photovoltaic system.

I. INTRODUCTION

High dependency on fossil fuels and consuming half of the world's total oil reserves results in a global preference towards the use of renewable green energy sources, such as photovoltaic systems. However, the power electronic inverters, used to integrate the photovoltaic systems to the grid lines, drastically raise many power quality issues through supply networks. This results in many technical problems such as: overheating of transformers, false operation of circuit breakers and relays, reduction in transmission system efficiency, and so forth.

To address the issues, active power filters (APFs) are employed to power systems, and accordingly many compensation algorithms have been proposed to direct the control of the APFs. In [1], a compensation algorithm based on the A–GTIP is suggested to control the SAPF particularly in face of non–linear loads. Since APFS include the DC/AC power inverter with similar structure to that of used to integrate renewable sources to the grid; hence, employing of APFs can be multipurpose. This reduces the power system cost by decreasing the number of inverters. Nonetheless, available compensation algorithms used to direct the control of the APF work unsatisfactory. This is due to the dependency of these methods to the nonlinear mathematical equations and distorted variables such as load–current and voltage waveforms. This condition is worsened when the plant includes wind turbine which inherently produces the 3rd, 5th, 7th and 11th voltage harmonics.

To improve the accuracy of the active power filters, the indirect compensation method was investigated in [2] where the THD of the source current is limited to 1.71%.

In indirect methods, the error between the SAPF capacitor voltage and its reference value, applied to a PI controller, is multiplied by a unity sine wave which is in phase with the load voltage. The unity sine signal is obtained from the load voltage, while it is assumed that no harmonic is included in the load–terminal voltage. So, when the load voltage involves harmonics and distortions, this method is unable to compensate the load–terminal current.

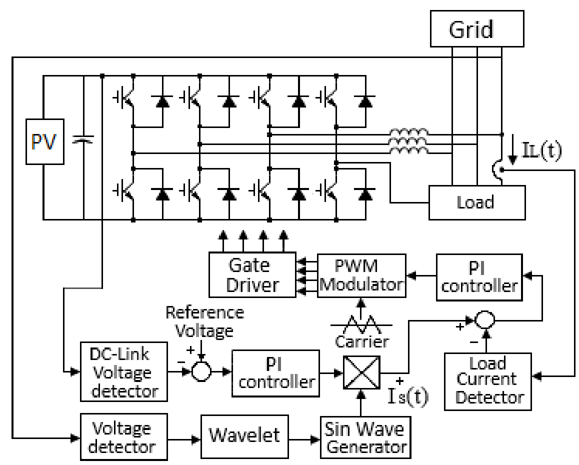

Fig.1. Grid-connected PV system by the proposed wavelet-based SAPF.

In [3], the online wavelet transform is applied to improve the accuracy of this method to direct the control of a single–phase active power filter. That method limits the THD of the compensated current to 1.01%.

This paper improves the accuracy of the indirect compensation method in three–phase four–wire system using wavelet, such that the compensation of the load–terminal current is accomplished even at the presence of the load voltage harmonics and distortions. Meanwhile, the THD of the compensated current is limited to 1.21% by employing a second–order generalized integrator (SOGI). For this purpose as can be seen in Fig.1, a new method is proposed to extract the fundamental component of the load voltage, using the DWT accompanied by online inverse DWT (IDWT).

The rest of the paper is organized as follows: Section II presents practical issues and proposed solutions to improve the indirect compensation method. In section III, the wavelet transform and proposed solutions are clarified. Section IV outlines the photovoltaic system. Simulation results are considered in section V. Finally, the conclusions that have been drawn from the present work are summarized.

II. THE PRACTICAL ISSUES AND PROPOSED SOLUTIONS

The block diagram of indirect compensation method to direct the control of a three-phase active filter has been depicted in

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Fig.2. In this method, the amplitude of the source currents in fundamental sequence is firstly obtained using the difference between the capacitor voltage and its reference value which is applied to a PI controller [4]. Then, the fundamental component of source current is extracted by multiplying the obtained current magnitude and a unity sinusoidal waveform. Afterward, subtracting the fundamental component of source current from the load current yields the SAPF reference signal, required for compensating of load-terminal harmonics and distortions.

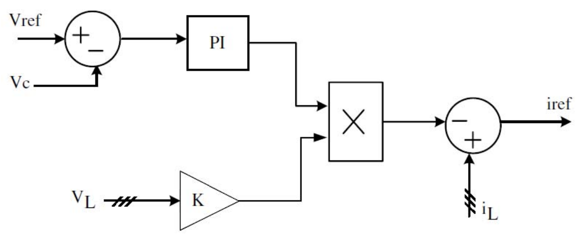
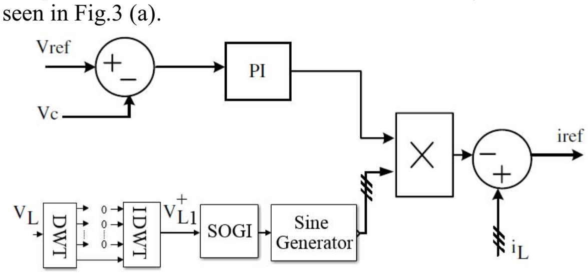


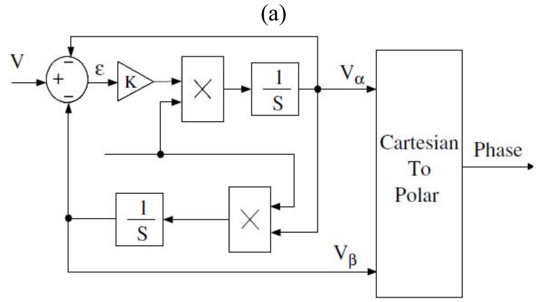
Fig.2. Block diagram of indirect compensation method.

In this method, the unity sinusoidal waveform is produced by scaling of the load–terminal voltage as can be seen in Fig.2. Therefore, the amplitude of the scaled unity sinusoidal waveform depends on the amplitude of the load voltage. And so, under network voltage harmonics and distortions, the compensation of load current harmonics and distortions would not be done.

In this paper, the wavelet transform is firstly proposed to take one step forward to accurately extract the fundamental component of the distorted load–terminal voltage as can be seen in Fig.3 (a).



(a)



(b)

Fig.3.(a) Block diagram of suggested controller of the three-phase shunt active filter; and (b) the proposed SOGI for decreasing the THD.

Secondly, the second order generalized integrator (SOGI) is suggested to remove the dependency of the unity sine wave from the amplitude of the load–terminal voltage. For this purpose, the proposed SOGI just uses the phase of the network voltage to generate the unity sinusoidal waveform. And so, the proposed method is independent of the amplitude of the load–terminal voltage as shown in Fig.3. (b). Moreover, the proposed SOGI also improves the quality of the generated unity sinusoidal waveform by eliminating the sub–harmonics, generated through the wavelet reconstruction (IDWT) process.

III. Wavelet–based sinusoidal signal generator

Wavelet transform, as a mathematical tool, is extensively employed in signal processing to localize signal events into a frequency–time domain [3]. The wavelet has the advantage of decomposing signal spectrum into non–overlapping frequency bands.

1) Continuous Wavelet transform (WT)

Continuous WT of signal $x(t)$ at a scale α and position τ can be written as below.

$$WT_x(\mathrm{a},\tau)=\frac{1}{\sqrt{|a|}}\int_{a=-\infty}^{\infty}x(t)\,\psi^*\left(\frac{t-\tau}{a}\right)dt \qquad (1)$$

where ψ denotes the mother wavelet and its upper star (i.e. " * ") represents the complex conjugate. a and τ are scale and displacement factors of continuous signal ($x(t)$), respectively.

The mother wavelet with zero average, used as a prototype for all windows, is dilated by the scale value of a, and shifted by τ. The continuous signal ($x(t)$) can also be reconstructed back as follows:

$$\begin{cases} x(\mathrm{t})=\dfrac{1}{\tau}\displaystyle\int_{a=-\infty}^{\infty}\int_{a=-\infty}^{\infty}\frac{1}{|a|^2}W(a,\tau)\,\psi_{a,\tau}(t)\,da\,d\tau \\ \psi_{a,\tau}(t)=\dfrac{1}{\sqrt{|a|}}\psi(\dfrac{t-\tau}{a}) \end{cases} \qquad (2)$$

2) Discrete Wavelet transform (WT)

Discrete wavelet transform (DWT), used in this study, is discrete form of wavelet transform (WT) of a signal, and includes three methods such as: multi–resolution analysis (MRA), windowed wavelet transform (WWT) technique, and the lifting wavelet transform (LWT) method. The MRA and WWT methods, however, cannot perfectly reconstruct every signal, since their inverse transform (IDWT) includes rounding errors within the floating point operation. Moreover, the whole data are firstly being analyzed in the MRA and WWT methods, and then half of the analyzed data are removed (through down–sampling step). Therefore, implementing of these two methods (i.e. the MRA and WWT) always need an extra memory, and a full in–place calculation is not possible.

On the contrary, the LWT method does not depend on Fourier transforms, nor involves complex mathematical calculations. In this method, the useless part of input data is firstly removed through down–sampling process; then, the WT analysis begin. So, the calculation time and required memory are accordingly reduced highly. Also, a fully in–place and with higher speed calculation become feasible.

The wavelet theory is employed to extract the positive component of the source voltage which is used as the input signal of a SOGI through generating the unity sinusoidal signal. The required wavelet levels to reach the lowest frequency band (i.e. 50Hz) that only contains the positive sequence component of the source voltage are determined by (3).

$$f_u \times 2 = \frac{f_s}{2^n} \quad (3)$$

where f_s represents the sampling frequency of original signal, f_u indicates the lowest frequency range, and n represents the required wavelet levels.

In this study, the sampling rate of 1600 Hz is selected for the orthogonal signals generator process; hence, three wavelet levels are needed to extract the fundamental sequence of positive component (50 HZ) of the source voltage. This makes a low–pass filter with cut off frequency of 100 Hz. Further, the inverse wavelet process is then required to reconstruct the fundamental positive component of original signal. This study applies five such inverse LWT levels to accurately extract the positive component of source voltage in fundamental sequence [3]. To reconstruct the fundamental positive component of source voltage in orthogonal signals generator process, the db8 mother wavelet is employed.

3) Unity sinusoidal signal generator

The unity sine wave signal generator is designed as follows. First, a discrete DWT and inverse DWT block are subsequently adopted to extract the fundamental positive component of load voltage. Then, the SOGI block as shown in Figs.3 (a), (b) generates the orthogonal signals. Now, the orthogonal signals in Cartesian coordinate frame are conversed to polar coordinate frame. And, the required phase correction is imposed through the final block (see figure 3 (a) for φ which is a constant value in radian, used for phase correction). Figure 4 shows that the suggested unity sinusoidal signal generator equipped with WT is able to produce satisfactory outcomes even under load voltage distortions and harmonics.

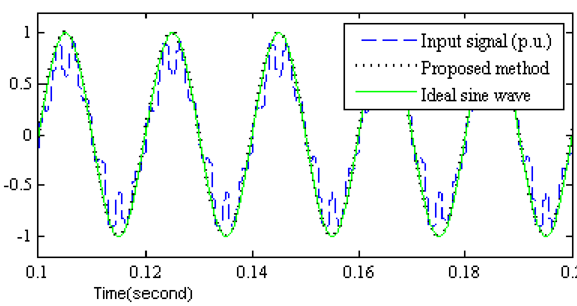


Fig.4. the orthogonal signals generator a) comparison between ideal voltage (phase a (pu.)) and produced sine signal using wavelet-based PLL b) comparison of produced sine signal using proposed wavelet-based PLL and a typical PLL.

Further, to control the SAPF's forth leg inverter to compensate the power grid/source neutral current, the required reference is produced by adding all the measured instant load currents as (4):

$$\begin{cases} i_{L-n}(\mathrm{t}) = i_{La}(\mathrm{t}) + i_{Lb}(\mathrm{t}) + i_{Lc}(\mathrm{t}) \\ i^*{}_{sh-n}(\mathrm{t}) = -i_{L-n}(\mathrm{t}) \end{cases} \quad (4)$$

IV. PHOTOVOLTAIC SYSTEM

Among renewable energies, the PV generation is one of the most promising technology. PV generation is used either in stand–alone mode integrated to battery storage or connected to the utility grid.

Depending on irradiance and ambient cell temperature, photovoltaic system converts the solar energy to electricity using photovoltaic effect. A solar cell equivalent circuit includes a current source in parallel with a diode as can be seen in Fig.5.

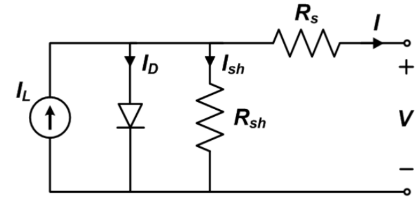


Fig. 5. Equivalent model of a PV cell.

A photovoltaic module consists of series and parallel of such solar cells to reach the required PV's output voltage and current. The relation between the PV–end current and voltage is as follows [1]:

$$I = N_p I_{pv} - N_p I_0 [\exp(\frac{(\frac{V}{N_{ss}} + \frac{R_s}{N_p} I)}{\alpha . V_T}) - 1] - \frac{\frac{N_p . V}{N_{ss}} + R_s . I}{R_{sh}} \quad (5)$$

where I_{pv} represents the output current of the solar cell, I_0 is the reversed saturation current of the solar cell; R_S and R_{sh} are equivalent series and parallel resistances of one solar panel; α is the ideality factor that ranges between 1 and 1.5; V_T=($NsKT$)/q is the thermal voltage of Ns solar cells in one panel, K=1.3806503×10^{-23} J/K is Boltzmann factor, T is the p–n junction temperature within the PV cell in Kelvin and q=1.60217646 × 10^{-19} C is the electron charge. N_{SS} and N_P are PV's respective series and parallel panels used to reach the required PV–terminal voltage and current.

Equation (5) shows that optimum operation of photovoltaic systems happen at one maximum power point. In practice, to reach this maximum power point a dummy load equals to the optimal load will be made at the PV's terminal using DC–DC converter.

V. SIMULATIONS AND DISCUSSIONS

The power system presented in Fig. 1 will be simulated in MATLAB to validate the effectiveness of the proposed compensation algorithm to eliminate the consequences of voltage–terminal harmonics and distortions on the grid–connected PV system.

Table 1 presents one solar module profile of the simulated PV system. Twenty eight of such modules in series and twenty of such strings in parallel are used to reach the required PV–end voltage and current levels.

TABLE 1
One solar module profile (at 25°C and 1000 W/m2)

Variable	$P_{max,m}$ [W]	$I_{sc,n}$ [A]	$V_{oc,n}$ [V]	K_v [V/K]	K_I [A/K]	T_n [°C]	G_n [W/m^2]
Value	200.14	8.21	32.9	–0.123	0.032	25	1000

The assumed load includes a diode rectifier and a hypothetical unbalanced load. Tables2, 3 present parameters of the employed loads.

TABLE 2
PARAMETERS OF RECTIFIED LOAD.

R_L	15 Ω
L_L	60 mH

TABLE 3

PARAMETERS OF HYPOTHETICAL UNBALANCED LOAD.

	P	Q
Phase a	37 kW	1000 var
Phase b	–	–
Phase c	37 kW	1000 var

The load–terminal voltage is demonstrated in Fig.6 (a). The nonlinear unbalanced load–terminal current is shown in figure6 (b). Under this non–ideal distorted waveforms, the SAPF that is controlled by the proposed wavelet–based method as can be seen in Fig.6 (c) not only fully suppresses all the source–end current harmonics and distortions with THD=1.21%, but it also injects the power, generated by the PV source to the grid lines.

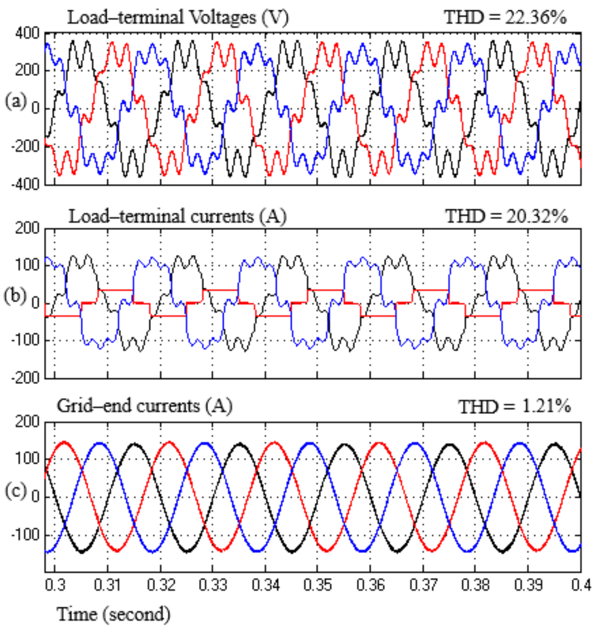


Fig.6. (a) Three–phase non–ideal load–terminal voltage waveforms (V) (THD=22.36%), (b) load–terminal unbalanced currents (A) (THD=20.32%), (c) power grid/source–end currents (A) after compensation by the proposed wavelet–based SRF method (THD 1.21%).

Figures 7 show that the injected SAPF–end current are in the same phase with the load–terminal current, but in the reverse phase with the grid–end current. This means that the generated current by the hybridized sources not only supply the nonlinear loads, but the excess power is also injected as purely sinusoidal currents into the grid lines (see Figs. 7 (c)). Thus, the integrated power system with PV source enjoys a fully sinusoidal current with THD=1.21%.

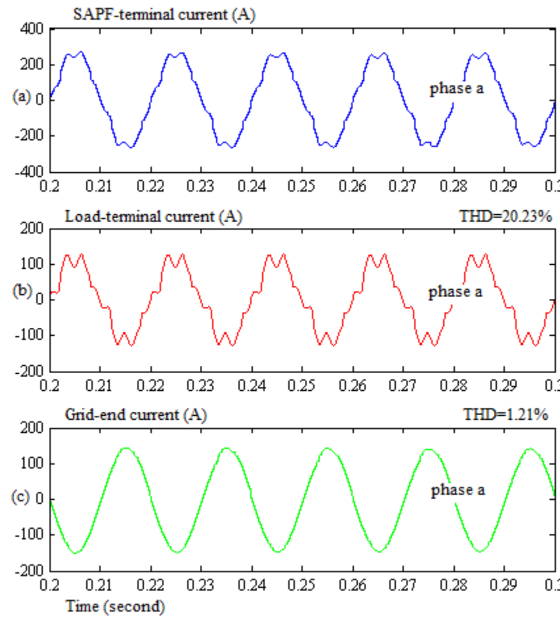


Fig.7. (a) Injected current by the SAPF (A), (b) non-linear load–terminal current (A) (phase-a) (c) power grid/source–end current (A) after compensation by the proposed wavelet-based method (THD 1.21%).

VI. CONCLUSION

This paper introduces a new method based on DWT and IDWT to eliminate the effects of load voltage harmonics and distortions on the indirect compensation method. To further improve the THD of the source–end current, the SOGI is proposed. The suggested SOGI just uses the phase of the network voltage to generate the unity sinusoidal waveform. And so, the proposed method is independent of the amplitude of the load–terminal voltage. This in turn improves the compensation of the load–terminal current.

Matlab/Simulink simulations confirm that the proposed solutions leads to a full compensation of the load–terminal current. Then, the PV system can inject a pure sinusoidal current with THD=1.21% into the power grid.

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