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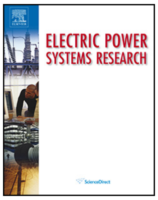

Performance improvement of shunt active power filter based on non-linear least-square approach

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ABSTRACT

Nowadays, the shunt active power filters (SAPFs) have become a popular solution for power quality issues. A crucial issue in controlling the SAPFs which is highly correlated with their accuracy, flexibility and dynamic behavior, is generating the reference compensating current (RCC). The synchronous reference frame (SRF) approach is widely used for generating the RCC due to its simplicity and computation efficiency. However, the SRF approach needs precise information of the voltage phase which becomes a challenge under adverse grid conditions. A typical solution to answer this need is the application of advanced phase locked loops (PLLs). The PLLs are closed-loop control systems that often have a response time more than two cycles of the nominal frequency. Besides, a special care should be paid in designing their control parameters to ensure their stable operation in all circumstances. This paper proposes an improved open loop strategy which is unconditionally stable and flexible. The proposed method which is based on non-linear least square (NLS) approach can extract the fundamental voltage and estimates its phase within only half cycle, even in the presence of odd harmonics and dc offset. The performance of the proposed method is verified under MATLAB/Simulink environment and validated experimentally and compared with advanced PLLs.

1. Introduction

The augmented application of electronic devices applied to the power conversion cause hazardous consequences to the power quality (PQ) of both transmission and distribution levels. The non-linear characteristics of these devices that are based on semi-conductors can cause harmonic contamination by drawing a non-sinusoidal current from the power supply [1]. Traditionally, passive power filters (PPF) are installed to mitigate the most dominant harmonics, and compensate for the reactive content needed by the loads. Although, this solution is characterized by the simplicity, low cost and easy maintenance, it cannot be a reliable solution because it highly depends on the grid impedance, which has a varying nature. Besides, PPFs are highly sensitive to variations in the load parameters and are prone to resonance with the line/load impedance. [2]. To overcome these drawbacks, the shunt active power filters (SAPFs) have received much attention to be an alternative solution for PQ issues [3,4]. Fig. 1 shows the schematic diagram of the SAPF. This latter is able to compensate for the harmonic contents, reactive power and unbalance, with a fast dynamic behavior and flexibility during the load variations.

The algorithm of identifying the reference compensating current (RCC) is a key factor for the dynamic behavior and preciseness of the SAPFs. In the frequency domain, probably the discrete Fourier transform (DFT) and the fast Fourier transform (FFT) are broadly used [5,6]. The DFT is a mathematical transform of a discrete signal with the number of points, while the FFT is a faster version of the DFT with an efficient algorithm to perform the DFT with a faster computation. The FFT however requires additional power because of computing all the frequency bins during the process [7]. Furthermore, the difficulty in calculating the inter-harmonics, the picket-fence effect and spectral leakage are weakness for this technique. In the time domain, the instantaneous reactive power (P-Q) theory [8] and the synchronous reference frame (SRF) methods are widely used [9,10]. Both methods are well-known by their simplicity and efficacy under steady state and transient operations. Moreover, the power factor (PF) and current unbalance are easily compensated using time domain methods. The SRF approach is considered more advantageous technique than the P-Q theory in terms of harmonic selectivity. The basic principle of the SRF approach is to use the phase locked loop (PLL) to synchronize the RCC with the voltage. Extracting the fundamental is achieved by estimating the angular frequency of the fundamental component of the volt-

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Nomenclature

$V_{s1,2,3}$	is the three-phase voltage
$V_{sf1,2,3}$	is the fundamental component of the distorted voltage
V^p	is the positive sequence of the voltage
$i_{s1,2,3}$	is the source current
$i_{lo1,2,3}$	is the load current
$i_{fi1,2,3}$	is the output filter current
w_f	is the fundamental frequency and it is set to $2\pi 50$ rad/s
$\hat{w}$	is the estimated grid frequency and $\hat{\theta}$ is the estimated phase
v^p and v^n	are the amplitudes of respectively the positive and negative sequences of the fundamental
ϕ'^{p} and ϕ'^{n}	are phase angles of respectively the positive and negative sequences of the fundamental
$\tilde{v}^p$ and $\tilde{v}^n$	are the amplitudes of respectively the positive and negative sequences of the harmonics
θ^p and θ^n	are the phase angles of respectively the positive and negative sequences of the harmonics
v_{dof}	is the dc offset component
p and n	refer respectively to the positive and negative sequences
h	is the harmonic order, $m = 1, 2, 3$ and $k = 0, -1, 1$
v_{ddc} and v_{qdc}	are the dc terms
v_{dac} and v_{qac}	are the ripples
A and B	are respectively the input and the output signals
T_w	is the window width
N	is the number of points that is corresponding to the window width
w_c	is the crossover frequency
b	is a constant selected to adjust both phase margin and transient response speed
w_p	is the cutoff frequency
ξ	is the damping factor
$V(t)$	is the observed voltage
$\mathcal{R}_i$	residues of i poles
$\mathcal{N}(t)$	noise related to the measurement
$\mathcal{I}_i =$	$-\theta_i + j\omega_i$
θ_i	damping factors of poles
ω_i	angular frequencies ($\omega_i = 2\pi f_i$)
Υ	is the number of data simples
p	is the tolerance
V	is the vector that contains the contaminated data
g	is the introduced matrix that that contains the data of the aimed harmonics
$\mathcal{R}$	is the extracted vector
Ra and Ma	are respectively the rank and the magnitude of the maximum point of the extracted buffered signal
ϕ	is the phase of the buffered signal
v	is the amplitude of v_α
$v_{\alpha df}$	is the fundamental component of $v_{\alpha d}$
i_{ddc} and i_{qdc}	are the dc components of the direct and quadrature currents i_d and i_q
i_{dac} and i_{qac}	are the ripples of the direct and quadrature currents i_d and i_q
T_s	sampling time

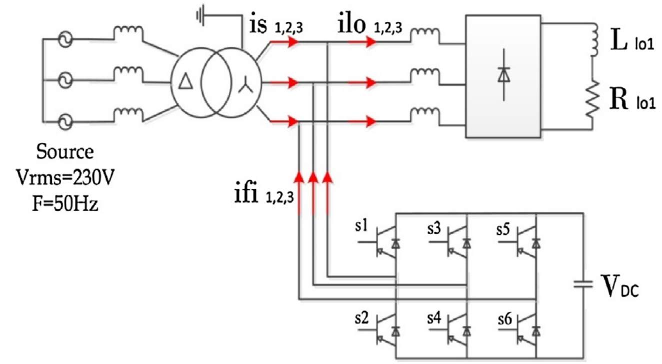

Fig. 1. Schematic diagram of the SAPF.

age using the PLL to perform Park transform. Consequently, the fundamental component of the distorted current appears as a dc component in the *dq* coordinates, while the rest harmonics appear as ripples. The RCC is obtained by separating the ripples from the dc component and transforming it back to the *abc* frame. The separation can be achieved using a low-pass filter, moving average filter, or other techniques. The SRF method however, offers poor performance under adverse grid conditions. Several pre-filtering and synchronization techniques can be applied to the voltage are proposed in the literature [11], such as: Kalman filter based synchronization method [12], the zero crossing detecting methods [13], frequency locked loop based technique [14], geometric template matching and recurrent artificial neural network [15] and least mean square based method [16]. Other techniques ap3ply advanced PLLs such as [17]: moving average filters (MAF) based PLL [18–21], delayed signal cancelation (DSC) operator based-PLL [22], decoupled double synchronous reference frame (DDSRF) based PLL [23], second-order generalized integrator (SOGI) [24], variable sampling period filter (VSPF) based PLL [25], multiple-complex coefficient-filter-based PLL (MCCF) [26]. However, most of these techniques depend on digital or complex filters that make a tradeoff between the dynamic response and the preciseness. As a consequence, obtaining an accurate estimation of the voltage phase, results in a large transient response that can exceed two cycles under adverse grid conditions. Moreover, the synchronization techniques based on PLL are a closed loop control system that requires a special care in designing its controller gains to avoid instability under all circumstances. This paper proposes a novel synchronization strategy based on NLS approach applied as a pre-filtering stage to estimate the voltage phase. The methodology is based on transforming the voltage to $\alpha\beta$ stationary reference frame using Clark transform. The main advantage of this transform is to reduce the number of filters which results in decreasing the computation burden. Then, the transformed voltage passes through a derivative to cancel any appearance of the dc off-set. Using a derivative with digital and complex filters to cancel the dc offset affects their accuracy due to the amplification of noise. However, it will be demonstrated in this paper that the NLS approach provides an accurate estimation of the fundamental component and its phase, even under noise contaminated signal. Consequently, the voltage phase can be estimated within a half cycle even in the presence of harmonic components, unbalance and dc offset, which results in optimizing the dynamic response, the accuracy and the flexibility of the SAPF with less computation burden. The effectiveness of the proposed technique is verified by Simulation and validated experimentally, and compared with advanced PLLs (MCCF–PLL and MAF–PLL) under unbalanced and distorted voltage. This paper is organized as follows: Section 2 introduces overviews of the MAF–PLL, MCCF–PLL and NLS approach. Section 3 describes the proposed method. In Section 4, the simulation results are presented and discussed. In Section 5, the practical results are validated. And finally Section 6 concludes this paper.