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Real-time performance analysis and comparison of various control schemes for particle swarm optimization-based shunt active power filters

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ABSTRACT

Selection of proper reference compensation current extraction scheme plays the most crucial role in the performance of an active power filter (APF). This paper mainly describes three different control schemes used in APFs namely, Conventional instantaneous active and reactive power (p–q), Modified p–q, and Instantaneous active and reactive current component (i_d–i_q) schemes. Our objective here is to bring down the total harmonic distortion (THD) of source current sufficiently below 5% at the point of common-coupling (PCC), in order to satisfy the IEEE 519-1992 Standard recommendations on harmonic limits. Comparative evaluation of the three control schemes shows that, i_d–i_q method is the best control scheme to be implemented on shunt APFs, irrespective of the supply voltage conditions, even under sudden load fluctuations. Results have been validated using MATLAB/Simulink simulations followed by real-time performance verification in Opal-RT Lab simulator. Here, the APF is comprised of a voltage source inverter (VSI) based on pulse-width modulation (PWM) technique. Hence, undesirable power loss takes place inside VSI due to the presence of inductors and frequent switching of IGBTs. This is effectively minimized with inverter DC-link voltage regulation using a PI controller, whose gains are optimized using particle swarm optimization (PSO).

1. Introduction

Active filters have grabbed huge attention as proficient devices in compensating the current harmonics and reactive power produced by non-linear loads. It can suppress different order harmonic components of non-linear loads simultaneously, by confining the harmonics at load terminals and hindering its penetration into AC lines [1–5]. It automatically adapts to changes in network and load fluctuations [6]. Few most important advantages of APF are: (i) intelligent filter, (ii) can be used globally or locally, (iii) extremely efficient even when the harmonic content varies randomly, and (iv) more than one device can be installed on the same supply.

The shunt APF has many configurations, amongst which the standard inverter type configuration is most widely used and discussed as given in [3] and the references there-in. APFs are generally developed with PWM converters of either current-source inverter (CSI) or voltage-source inverter (VSI) type [3,6–8]. The CSI structure as shown in Fig. 1a presents good reliability [3,6], but has important losses and requires higher values of parallel capacitor filters at the AC terminals to remove unwanted current harmonics. A diode is used in series with the self-commutating IGBT for reverse voltage blocking. On the other hand, VSI structure shown in Fig. 1b is more convenient as it is lighter, cheaper, and expandable to multilevel and multistep versions, for improved performance at high power ratings with lower switching frequencies [3,7]. It has to be connected to the AC mains through coupling reactors. An electrolytic capacitor keeps the DC-link voltage constant and ripple-free [6]. Therefore, here we have preferred to use the VSI configuration.

Two types of VSI configurations are possible for three-phase four-wire power systems, (i) three-leg six-switch structure, where neutral conductor is connected to midpoint of DC-link capacitor as depicted in Fig. 2a, and (ii) four-leg eight-switch structure, where an additional fourth leg is provided exclusively for neutral current compensation as shown in Fig. 2b. The latter is preferred, as many researchers have appointed this configuration as the most proficient alternative for shunt APFs [9–13]. The three-leg configuration suffers from several shortcomings such as: (i) control circuit is somewhat complex, (ii) voltages of the two capacitors of split-capacitor need to be properly balanced, and (iii) large DC-link capacitors are required. Despite of the fact, this topology is seldom preferred owing to less number of switching devices and lower switching losses compared to the eight-switch topology. The higher order harmonics generated in eight-switch configuration due to frequent switching of semiconductor devices can be eliminated by

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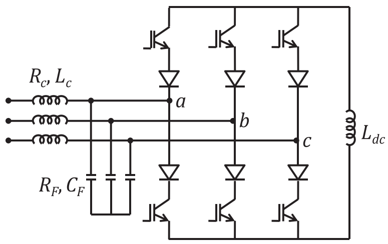

Fig. 1a. CSI configuration.

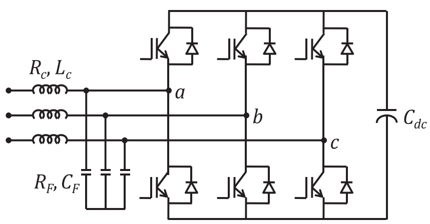

Fig. 1b. VSI configuration.

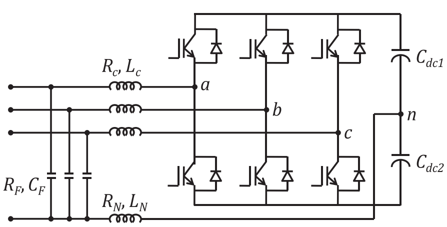

Fig. 2a. Three-leg VSI-PWM based APF.

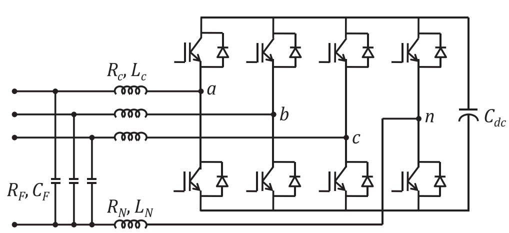

Fig. 2b. Four-leg VSI-PWM based APF.

the use of RC high-pass filter as shown in Fig. 2b. Switching losses occurring in VSI can be minimized using DC-link voltage regulator, which is basically consisted of a PI controller. For optimal harmonics mitigation, particle swarm optimization (PSO) has been employed to find out the gains of PI controller. Section 2 describes the entire DC-link voltage regulation action elaborately.

The control schemes for APF constitute a crucial part in harmonic compensation, as any inaccuracy leads to inexact compensation. Various schemes such as Instantaneous active and reactive power (p–q), Instantaneous active and reactive current component (i_d–i_q), Perfect harmonic cancellation (PHC), Generalized integral, Adaptive filter, Delay-less filtering based on Artificial Neural Network (ANN), Adaptive Linear Neuron (ADALINE), Wavelet Transform, Fast Fourier Transform (FFT) and Recursive Discrete Fourier Transform (RDFT) have been proposed since the development of APFs [13–16]. Time-domain methods are preferred here because of fast response to changes in power system, easy implementation with less memory requirements, and less computational burden unlike frequency-domain methods, where the number of calculations increases with an increase in the highest order of harmonic to be eliminated, resulting in longer response time. The ANN and ADALINE methods are also associated with few shortcomings. Number of ADALINE required to tune is equal to the number of harmonics considered in load current, thus slowing down the convergence. Generation of the input vector, $X = [\cos\omega t, \sin\omega t, \ldots, \cos\, n\omega t, \sin\, n\omega t]^T$ is difficult and involves a tedious process. Moreover, the error being minimized by gradient-based method has likelihood of converging to local minima [16].

The p–q scheme proposed by Akagi in 1984 is recognized as a viable solution to the problems created by non-linear loads, and is most widely used [17,18]. This offers a very precise reference compensation current template and allows obtaining a clear difference between instantaneous active and reactive powers. However, it is criticized as a disappointment under non-ideal supply conditions [9,19–21]. Therefore, an enhancement to this scheme was proposed in the year 2005 and was validated to be better than Conventional p–q scheme for both three-phase three-wire and four-wire systems [9,19]. Few other papers have been reported that state, i_d–i_q scheme to be more efficient than p–q scheme [20,21]. The present discussion is focused on the competency of i_d–i_q and Modified p–q schemes, in contrast to Conventional p–q scheme for load compensation in three-phase four-wire distribution systems. This paper is aimed at both summarizing the aforementioned APF control schemes and comparing their relative performances. The balanced sinusoidal, balanced non-sinusoidal and unbalanced sinusoidal mains supplies are taken into consideration in conjunction with typical non-linear balanced/unbalanced loading and sudden load change scenarios, so as to achieve compensated source currents which are as realistic as possible. The actual filter currents are compared with their references, and errors are processed in Hysteresis controller to generate PWM signals for VSI. The VSI in turn generates required compensation currents to be injected into the AC lines at PCC. Fig. 3 depicts the system configuration of shunt APF.

Testing and validation of power conditioning devices has become very essential in the design and engineering process. Here, MATLAB simulation results are validated with real-time performance analysis in RT-Lab Simulator developed by Opal-RT technologies [22]. It is one of the most promising real-time simulation tools for analyzing the system build models by running them on fixed-step solvers for automatic code generation. RT-Lab is a very fast, flexible, scalable, industrial grade and real-time platform for simulation, control testing and related applications. Other advantages include: (i) computation time within each time step is almost independent of system size, (ii) overruns cannot occur once the model is running, (iii) simulation time step can be very small i.e. in the order of 250 ns, (iv) in the design of real prototype, it may be prone to many troubles related to integration of different modules at a time and (v) off-line non-real-time simulation may become tediously long for any moderately complex system.

Section 2 describes the regulation of DC-link capacitor voltage using a PSO-based PI controller. The Conventional p–q, Modified p–q and i_d–i_q control schemes have been thoroughly discussed in the next section. The MATLAB and Opal RT-Lab simulation results for comparative evaluation of the three control schemes under ideal, distorted and unbalanced supplies along with sudden load fluctuation conditions are presented in Sections 4 and 5 respectively. The conclusion is summarized in Section 6.

2. PSO for DC-link voltage regulation

During steady state of operation, real power supplied by the source is equal to the real power demand of the loads plus a small power to compensate the losses occurring inside APF due to the