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A new control strategy for active power line conditioner (APLC) using adaptive notch filter

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ABSTRACT

This paper proposes a new adaptive control algorithm for a three-phase current-source shunt active power-line conditioner (APLC) operating under unbalanced and distorted network conditions. This control scheme aims at compensation of network's reactive power, elimination of active power's oscillating components, compensation of network current and voltage harmonic contents resulting in sinusoidal waveforms, and equilibrating the drawn power from the source evenly between the three-phases. Unlike many of the existing methods, the proposed strategy does not require any coordinate transformations or complicated calculations. The reference signals for the hysteresis-band current controlled voltage-source converter (HBCC-VSC) are generated by passing the measured current and voltage signals through two layers of modified adaptive notch filters (ANFs). To ensure superb performance and minimum total harmonic distortion (THD) level of the power system, parameters of the HBCC-VSC are obtained using differential evolution (DE) optimization algorithm. The proposed strategy is simple, easily implementable, and robust against uncertainty or variations of power system parameters and loads. The effectiveness of the proposed control scheme is validated by simulation results of a selected network under various load and power system conditions.

1. Introduction

Growing use of nonlinear equipments and in particular power electronic devices has led to intense propagation of harmonic contents in power systems. If this harmonic pollution is left unattained, the quality of the supplied power will dramatically reduce. Many papers have addressed this issue and have proposed methods for compensating harmonics [1–3]. According to IEEE Standard 519-1992 [4], the maximum allowable total harmonic distortion (THD) for distribution lines, i.e. 69 kV and below, is 5%.

Another significant problem in power systems, especially transmission lines is reactive power. Various types of compensators have been developed for resolving this issue and setting the power factor near unity [1,5,6]. The author in [6] has reviewed the most general concepts of power factor correction for polyphase systems. In addition to reactive power, elimination of active power's oscillating component is also crucial. This is to draw a non-oscillating amount of instantaneous active power from the source [7]. Facing unbalanced loads, another objective in the three-phase power systems is equilibrating the transferred energy evenly between the three phases of the transmission lines, leading to a three-phase balanced set [7,8].

The ability of active power filters (APFs) and active power line conditioners (APLCs) in achieving one or all of the above mentioned objectives and their performance quality directly depends on their control method, i.e. reference signal generating algorithm. These control schemes are mainly based on the instantaneous reactive power theory also known as the p–q theory, first introduced by Akagi in 1984 [5], the improved instantaneous active and reactive current component theory [9,10] the modified p–q theory [2,11], the d–q or park transformation [12], the p–q–r reference frame [13], and the synchronous reference frame theory [14]. All these methods use coordinate transformations in order to generate the required reference signals. A comparative study on these control methods is carried out in [15]. Despite the massive and complex calculations of these methods, their resultant THD level can rise up to 10% which is higher than the maximum allowable values according to IEEE Standard 519-1992 [4]. Moreover, in general unbalanced and non-sinusoidal conditions, special considerations must be taken into account.

Other advanced techniques used to improve the performance of APLCs and APFs are wavelet theory, fuzzy logic, resonant controllers, artificial neural networks (ANNs), hybrid APFs, and prediction control based schemes [3,16–20]. In [16], the fundamental components of voltages and currents are extracted using wavelet-transform decomposition. The required reference signals for a UPQC active filter are then generated using the positive sequence of these

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voltages and currents. The drawbacks of this strategy are its complexity and the requirement for two voltage source converters (VSCs) rather than one. The authors in [17] have applied Takagi–Sugeno type fuzzy controller to an APF for power quality improvements and reactive power compensation, however despite the achieved improvements, it is not applicable to practical systems since the three-phase voltages are assumed to be balanced and sinusoidal. Resonant-type compensators are another type of current control methods that require a careful and complicated design. A resonant-type controller for a Shunt APF is designed using genetic optimization algorithm in [18]. This approach is capable of compensating the harmonic contents of the current. However, the resultant THD, although below 5%, is near the maximum allowable boundary, which is quite high comparing to other methods. Moreover it requires other considerations in order to compensate reactive power and other common distortions of the power system. Another promising method for reference signal generation is utilization of ANNs. An example of this type of APF is represented in [3] where an Adaline ANN is trained to generate the required voltage component for recovering the system voltage to a balanced set, and another Adaline ANN extracts the current's harmonic contents. The required reference signals for the APF are then generated using these outputs. Hybrid shunt APF is another topology in which the APF is connected to the network thorough a passive filter. Reduction of VSC voltage magnitude and thus utilizing lower rated and cheaper switching devices are the main advantages of hybrid shunt APFs [19]. Prediction control based reference signal generating schemes have also been addressed in the literature as effective control strategies for APFs, where the reference current signal is calculated based on the predicted current value of the system [20]. These schemes require the load to have slow dynamics and are not applicable to systems with rapidly varying or unpredictable loads, thus are not suitable for practical networks.

An approach for extraction of active and reactive currents and harmonic components of a single-phase system using two enhanced phase-locked loops (EPLLs) is presented in [21]. Inspired by this work, a new signal generating approach for APFs operating in unbalanced and distorted three-phase networks is proposed here. The main objectives of this approach are compensation of the reactive power, elimination of active power's oscillating component, compensation of the harmonic contents of currents and voltages, and equilibration of the transferred energy through the transmission lines evenly between the three phases in order to obtain a three-phase sinusoidal balanced set. The proposed strategy consists of two layers of adaptive notch filters (ANFs), connected in series, such that the outcome of the second layer is the input reference signal to a hysteresis-band current controlled voltage-source converter (HBCC-VSC). In addition, in order to acquire optimum results, internal parameters of the ANFs are tuned globally using differential evolution (DE) optimization algorithm. The parameters of the HBCC-VSC are also obtained using DE algorithm in order to have the least THD level in the compensated network.

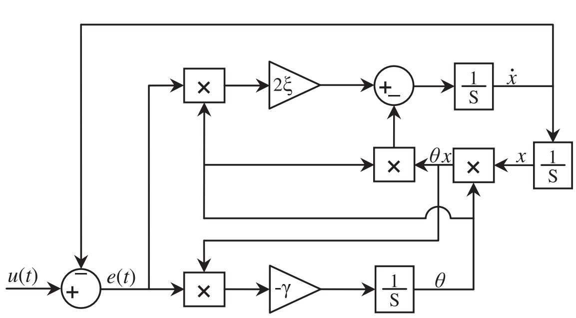

Fig. 1. Block diagram of the modified ANF.

This paper is organized as follows. In Section 2, a brief overview on ANF is presented and it is globally tuned using DE optimization algorithm. The proposed compensation strategy is presented in Section 3. Section 4 is dedicated to describing HBCC-VSC and the procedure of obtaining its parameters using DE optimization algorithm. In Section 5, simulation results on a realistic power system model under different conditions and loads are presented. Finally Section 6 is devoted to the conclusions.

2. Adaptive notch filter

2.1. Overview

Notch filter is a linear time-invariant structure that multiplies its input signal in a gain equal to unity in all frequencies except the notch frequency, in which the gain is null. Therefore, all frequencies except the notch frequency will exist in the frequency spectrum of the filter's output signal. If the filter becomes capable of locking the notch frequency on the fundamental frequency of the input signal and tracking it accordingly, it is then called an adaptive notch filter (ANF) [22].

Here, a modified version of the lattice-based discrete-time ANF [22,23] with the following dynamic behavior is employed:

$$\begin{aligned} &\ddot{x} + \theta^2 x = 2\xi\theta e(t) \\ &\dot{\theta} = -\gamma x \theta e(t) \\ &e(t) = u(t) - \dot{x} \end{aligned} \tag{1}$$

where $u(t)$ is the input signal, θ is the estimated angular frequency, and ξ and γ are real positive numbers that determine the performance of the ANF in terms of accuracy and convergence speed, respectively. Note that there is always a trade-off between these two parameters. The block diagram of the introduced ANF is shown in Fig. 1.

Stability analysis of the ANF characterized by (1) and its convergence to a unique periodic orbit are presented in [22–24]. For a sinusoidal input $u(t) = A\sin(\omega t + \varphi)$, i.e. the measured voltage or current of the network, the presented dynamic system converges to a unique periodic orbit as follows [22,23]:

$$O = \begin{pmatrix} x \\ \dot{x} \\ \theta \end{pmatrix} = \begin{pmatrix} -\frac{A}{\omega}\cos(\omega t + \varphi) \\ A\sin(\omega t + \varphi) \\ \omega \end{pmatrix} \tag{2}$$

In the above equations, A is the input signal amplitude, ω is the angular frequency, and φ is the phase. According to (2), the amplitude of the input signal fundamental component can be obtained by

$$A = \sqrt{(\dot{x})^2 + (\theta x)^2} \tag{3}$$

The system described by (2) is robust against noise, disturbances, distortions, and other pollutions of the power system and can successfully follow fundamental frequency variations of the input signal [24].

2.2. Parameter tuning

The values of ANF's internal parameters, ξ and γ, depend on its application and desired output. Here, fast and accurate extraction of the input signal fundamental component is desired. In order to have the best performance the internal parameters have to be determined with extra care. Therefore, DE optimization algorithm is employed to obtain their optimum values.

In order to tune the ANF, a distorted signal with a wide range THD, as depicted in Fig. 2a, is considered as the input. The cost function of the optimization procedure is defined as the weighted