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# A steady-state harmonic controller for a series compensator with uncertain load dynamics

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ABSTRACT

Series compensators can be used to solve a number of power quality issues in electrical distribution systems. These devices are connected in series between the point of common coupling and a load and they inject a series voltage to compensate voltage sags, swells, unbalances, and many other power quality issues. A series compensator requires a harmonic-tracking algorithm within its controller to eliminate harmonics. However, the uncertainty introduced by linear and non-linear loads connected downstream makes it difficult to guarantee closed-loop stability in every case. To overcome this problem this paper proposes a control algorithm to compensate harmonics that can be adapted in real time avoiding the need for an accurate model of the plant at the design stage. This controller is implemented in a series compensator to eliminate harmonics in two situations: filtering voltage harmonics from the grid voltage and filtering current harmonics generated by a non-linear load. The proposed algorithm was validated on a 5 kVA prototype of a series compensator.

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## 1. Introduction

Traditionally, the concept of voltage quality was referred to the average voltage level at the Point of Common Coupling (PCC) and, in most cases, an inadequate voltage value was caused by contingencies in the electrical system such as short-circuit faults, which lead to over-currents in distribution feeders that result in a sudden reduction of the voltage level (commonly known as "voltage sags") [1]. A more recent concept of voltage quality is not only tied to the average voltage level but also to the voltage waveform [2]. A Dynamic Voltage Restorer (DVR) is a kind of series compensator conceived to protect sensitive loads against voltage disturbances. When a voltage sag takes place, the DVR injects the required voltage in series with the feeding line and the load voltage remains unchanged [3]. A DVR can also be used to improve the load voltage quality of sensitive loads using an appropriate controller to track harmonics [4]. In this case, DVRs are sometimes called Series Active Conditioners (SACs) [5] or Static Series Compensators (SSCs) [6]. Series compensators can also be used to filter out current harmonics generated by non-linear loads. In this case the device is commonly known as Series Active Power Filter (SeAPF) [7]. Filtering current harmonics with a series compensator is only recommended when loads are of the so-called voltage-sourced type, otherwise a Shunt Active Power Filter (ShAPF) is best suited for this application. However, a SeAPF can be cheaper than a ShAPF because components ratings can be reduced [7]. SeAPFs are sometimes used to filter out current harmonics in medium-voltage drive applications [8] and, if the DC side of the non-linear load is accessible, the SeAPF can be installed there [9]. The main drawback of SeAPFs is that the load voltage must be distorted to eliminate the current harmonics generated by the load. If this voltage harmonic distortion required to compensate the current harmonics is too high, a Hybrid SeAPF is a possible solution [10,11]. This device adds a shunt-connected passive filter to the load side of the SeAPF to provide a low-impedance path for the current harmonics [8]. Therefore, the load voltage is hardly disturbed while current harmonics do not reach the PCC. A more comprehensive solution to tackle voltage and current quality problems simultaneously is a Universal Power Quality Conditioner (UPQC) [8,12]. However, this device is typically more expensive than a series compensator since it requires an additional converter and a more sophisticated control system.

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There are many control algorithms to deal with harmonics in series compensators. Between them, Proportional Resonant Controllers (PRCs) [13] and Repetitive Controllers (RCs) [14] are the most popular ones. RCs are used by Roncero-Sánchez et al. [4] for a DVR to protect sensitive loads against voltage sags, voltage harmonics, and unbalances. RCs are an adequate choice when the number of harmonics to be deal with is high since all the harmonics within the bandwidth of the controller are eliminated. RCs can also be adapted to work under frequency variations that are common in electric power systems [15,16]. However, RCs require an explicit model of the plant within the controller [4,15]. Therefore, if the series compensator is working as a SeAPF, a sudden variation of the load can make the system unstable since the dynamics of the load current are greatly affected by the load characteristic (that can be linear or non-linear). An alternative to RCs to track harmonics are PRCs, which are easy to design and implement [17]. Compared to RCs, PRCs do not need an explicit model of the plant within the controller. However, a rather accurate model of the plant is required at the design stage [18]. PRCs are well suited to work under frequency variations, although frequency adaptation is not straightforward [19]. PRCs have been applied to eliminate voltage harmonics with a DVR by Jowder et al. [20]. However, PRCs have the same problem of RCs: if the device is used as a SeAPF and the load changes, the system may become unstable. Multiple Reference Frame (MRF) controllers have also been used to deal with harmonics in power electronics applications and they are quite popular since they are inherently frequency adaptive and they are simple to design [21]. This kind of controllers can be tuned automatically when the device starts working [22]. However, changes in the load during operation can make the system unstable, so the controller must be turned off, retuned, and then switched on again. Another alternative to tackle harmonics in a SeAPF based on the Discrete Fourier Transform (DFT) is proposed by Le Roux et al. [23]. This controller provides accurate results and a detailed plant model is not required: only the frequency response of the plant at the harmonic frequencies is needed. A similar approach based on the DFT is proposed in [24], but for a DVR. Harmonic controllers can be avoided using fast analogue controllers [25]. However, analogue controllers are less versatile for practical applications than microprocessor-based controllers. All the algorithms explained before require an accurate model of the plant before they start working. This is a clear drawback for a SeAPF since the load is usually unknown and, even worse, it can be non-linear and change over time. To overcome this problem, an alternative is to use an open-loop control algorithm [26]. This choice is very common in SeAPFs because stability can be easily guaranteed. However, zero steady-state error cannot be achieved.

This paper proposes a control algorithm to deal with harmonics for plants with unknown dynamics. This controller does not assume control of fast dynamics, which are tackled with the main controller. The proposed controller will be called Steady-State Space-Vector-Based Harmonic Controller (or SVB controller, for short) and it is similar to a MRF controller. However, it is applied using a slow sampling period to make sure that the plant reaches its steady state each time a new command signal is applied. This will make possible to estimate the steady-state response of the plant during each sampling period in order to ensure closed-loop stability. This does not mean that a model of the plant is not required at the design stage because, clearly, the controller and the device must be properly sized. However, it will be shown that thanks to the adaptability of the SVB controller a series compensator can be applied to eliminate voltage harmonics (working as a DVR) or current harmonics (working as a SeAPF) without prior knowledge of the load dynamics and without changing the control system. In addition, it will be shown that this controller can provide reasonable transient responses despite the fact that it is implemented with a slow sampling period. All the proposals in the paper are tested on a 5 kVA prototype of a series compensator.

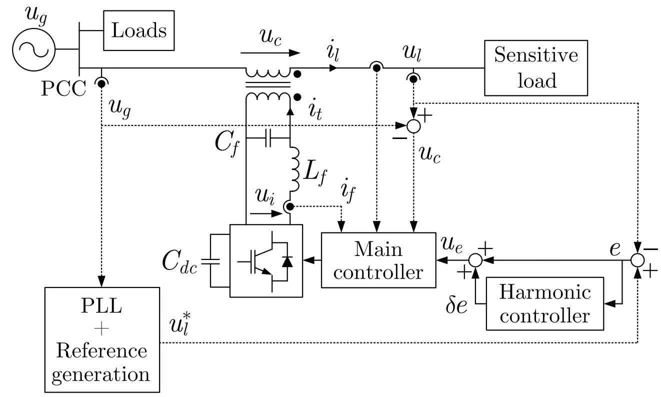


**Fig. 1.** Single-phase schematics and control system for a series compensator working as a DVR.

This paper is organized as follows. Section 2 describes the principles of series compensators. The SVB controller structure and the plant modelling are explained in Section 3, which is followed in Section 4 by the design procedure and a stability analysis. Section 5 discusses the plant model identification required to apply the SVB controller. Section 6 describes the practical application of the SVB controller for a series compensator and experimental results are given in Section 7. Section 8 provides the conclusions of this paper.

## 2. Series compensator principles

A series compensator working as a DVR is depicted in Fig. 1. The device is connected in series with a distribution line using a coupling transformer and an *LC* filter ($L_f$ and $C_f$). The DC capacitor of the VSC is called $C_{dc}$. Space vectors are marked with a right arrow over the variable name (e.g. $\vec{u}_l(t) = u_{l-d}(t) + ju_{l-q}(t)$), where subscripts $d$ and $q$ stand for direct axis and quadrature axis, respectively. Park's transformation is used to model the electrical system based on a reference frame that rotates synchronously with the $d$-axis component of the grid voltage space vector ($\vec{u}_g$). The reference frame is chosen to force $u_{g-q} = 0$, so $\left|\vec{u}_g\right| = u_{g-d}$. Therefore, a set of decoupling equations is required to decouple the $d$- and $q$-axis dynamics [24,27].

Fig. 2 shows how a series compensator can be controlled to maintain the fundamental value of the load voltage constant and (a) supply a clean voltage to a sensitive load (DVR) or (b) block current harmonics generated by non-linear loads (SeAPF) (only the $d$-axis is shown). When the device is working as a SeAPF the load-voltage waveform must be distorted to eliminate current harmonics and the way in which this may affect the load has to be assessed in each application. In both cases, a state-feedback controller is used for the main controller to control the load voltage ($u_l$) and to damp the *LC* filter resonance. The main controller deals with the fundamental component of the load voltage, rapidly, while the harmonic controller is in charge of eliminating steady-state harmonic distortion [15].

## 3. SVB controller and plant modelling

### 3.1. SVB controller overview

Fig. 3 portrays the block diagram of the SVB controller. The controller has two sampling periods: a fast one and a slow one. The fast one is similar to the one used for the rest of the control system and it will be called $t_s$. The slow one is an integer multiple of the fast one and it is equal to a period of the algorithm used to

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