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Troubleshooting a digital repetitive controller for a versatile dynamic voltage restorer

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ABSTRACT

Voltage sags and swells, voltage harmonics and voltage imbalances in power systems may affect sensitive loads causing production interruption or equipment damage. Nowadays, series voltage compensation using power electronics devices is a promising solution for these problems and the design, control and application of this type of devices have drawn much attention in the literature. Comprehensive controllers for Dynamic Voltage Restorers (DVR's) have already been proposed to tackle all those problems simultaneously with promising simulation results. However, several implementation aspects need closer attention and are addressed in this paper. The proposed controller is divided into a main one and an auxiliary one. The former is based on a state-feedback controller to achieve a fast transient response when voltage sags occur. The latter uses a repetitive controller to improve steady-state reference tracking and disturbance rejection in order to tackle harmonic and imbalance problems. This paper focuses on the repetitive-controller part. Firstly, the full digital implementation of the controller is presented. Secondly, a new method to improve the repetitive controller performance with small frequency deviations in the grid is discussed. Thirdly, strategies to avoid internal instability problems not detected in the previous literature are studied. Finally, the main contributions of the paper are tested on a 5 kVA prototype.

1. Introduction

The importance of power quality has risen considerably in modern electric power systems due to the increase of the number of sensitive loads. A great deal of power quality disturbances in modern power systems are of the voltage-quality type and, among them, the best known problems are voltage sags and swells, voltage harmonics and voltage imbalances. These problems may affect the end user leading to production downtime and, in some cases, equipment terminal damage [1].

Voltage sags are normally caused by short-circuit faults in the power network [2] or by the starting of large-rating electric motors [1,3], and they cause the disconnection of sensitive equipment, distributed generators and industrial processes with important economical losses. Voltage harmonics are produced by non-linear equipment such as arc furnaces and diode or thyristor rectifiers. They may produce pulsation torques in large electric motors, extra iron losses in electric rotating machines and extra copper losses in the whole system.

A Dynamic Voltage Restorer (DVR) is a power electronics device conceived to restore the voltage waveform when a voltage sag occurs. This will protect sensitive loads and should improve fault ride-through capability of distributed generators, such as wind or solar plants [4]. On the other hand, a Series Active Power Filter (SeAPF) is conceived to suppress voltage harmonic distortion [5]. Both devices share the same basic hardware consisting of an electronic voltage source converter (VSC), a constant DC-link voltage, an AC filter and a coupling transformer which is series connected in the line. Therefore, it is reasonable to think that the same device (to be called here Series Active Conditioner or SAC, as suggested in [5]) can be controlled so that voltage sags, voltage imbalance and voltage harmonics can be compensated simultaneously at the point of connection of a sensitive load. In fact, a comprehensive controller to tackle all those voltage-quality problems has already been proposed and simulated using a continuous-time approach in ideal circumstances [1,6]. The proposed controller is based on a fast main controller to restore the load voltage in case of a voltage sag, and an auxiliary controller, to mitigate harmonic distortion. The auxiliary controller proposed there is of the so-called repetitive-controller (RC) type which can tackle an undetermined number of harmonics simultaneously within the bandwidth designed.

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While the main controller implementation has been deeply studied in the literature [7,8], the auxiliary one still requires further work. For example, such a controller is bound to be applied in a microprocessor using discrete-time-based algorithms and some implementation issues must now be addressed [9].

Digital repetitive controllers have shown good performance in power electronics applications but have some considerable drawbacks. First of all, they require exact knowledge of the grid frequency at the design stage so that the sampling period can be chosen to make sure that the grid period is an exact multiple of the sampling period. Under this condition, the grid magnitudes (current and voltages) can be sampled synchronously. However, the growing number of grid-connected renewable energy sources [10] together with the deregulation of electrical-energy markets [11], are creating conditions which are amenable for widespread frequency fluctuations. Frequency oscillations may be even larger in isolated grids [12] and in micro-grids. The second relevant problem of RC's in a SAC application is the interaction between the often-used series-coupling transformer and the RC. As shown later, the controller cancels a zero of the plant due to the transformer with an unstable pole and the closed-loop system cannot be internally stable. This means that, even if the closed-loop transfer function from the reference voltage to the output voltage is stable, there might be at least one input-to-internal-variable closed-loop transfer function in the system which is unstable [13–15]. This problem did not show either in [1] or in [6] because the simulation was run for a short time and ideal measuring devices were used.

In spite of the drawbacks mentioned, the comprehensiveness of the above controller is very attractive and has not been challenged so far. For example [16], proposes a hysteresis-band controller for a DVR which can be used to protect low-power devices from voltage sags but cannot deal with supply voltage harmonics efficiently and [17] simulates a control scheme for a DVR using a phasor-based load voltage controller but cannot address harmonic problems, either. A detailed analysis of PID controllers for DVR's is presented in [18] for low-power devices but the harmonic problem is also overlooked. As a novel contribution of this last reference, however, it is worth mentioning that they provide independent control for each phase with galvanic isolation in the DC link and the internal instability problem does not arise.

Novel solutions for the above-mentioned major drawbacks and some other implementation issues for the application of RC's will be addressed in this paper in the context of a Series Active Conditioner (with DVR and SeAPF capabilities). First of all, the control algorithm will be formulated in discrete time (main and auxiliary). Secondly, the grid frequency will not be considered strictly constant in order to open the application of such a controller to isolated or weak systems. The effects of frequency variations will be illustrated in, both, the main and the auxiliary controllers. Since many algorithms for grid-frequency estimation already exist [19,20], it will be accepted that the grid frequency can deviate from the design value but it can be estimated during operation so that the repetitive controller can be adapted. It will also be considered that frequency variations, if any, will be much slower than the repetitive control dynamics. This approach is different to the one in [21] where a DVR was controlled so that the critical load to be protected did not see the frequency variations of the grid. Thirdly, the internal instability problem in the RC will be presented. It will be shown in the paper that the use of the coupling transformer may, in fact, impair the closed-loop stability of the system and, hence, effective solutions will be discussed and compared. All the proposals of this paper have been tested on a 5 kVA prototype.

2. SAC control and modelling

2.1. Control scheme

A proposal for a SAC is depicted in Fig. 1. Different types of loads are assumed to be connected to the point of common coupling (PCC) which may be affected by voltage disturbances. The SAC is connected between the PCC and the sensitive load and its primary function is to supply constant and undistorted voltage (u_l) to the sensitive load in spite of the voltage disturbances at the PCC (sags, harmonics, etc.). This goal is achieved controlling the injected voltage u_c. Therefore, the injected voltage is measured and compared with an ideal voltage reference, called u_c^*, which is calculated depending on the voltage-compensation method to be used [22]. In this paper the so-called minimum power compensation method for DVR's will be used, and this means that the series injected voltage is calculated to minimise the power required by the SAC to restore the load voltage. In addition, the PCC voltage harmonics are compensated so that they do not reach the load. The compensating device is based on a PWM voltage-source converter (VSC) with a DC capacitor (C_{dc}) and a diode rectifier that provides the required power in case of voltage sags. With this topology, it is possible to compensate shallow voltage sags without energy storage [23].

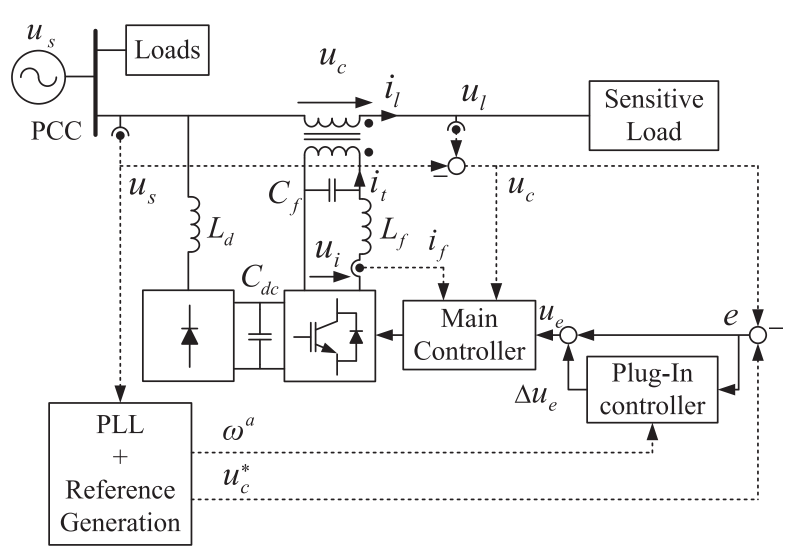

Fig. 1. Proposed set-up and controller for a Series Active Conditioner.