Periodic and non-periodic disturbance rejection techniques for an advanced 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. Now-a-days 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 Restores (DVR's) have already been proposed to tackle all those problems simultaneously, although several aspects need closer attention. This paper addresses several implementation issues for a discrete-time algorithm to control a three phase advanced DVR. The 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. The latter, where this paper is focused, uses a repetitive controller to improve precision in reference tracking and disturbance rejection in order to tackle harmonic and imbalance problems. Firstly, a method to improve the repetitive controller performance with small frequency deviations in the grid is presented. Secondly, the classical repetitive controller is modified so that the response to non-periodic disturbances is improved. Finally, the main contributions of the paper are illustrated by simulation using a test system built with SIMULINK and its PowerSim toolbox.**

I. INTRODUCTION

Modern equipment used in industry is often based on microprocessors and other complex devices and it is necessary to guarantee high quality input power to ensure correct operation. Most common power quality problems are of voltage-quality type, such as voltage sags and swells, but also voltage harmonics and voltage imbalances are frequent [1]. In many cases voltage disturbances result in shutdowns, loss of production and, hence, a major cost burden [2]. The most common voltage sags are due to faults in the power distribution network, but other reasons like induction motor starting or capacitor switching are also reported in the literature [1], [3]. Voltage sags can have a duration between half a cycle and a few seconds, depending on the type of sag and the clearing time of the protection systems. Voltage harmonics are produced by transformer saturation and non-linear loads such as diode or thyristor rectifiers [4].

A Dynamic Voltage Restorer (DVR) is a power electronics device conceived to restore the voltage waveform when a voltage sag occurs while a Series Active Power Filter (SAPF) is conceived to suppress voltage harmonic distortion. Both devices share the same basic hardware equipment 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 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 [5] and [6]. The controller proposed there is of the so-called repetitive-controller (RC) type. However, such a controller is bound to be applied in a microprocessor using discrete-time-based algorithms and some implementation issues must now be addressed.

RC's require exact knowledge of the grid period at the design stage so that the sampling period can be chosen to make sure that the former period is an exact multiple of the latter. However, the growing number of grid-connected renewable energy sources [7] together with the deregulation of electrical energy markets [8], are creating conditions which are amenable for widespread frequency fluctuations. Frequency oscillations may be even larger in isolated grids [9].

RC's use the actual error to eliminate periodic disturbances one cycle later. When a non-periodic disturbance takes place (e.g. a voltage sag), the controller will use the actual error (which is not periodic) to cancel periodic disturbances in the next cycle, producing an effect called "repetition" which has been reported in many applications where periodic and non-periodic disturbances appear simultaneously [10], [11].

This paper focuses on the implementation of a RC for a series electronic compensator for a power line with DVR and SAPF capabilities. The control algorithm will be formulated in discrete time and the computation time will be taken into account from the beginning. Besides, the grid frequency will not be considered strictly constant in order to make the controller also applicable to isolated or weak systems. Since many algorithms for grid-frequency estimation already

$$C_o(s) = \frac{e^{-t_p s}}{1 - e^{-t_p s}} \tag{3}$$

B. Discrete time formulation

In most power electronics applications presented in the literature, the RC has been implemented digitally as a "plug-in" controller (see Fig. 3) with a sampling period t_s so that $N = t_p/t_s \in \mathbb{N}$. In that case, the discretisation of $C_o(s)$ can be done changing $e^{-t_p s}$ to z^{-N} [4].

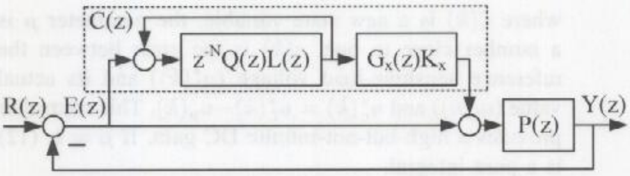

Fig. 3. Implementation of a plug-in repetitive controller

In Fig. 3 $C(z)$ is the discrete-time RC and $P(z)$ is the basic servo plant. The transfer function $G_x(z)$ and the gain K_x are used to achieve closed-loop stability, and $Q(z)$ is used for limiting the bandwidth. The transfer function $L(z)$ is not often used in the literature but it is included in this analysis because it will be used in subsequent sections for frequency adaptation and it is an important contribution of this paper. It can be shown that, if $G_p(z)$ calculated as:

$$G_p(z) = \frac{P(z)}{1 + P(z)} \tag{4}$$

is stable, a sufficient condition for stability of the RC is [4]:

$$\max\left\{|z^{-N}Q(z)L(z)||1 - K_x G_x(z) G_p(z)|\right\} < 1 \tag{5}$$
$$\text{with } z = e^{j\omega t_s} \text{ for all } |\omega| < \frac{\pi}{t_s}$$

The importance of a well-designed main controller has to be emphasised here because $G_p(z)$ is the main loop mentioned before. To simplify (5) $G_x(z)$ can be chosen, with an estimation of the basic servo plant $\hat{P}(z)$, as:

$$G_x(z) = \hat{G}_p^{-1}(z) = \left[1 + \hat{P}(z)\right] / \hat{P}(z) \tag{6}$$

C. Implementation problems

The implementation of a RC in a system such as the one in Figure 1 brings several problems. First of all, in weak and isolated systems, the grid frequency could have slow variations during the day and, if the actual grid frequency is not exactly equal to the design frequency, the RC performance deteriorates. Fundamental-frequency variations in RC's have been addressed in two ways, so far. In [17] a higher-order RC (HORC) is proposed while a multi-rate RC is used in [18]. The HORC is robust against frequency variations, but it has a poor stability margin, it requires more memory allocation and it shows a much longer transient response than the conventional RC. A multi-rate RC is difficult to implement, it tends to produce inter-harmonic distortion and the stability is not easy to study. The proposal of this paper is a simple addition to the conventional RC and does not affect the dynamic performance or the stability margins.

Secondly, the RC can track or remove periodic signals but, when a non periodic disturbance appears, the RC takes a couple of periods to forget it and the transient response deteriorates. A solution to improve the RC performance with non-periodic disturbances is presented in [11] but this paper implements a simpler form with good performance.

Finally, even if the coupling transformer for series compensation is often modelled as a simple leakage inductance, it also acts as a DC filter due to the often-unmodelled magnetising inductance. Unfortunately, a conventional RC has an infinite DC gain and this coincidence makes the closed-loop system internally unstable when using a conventional RC with a transformer in the actuator. In order to make the application of a RC possible, a DC removal system has to be used in $C(z)$ [19].

IV. Adaptive Repetitive Controller

A. Frequency adaptation method

Even if the control sampling period t_s was designed so that it was contained an integer number of times within the grid period t_p, the latter may change during operation and the ideal condition will not be met any longer. In this case, $t_p = Nt_s + l_e t_s$, where $N \in \mathbb{N}$ and $l_e \in (0, 1)$. If, as mentioned in Section I, the grid frequency is estimated (giving ω^d in Fig. 1), l_e can be calculated and (3) can be written as:

$$C_o(s) = \frac{e^{-Nt_s s} e^{-l_e t_s s}}{1 - e^{-Nt_s s} e^{-l_e t_s s}} \tag{7}$$

The discretisation of (7) can be carried out in two steps:

1) The delay consisting of an integer number of sampling periods can be represented exactly by z^{-N}.
2) The rest of the delay in (7) can be approximated by a first-order Pade's approximation:

$$e^{-l_e t_s s} \approx \frac{1 - \frac{t_s l_e}{2} s}{1 + \frac{t_s l_e}{2} s} \tag{8}$$

which can be discretisied using Tustin's approximation, yielding $L(z)$:

$$s = \frac{2}{t_s}\frac{z-1}{z+1} \implies L(z) = \frac{(1 - l_e) + (1 + l_e) z^{-1}}{(1 + l_e) + (1 - l_e) z^{-1}} \tag{9}$$

Interpolation to tackle a non-integer number of sample periods in the reference or disturbance period was already proposed in [19] but with a different formulation which did not preserve stability. With the proposal of this paper, the stability condition in (5) is not modified, as long as $|L(e^{j\omega t_s})| = 1\ \forall\omega$. The frequency adaptation method is depicted in Fig. 4. Once the estimated grid frequency (ω^a) is known, the parameters N and l_e are computed and updated in $L(z)$ and z^{-N}.

B. Non-periodic disturbance rejection techniques

Let's assume that it is possible to detect a non-periodic disturbance (a voltage sag, for example) in n_d samples and that the transient response of the inner closed-loop system takes n_t samples to vanish. In order to free the RC of the transient a

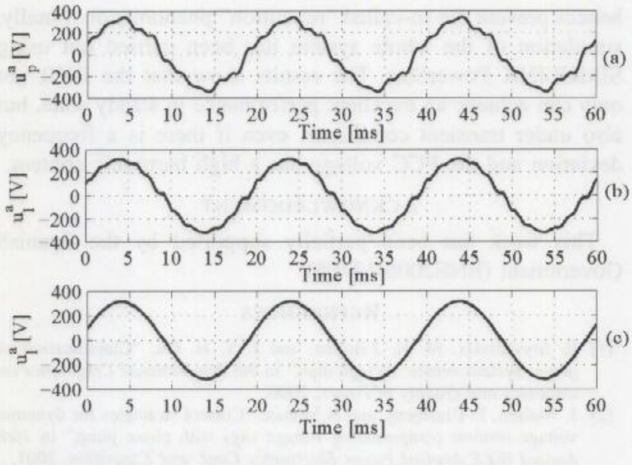

Fig. 6. Steady-state voltage at (a) the PCC and across the sensitive load using non-adaptive controller (b) and adaptive controller (c).

$L = 50$ mH. The sensitive load consists of a linear load of $R_l = 3\ \Omega$ and $L_l = 50$ mH.

The SVComp has a 2-level 3-leg IGBT-based VSC with 650 V DC voltage. The SVComp uses a 20-kVA coupling transformer with a unity turns ratio and a star-connected VSC-side winding with $R = 0.3\ \Omega$ and $L = 6$ mH. The filter capacitor value is $C_f = 1.05\ \mu$F giving a cut-off frequency of the filter of 2 kHz. The inverter switching frequency and the sampling frequency have been made equal to 5 kHz. In addition, the state-feedback controller in Section V-A has been designed so that the closed-loop poles are in Butterworth configuration with module equivalent to 2 kHz while $\mu = 0.98$ for the low frequency pole of the controller.

B. Repetitive-controller parameters

The low-pass filter $Q_{lp}(z)$ is designed as a sinc FIR filter [4] while $\lambda = 0.9999$ is used in $Q_{hp}(z)$ and $K_x = 1$. For the design (nominal) frequency, $N = 100$ and $l_e = 0$, but the frequency deviation forces $N = 99.5$ and $l_e = 0.5$. To improve non-periodic transient performance $n_t = 7$ and $n_s = 7$, making $D = 14$. To obtain the load voltage reference signal $u_l^*(t)$ and the mains frequency ω^a, a PLL is used as in [13]. The non-periodic events are detected by the PLL when a change in $|u_p|$ space-vector occurs.

VII. Simulation Results

A. Steady state performance

Fig. 6 (a), shows the line-to-neutral voltage at the PCC. The supply is balanced but is polluted with harmonics. Fig 6 (b) and (c) show the line-to-neutral voltages at the sensitive load using a RC with and without frequency adaptation, respectively. FFT results of these waveforms, at key frequencies, are depicted in Fig. 7. Clearly, the RC tracking performance improves using $L(z)$.

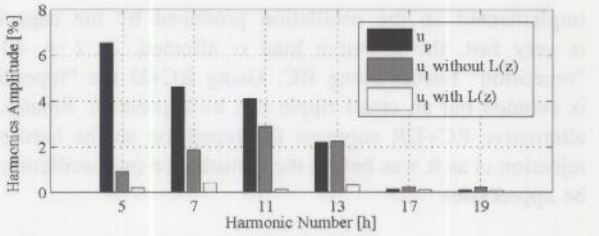

Fig. 7. Harmonic content of Fig. 6 (a), (b) and (c).

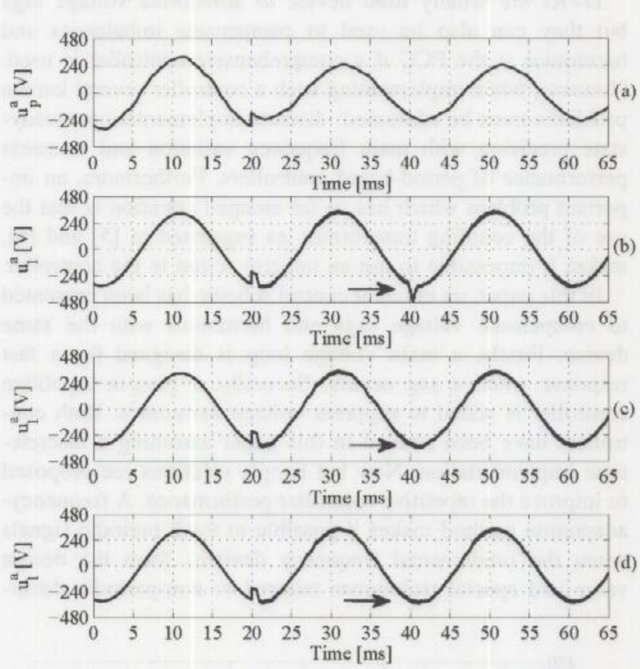

Fig. 8. PCC voltage when a fault occurs at the PCC (a) and load voltage using RC (b), RC+D (c) and RC+DR (d)

B. Transient performance

Fig. 8 (a) shows the line-to-neutral voltage at the PPC when a fault occurs at the PCC, causing a sag at $t = 20$ ms. The harmonic amplitudes of the supply voltage at the PCC have been reduced with respect to Fig. 7, in order to appreciate the "repetition" phenomenon. Figs. 8 (b), (c) and (d) shows the line-to-neutral sensitive-load voltage using RC, RC+D and RC+DR respectively. When the sag occurs, the load voltage is restored by the main voltage controller. As the controller is digitally implemented, some samples are required to compensate the voltage sag. At $t = 40$ ms "repetition" occurs using RC, but not with RC+D and RC+DR.

Fig. 9 (a) shows the line-to-neutral voltage at the PPC when a capacitor bank is connected at the PCC, causing a transient oscillation at $t = 20$ ms. The harmonic amplitudes of the supply are as in Fig. 8. Figs. 9 (b), (c) and (d) show the line-to-neutral sensitive-load voltage using RC, RC+D and RC+DR respectively. When the sag occurs, the load voltage is restored by the main voltage controller. As the controller is digitally