Control of Dynamic Voltage Restorers Using a Fully-Configurable Digital Estimation Technique

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Abstract

Dynamic Voltage Restorers (DVRs) allows the compensation of voltage disturbances which could affect sensitive loads as variable speed drives.

Different techniques have been proposed to establish the instantaneous output voltage of the DVR but, in most cases, these controllers only can compensate a kind of voltage disturbance.

This paper proposes a new digital controller for DVRs with the capability of compensate simultaneously voltage dips, over-voltages and voltage harmonics without change the controller structure.

Keywords: Dynamic voltage restorer, voltage dips, over-voltages, voltage harmonics.

1. Introduction

The effects of voltage dips, over-voltages and voltage harmonics on electric loads can be mitigated using DVRs. The general structure of a DVR can be seen in figure 1 where the it is connected to the sensitive load through an injection transformer [1]. The energy storage can be a group of batteries or a DC capacitor filtering the output of a diode rectifier conected to the electrical grid. The power converter switches at high frequency generating a PWM output voltage waveform which must be low-pass filtered (L_F, R_F and C_F) before arrive to the injection transformer. Switches S_1, S_2 and S_3 control the compensation status of the DVR [2].

The structure of the controllers applied to DVRs varies but in general, it can be divided in two fundamental blocks: the generation of the reference signal for the voltage injection, measuring the source (V_S) or the load voltage, and the control of the output voltage to ensure that it corresponds to the reference signal, which considers the state variables in the LPF (I_F and V_F).

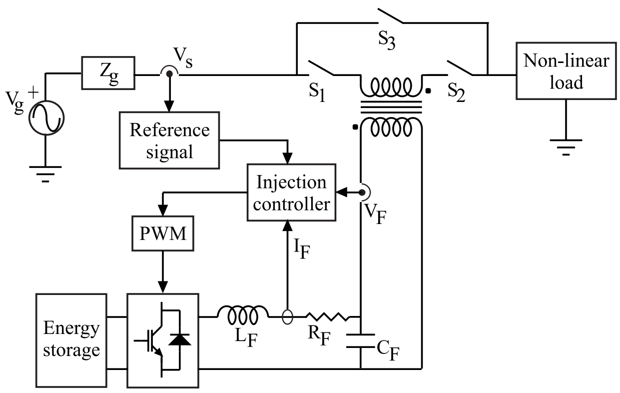

Fig. 1. Hardware structure of a DVR

The second block can be implemented in three ways. Feedback structures allow a good stationary response while forward structures generate quick responses during voltage transients. Feed-forward strutures allows both behaviours being more used [3]. The generation of the reference signal depends strongly on the compensation objectives: voltage dips, over-voltages or voltage harmonics. The rms value of the grid voltage can be measured to detect voltage dips and over-voltages, once detected, the PLL used to synchronize the compensation signal must be frozen (not applied to the voltage signal) to maintain the previous phase. When the load voltage harmonics are the compensation objective, a repetitive controller can be applied to mitigate the effect of all voltage harmonics [3]. In this case the reference signal is generated inside the voltage controller and doesn't allow selective harmonic compensation, both in harmonic order and harmonic magnitude.

Previously proposed methods for the control of DVRs operate in the time domain or in the frequency domain. Time domain methods have a fast dynamical response but don't allow the selective compensation of voltage disturbances. Methods based on the FFT allow the selection of the voltage disturbance to be compensated but have a slow dynamical response. This paper proposes a new digital technique which operates in the time and frequency domains, allowing selective compensation with fast dynamical response.

2. Proposed Estimation Technique for the Generation of the Reference Signal

The structure of the proposed algorithm can be seen in figure 2. A stationary frame discrete Kalman filter obtains the amplitudes V_i of each voltage harmonic component [4]. These voltage harmonic components are used to establish the presence of a voltage disturbance comparing the measured values and the established operation values. Voltage dips and over-voltages are detected using the grid voltage fundamental harmonic component, the amplitudes of other measured voltage harmonic components are measured to establish the presence of harmonic distortion to be compensated. Once the DVR is switched-on using S_1, S_2 and S_3, harmonic references $V_i^*(k)$ are obtained as difference of the measured voltage harmonic components and the desired ones.

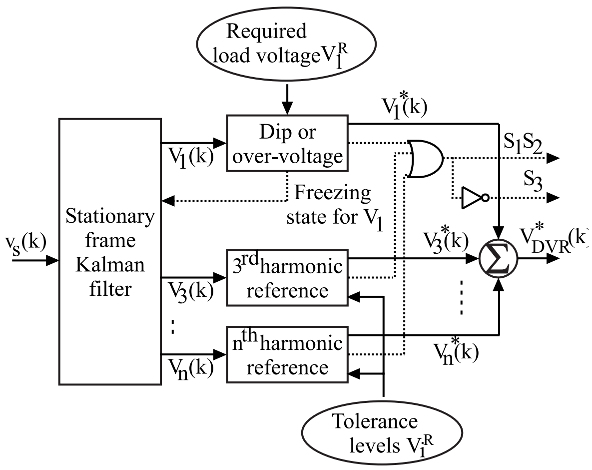

Fig. 2. Reference voltage estimator

The discrete Kalman filter uses a stationary frame voltage signal model, then, each voltage harmonic component at time instant k can be described as:

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{w}_k \quad (1)$$

Being:

$$\mathbf{x}_k = \begin{pmatrix} V_{1\alpha} \\ V_{1\beta} \\ \vdots \\ V_{n\alpha} \\ V_{n\beta} \end{pmatrix}_k \quad \mathbf{A} = \begin{pmatrix} M_1 & 0 & \cdots & 0 \\ 0 & \ddots & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & M_n \end{pmatrix} \quad (2)$$

Where $V_{i\alpha}$ and $V_{i\beta}$ correspond respectively to the in-phase and the in-quadrature components of the fundamental frequency voltage harmonic of order i, $\mathbf{w}_k$ is the signal model noise vector and $\mathbf{M}_i$ is defined as:

$$\mathbf{M}_i = \begin{pmatrix} \cos(i\omega T_s) & -\sin(i\omega T_s) \\ \sin(i\omega T_s) & \cos(i\omega T_s) \end{pmatrix} \quad (3)$$

Being ω the angular frequency of the fundamental grid voltage harmonic component and T_S the sampling time of the proposed discrete algorithm.

The applied recursive discrete Kalman filtering loop corresponds to equations [5]:

$$\mathbf{P}_{k|k-1} = \mathbf{A}\mathbf{P}_{k-1|k-1}\mathbf{A}^T + \mathbf{Q}_{k-1} \quad (4)$$

$$\mathbf{G}_k = \mathbf{P}_{k|k-1}\mathbf{C}^T\left(\mathbf{C}\mathbf{P}_{k|k-1}\mathbf{C}^T + \mathbf{R}\right)^{-1} \quad (5)$$

$$\mathbf{P}_{k|k} = (\mathbf{I} - \mathbf{G}_k\mathbf{C})\mathbf{P}_{k|k-1} \quad (6)$$

$$\hat{\mathbf{x}}_{k|k-1} = \mathbf{A}\hat{\mathbf{x}}_{k-1|k-1} \quad (7)$$

$$\hat{\mathbf{x}}_{k|k} = \hat{\mathbf{x}}_{k|k-1} + \mathbf{G}_k\left(v_{Sk} - \mathbf{C}\hat{\mathbf{x}}_{k|k-1}\right) \quad (8)$$

Where $\mathbf{P}_{k|k+1}$ is the estimation of process covariance matrix at time instant k using its value at time instant k-1, $\mathbf{Q}_{k-1}$ is the variance matrix associated to vector $\mathbf{w}_k$, $\mathbf{G}_k$ is the Kalman gains matrix at time instant k, vector **C**, using this signal model, is defined as:

$$\mathbf{C} = \begin{pmatrix} 1 & 0 & \cdots & 1 & 0 \end{pmatrix} \quad (9)$$

R is the variance matrix of the voltage measurement error and $\hat{\mathbf{x}}_{k|k-1}$ is the prediction of voltage harmonic components in the stationary frame αβ at time instant k using the estimation at time instant k-1 $\hat{\mathbf{x}}_{k-1|k-1}$.

The amplitude of the fundamental voltage harmonic component at instant k is evaluated as:

$$V_1(k) = \sqrt{V_{1\alpha}^2(k) + V_{1\beta}^2(k)} \quad (10)$$

which is compared with the required load voltage. When a voltage dip or over-voltage is detected the recursive Kalman filter is frozen at the fundamental frequency and the described filtering loop is reduced to eq. 7 at the fundamental harmonic component, using previously buffered values of $V_{1\alpha}(k)$ and $V_{1\beta}(k)$. The compensation reference signal at the fundamental frequency is obtained as:

$$V_1^*(k) = \frac{V_1^R - V_1(k)}{V_1^R} V_{1\alpha}(k) \quad (11)$$

where V_1^R is the required load voltage amplitude. The compensation references for higher order harmonic components of $v_s(k)$ are only applied when the established tolerance levels are reached. These signals are obtained as:

$$V_i^*(k) = \frac{\sqrt{V_{i\alpha}^2(k) + V_{i\beta}^2(k)} - V_i^R}{\sqrt{V_{i\alpha}^2(k) + V_{i\beta}^2(k)}} V_{1\alpha}(k) \quad (3)$$

where V_i^R is the tolerate amplitude of the voltage harmonic of order i>1.

Finally, the complete compensation reference signal at instant k can be obtained using:

$$V_{DVR}^{*}(k) = \sum_{i=1}^{n} V_i^{*}(k) \qquad (4)$$

Where each $V_i^*(k)$ depends on the established tolerance level V_i^R**,** allowing the selective compensation of voltage disturbances

3. Simulation Results

The proposed algorithm has been tested in simulation, using the SimPowerSystems BlockSet from MatLab, according to figure 1.

The reference estimation technique has been applied using a sampling time of T_S=156 µs and the grid voltage signal has been modeled using 1st, 3rd, 5th, 7th and 9th voltage harmonics, which correspond to the usual grid voltage harmonic content.

The DVR has been modeled using a power converter with 400Vdc and a low-pass filter with L_F=3 mH, R_F=1.0 Ω and C_F=230 µF. The nominal power of the injection transformer is 12 kVA with a primary and magnetization impedances of L_1=0.17mH, R_1=35mΩ, L_m=252mH and R_m=80Ω. The source voltage contains a 50Hz 325 V signal and a 5th harmonic of 5%.

A diode rectifier with a RC load (C_L=1000µF, R_L=500Ω) has been used as protected load. The obtained simulation results when the distorted grid voltage is applied can be shown in figure 3. The voltage dip is applied at t=100 ms being the voltage amplitude reduced to 195 V. The response time, including the voltage dip detection time and the controller response, is less than one cycle at the fundamental frequency which confirms the appropriate behavior of the proposed DVR control technique for the compensation of voltage dips.

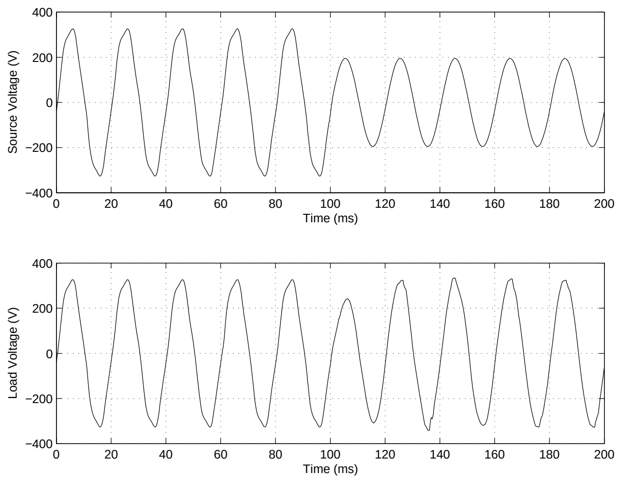

Fig. 3. Source and load voltage waveforms for a 40% voltage dip

Figure 4 shows the obtained simulation results when a 30% over-voltage is applied at 100 ms. As it can be seen, once the over voltage is detected, the DVR acts reducing the load voltage amplitude to the load nominal voltage and the dynamical response takes 30 ms. This demonstrates that the proposed controller allows a properly compensation of over-voltages.

Finally, the voltage harmonic compensation capability of a DVR controlled using the proposed estimation reference technique is shown in figure 5. A grid voltage (v_s) with a 5% of 5th harmonic component is applied.

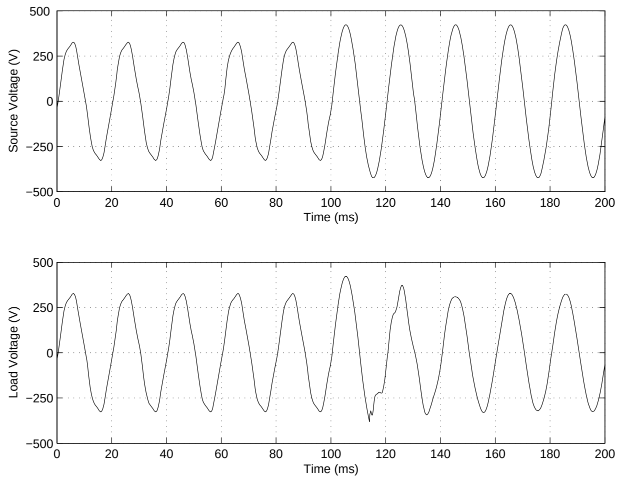

Fig. 4. Source and load voltages when a 30% over-voltage is applied

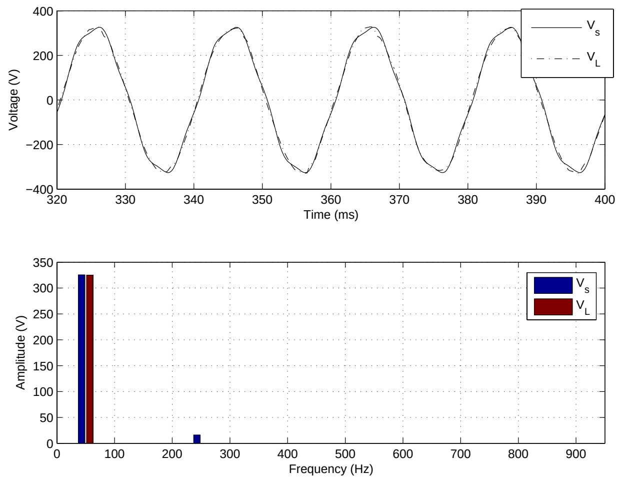

Fig. 5. Source and load voltage waveforms and spectra for the 100% compensation of the 5th voltage harmonic.

The tolerance level for the 5th voltage harmonic (V_5^R) is fixed to 0 V for fully compensation. Obtained results show that the proposed control technique allows the 100% mitigation of the 5th voltage harmonic component.

4. Conclusions

A new digital control technique which applies a discrete Kalman filter to generate the compensation reference signal in DVRs has been presented and tested in simulation.

The structure of the proposed reference voltage estimator allows the compensation of voltage dips, over-voltages and voltage harmonics simultaneously. Moreover, the disturbance compensation degree can be fixed allowing a more flexible operation.

Obtained simulation results allow to establish the appropriate dynamical and steady-state responses of the proposed estimation technique applied to DVRs.

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