HARMONIC VOLTAGE COMPENSATION FOR SINGLE PHASE POWER SYSTEMS

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Abstract

In this paper the problem of improving the power quality for single phase power systems is approached. It is considered the particular case of voltage utility distortion due to the presence of a nonlinear load that generates some voltage harmonics in the network. The proposed solution includes a full-bridge serial voltage active filter equipped with a control law that guarantee, besides global internal stability, perfect cancellation of a pre-specified harmonic. The usefulness of the proposed controller is validated via digital simulations (carried out with the Power Systems Blockset of MATLAB) that incorporates at a large extent the actual behavior of the circuit. In addition of the validation of the theoretical properties, the problem of obtaining high performance in spite estimation instead of measurement of the harmonics was also studied. In this case the load voltage was re–constructed by computing its Fourier series and this (estimated) information was fed back to the controller. The remarkable results was also illustrated with digital simulations.

1 Introduction

Due to the increased use of nonlinear loads, power systems operation has been affected by the appearance of undesirable dynamics (basically current and voltage harmonics) leading to a remarkable deterioration of the power quality. As a result, in the last decades several solutions have been proposed with the aim to compensate these distortions in the electrical variables, including the use of static (passive) filters. In this sense, one alternative that has obtained best results is the use of power electronic devices to implement inverter-based converters whose main objective is to try to cancel the undesirable behavior by properly injecting current (or voltage) signals of the same magnitude but opposite sign of the harmonics. These devices are called parallel (or serial) active filters [1].

Although the operation of active filters is conceptually simple, its implementation establishes a challenge. Besides the problems involved with power electronics, which at a large extent have been overcome due to the outstanding development of the semiconductor technology, it can be identified two main concerns: The first one is related with the requirement of measuring, identifying and processing the quite fast undesirable harmonics dynamics. The second is related with the control algorithm used to operate the converter in order to generate the proper (fast changing) current (or voltage) canceling signals.

In this paper the high performance control problem for a single–phase serial active filter is approached, i.e. the voltage harmonic compensation problem for single–phase power systems is studied. The main contribution is the evaluation, with filtering purposes, of a controller that has been previously evaluated for Uninterruptible Power Supply applications [2]. This controller is of the passivity-based kind [3], in the sense that for its design the energy–dissipation properties of filter have been exploited, and its usefulness comes from the following properties: Simple structure, facility for tuning and programming, robustness with respect to low switching frequency, low dimension (and cost) of passive filter elements and uncertainty in the harmonics, and fast dynamic response. Moreover, as will be clear below, it is interesting to notice that although the results in this paper are concentrated (for ease of presentation) in the serial case, the controller can also be applied to solve the control problem of parallel (current compensation) active filters [4].

It must be pointed out that, although equally complex and important, the problem of harmonics processing is not addressed here. Instead of going into a deep study about this topic, what was done in order to evaluate the controller performance was to re–construct the signals to be compensated by computing the Fourier series components which correspond to the harmonic frequency that is desired to measure. This choice has a twofold justification: First, this technique is widely accepted by the engineering community as a reasonable solution to the harmonics measurement problem. Second, there are several drawbacks that can be identified in this approach (e.g. complex implementation, inaccuracy in the estimation of harmonic structure) that in our case were used as additional complications that the controller must deal with.

The paper is organized as follows: In section 2 the filter topology considered for the control law design is presented. The controller to be evaluated and its theoretical properties are presented in section 3. Two different simulation experiments (carried out by using Power Systems Blockset of MATLAB) of increasing complexity are illustrated in section 4. Section 5 closes the paper with some concluding remarks.

2 Problem formulation

The schematic diagram of the serial active filter considered in this paper is shown in Fig. 1. It is composed by a full-bridge DC–AC converter equipped with a LC filter and connected to the network via a current transformer[1]. Roughly speaking, the operation of this circuit can be explained as follows: The pair of switches S_1-S_4 and S_2-S_3 are complementarily turned on and off producing a square wave which is filtered by the L_fC_f filter. This filtered voltage signal is "injected" to the network, by means of the current transformer, in such a way that the final result is equivalent to add a new voltage source in series with the utility V_{line}. Assuming that the voltage in terminals of the nonlinear load can be decomposed as $V_{NL} = V_f + V_h$, where the first term is the fundamental component of the voltage wave while the second is the voltage contribution of the harmonics, the control objective can be stated as to produce, with the additional voltage source introduced by the filter, the signal V_h, leaving to the utility the generation of the (sinusoidal) component V_f.

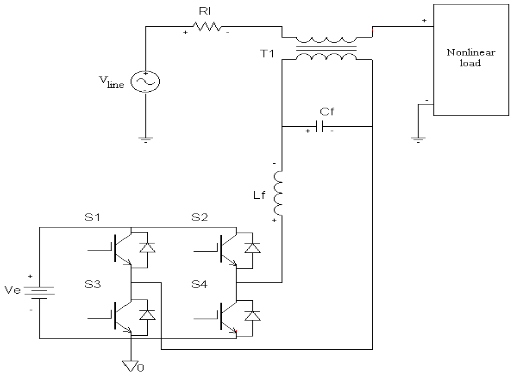

Figure 1: Schematic diagram of the half-bridge DC-AC converter

From a model–based perspective, the stated problem can be formalized if it is considered the widely accepted averaged dynamics of the circuit [6] represented by

$$L_f \dot{z}_1 = -z_2 + V_e \mu \tag{1}$$

$$C_f \dot{z}_2 = z_1 - \frac{1}{n^2 R_l} z_2 - \frac{1}{n R_l}\left(V_{NL} - V_{line}\right) \tag{2}$$

where $z_{1,2}$ are the inductance current and output capacitor voltage, respectively, n is the transformer coefficient, V_{NL} is the voltage in terminals of the load and $\mu \in (0,1)$ is the duty ratio function of a PWM circuit controlling the switches position in the converter.

Remark 1. Notice that model (1-2) can be written in matrix form as

$$\mathcal{D}\dot{z} + \mathcal{J}z + \mathcal{R}z = \mathcal{M}\mu + \psi \tag{3}$$

with

$$\mathcal{D} = \begin{bmatrix} L_f & 0 \\ 0 & C_f \end{bmatrix}; \quad \mathcal{J} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix};$$

$$\mathcal{R} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{n^2 R_l} \end{bmatrix}; \quad \mathcal{M} = \begin{bmatrix} Ve \\ 0 \end{bmatrix};$$

$$\psi = \begin{bmatrix} 0 \\ -\frac{1}{nR_l}\left(V_{NL} - V_{line}\right) \end{bmatrix} \qquad ,$$

where $\mathcal{J}$ is a skew-symmetric matrix.

Under these conditions, the control problem to be solved can be formulated in the following way

Problem formulation

Consider the serial active filter model given by (3) with measurable state z_1 and z_2. Design a control law μ such that

$$\lim_{t\to\infty} z_2 + nV_h = 0$$

where V_h is voltage contribution of the harmonics in the load terminals.

Remark 2. It is important to notice that the control objective is stated in such a way that the desired behavior for the output capacitor voltage is defined, on the one hand, considering the voltage applied in transformer port connected to the serial port and, on the other hand, taking into account that the purpose of the circuit is to cancel the voltage distortion produced by the harmonics, i.e. it is desired to inject this signal but with opposite sign.

Remark 3. It is evident from the problem formulation, that besides the challenge of designing the control law, an additional (important and complex) problem is the measurement or reconstruction of V_h. As pointed out in section 1, this problem is out the scope of this paper and a standard solution will be implemented in the validation of the proposed controller.

3 Controller design

In this section it is presented the proposed controller that solves the problem stated in the last section. To this end, it is necessary to introduce the following assumptions

[A.1] All the parameters involved in (3) are known.

[A.2] The utility voltage V_{line}, the voltage in terminals of

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[1] This topology is well-known in the literature. The interested reader is refereed to [5] for a complete study about it.

the load V_{NL} and the inductance current z_1 are available for measurement.

[A.3] The source voltage V_e is known and different from zero.

Under these conditions it is possible to present the following

Proposition.

Consider the serial active filter model (3) in closed–loop with the control law

$$\mu = \frac{1}{V_e}\left[L_f \dot{z}_{1d} + z_{2d} - k_1\left(z_1 - z_{1d}\right)\right]; \tag{4}$$

with k_1 a positive constant, z_{1d} given as

$$z_{1d} = C_f \dot{z}_{2d} + \frac{1}{n^2 R_l} z_{2d} + \frac{1}{n R_l}(V_{NL} - V_{line}); \tag{5}$$

and $z_{2d} = -nV_h$. Then

$$\lim_{t \to \infty} (z - z_d) = 0$$

Proof.

Model (3) can be equivalently written as

$$\mathcal{D}\dot{\tilde{z}} + \mathcal{J}\tilde{z} + \mathcal{R}\tilde{z} = \mathcal{M}\mu + \psi - \{\mathcal{D}\dot{z}_d + \mathcal{J}z_d + \mathcal{R}z_d\}$$

by defining the error $\tilde{z} = z - z_d$. Hence, by substituting the proposed control (4) and the desired value of the inductance current (5), it is obtained that

$$\mathcal{D}\dot{\tilde{z}} + \mathcal{J}\tilde{z} + \bar{\mathcal{R}}\tilde{z} = 0 \tag{6}$$

where

$$\bar{\mathcal{R}} = \left[\begin{array}{cc} k_1 & 0 \\ 0 & \frac{1}{n^2 R_l} \end{array}\right]$$

Consider now the following Lyapunov function candidate

$$\mathcal{H} = \frac{1}{2}\tilde{z}^T \mathcal{D}\tilde{z}$$

whose time derivative along the solutions of (6) leads to

$$\dot{\mathcal{H}} = -\tilde{z}^T \bar{\mathcal{R}}\tilde{z} \leq -\gamma\|\tilde{z}\|^2$$

where $\gamma = min\{k_1, \frac{1}{n^2 R_l}\}$. Then, since $\mathcal{D} = \mathcal{D}^T > 0$ it can be shown that

$$\dot{\mathcal{H}} \leq -\alpha\mathcal{H}$$

where $\alpha = \frac{min\{k_1, \frac{1}{n^2 R_l}\}}{max\{L_f, C_f\}}$. Integrating this result from 0 to t and applying the comparison principle [2], we have

$$\mathcal{H}(t) \leq \mathcal{H}(0)\mathrm{e}^{-\alpha t}.$$

Now, since $\mathcal{H}(t)$ can be bounded from below by $min\{L_f, C_f\}\|\tilde{z}(t)\|^2$ and $\mathcal{H}(0) \leq max\{L_f, C_f\}\|\tilde{z}(0)\|^2$ holds, then it can be shown that $\|\tilde{z}\|^2 \leq \beta\mathrm{e}^{-\alpha t}$ with β a positive constant, fact that concludes the proof.

The following remarks are in order about the proposition above:

Remark 4. Notice from the topology of the filter that the term $V_{NL} - V_{line}$ is equal to the sum of the voltage in terminal of the resistance line R_l plus the "injected" voltage in the current transformer terminals nz_2. Thus, it is possible to reduce the necessity of using two sensor by measuring only the output capacitor voltage z_2. However, it must be noticed also that this reduction on the number of sensor implies knowledge on the system parameters R_l and n.

Remark 5. The output voltage regulation objective is achieved in an indirect way by regulating first the inductance current to a value that corresponds with the desired output variable. This stabilization mechanism coincides with the reported in [7], where it is shown that z_1 defines a minimum–phase output, while trying to stabilize the system by using z_2 as output leads to the situation of working with a non–minimum phase system.

Remark 6. The problem of cancelling current instead of voltage distortions can also be approached with the proposed controller. To justify this claim, besides minor changes in the topology circuit and the control law, it is fundamental to understand the role of equation 5. Notice here that the "desired" inductance current of the filter is computed as a function of the desired output voltage (z_{2d}) and its time derivative. In the case of parallel filters this mechanism is inverted, i.e. the input information is the desired current (z_{1d}) while the computed variable is the output voltage (z_{2d}). Evidently, the main difference is that instead of working with an algebraic expression the solution of a (linear stable) differential equation is required.

4 Simulation results

The usefulness of the proposed controller was illustrated by digital simulations. To this end, two experiments were carried out. The purpose of the first one was to evaluate the theoretical properties of the control scheme. Hence, it was considered the case when the harmonics to be compensated are known and this information is directly used to generate the reference for the controller. In the second case, a completely unknown load voltage is generated and, by means of computing the components of the Fourier series of this signal, the harmonics up to order 25 are identified and used to generate the controller reference.

The following remarks apply to both experiments:

- The Power Systems Blockset and Simulink of MATLAB were used to carry out the simulations. In this sense, ideal switches were considered to build the full–bridge inverter.

- The time derivative of the desired behavior of states $z_{1,2}$, required for implementing the controller, were approximated by using a filter with transfer function of the form
$$G(s) = \frac{\lambda s}{s+\lambda}$$
- For PWM purposes, a triangular wave (4000 Hertz frequency) is compared with the signal to be modulated via an open loop comparator.
- The set of parameters considered were $V_e = 200V$, $L_f = 1mH$, $C_f = 0.33\mu F$, $n = 0.0556$, $R_l = 47\Omega$, $V_{line} = 200\sin(120\pi t)$, $\lambda = 8000$, $k_1 = 60$. These values were taken from [9] and correspond to real-evaluated circuit.

4.1 Ideal case

When it was assumed that the distorted load voltage was known, it was considered the following voltage in terminals of the load

$$V_{NL} = 115sen(120\pi t) + 20sen(360\pi t) + 10sen(600\pi t)$$

where it can be noticed the existence of a fundamental and two (the third and fifth) harmonics signals. With this information, the desired behavior for the output capacitor voltage was considered as $z_{2d} = -0.25\,(20sen(360\pi t) + 10sen(600\pi t))$, since $n = 0.25$. Figure 2 shows the behavior of the actual V_{NL} and the desired z_{2d} output voltage capacitor while in Figure 3 their corresponding inductance currents are shown. The time t_{ON} stand for the instant when the proposed controller was turned on. Although in these Figures the boundedness of the signals, i.e. the internal stability, can be verified, the usefulness of the controller can be better evaluated by means of Figure 4, where both the utility and load voltages are compared. In this picture it can be observed how, in spite of a distorted load voltage, the voltage generated by the utility is nearly sinusoidal, improving then the power quality. With the aim to numerically verify this improvement, in Figure 5 the harmonic content, after and before the compensation, of the utility is depicted, where it is evident the reduction on the third and fifth harmonics magnitude.

4.2 Unknown voltage case

Once the theoretical properties of the controller have been illustrated, in this section the problem of estimating the harmonics to be compensated is faced. As previously mentioned, this task is carried out by directly computing the corresponding terms in the Fourier series of the load voltage and the main objective is to evaluate the performance of the proposed controller when the estimated instead the

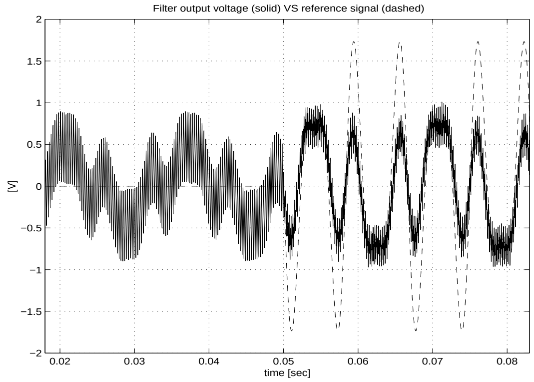


Figure 2: Actual and desired output voltage capacitor: ideal case

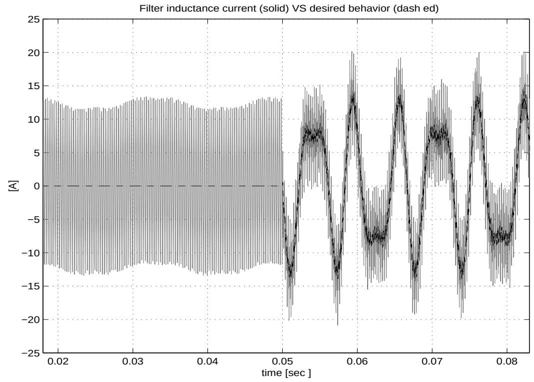


Figure 3: Actual and desired inductance current: ideal case

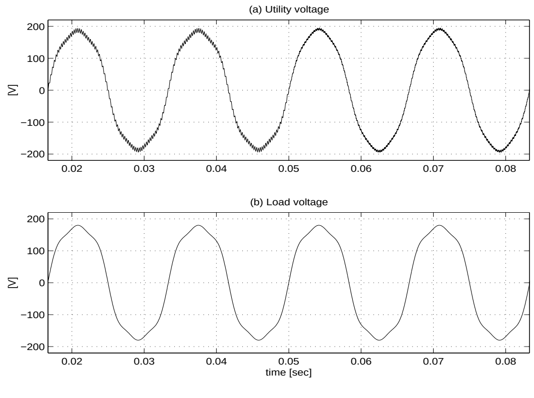


Figure 4: Utility and load voltages: ideal case

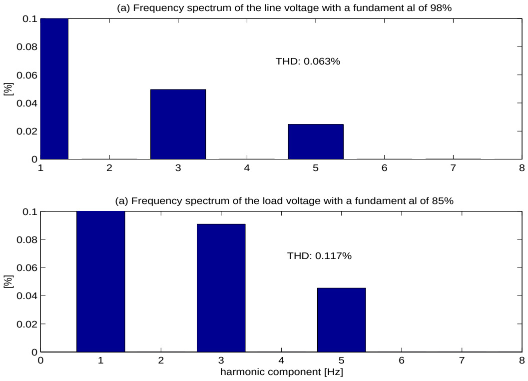


Figure 5: Harmonic content of utility voltage: ideal case

actual harmonics are used to generate the reference voltage.

The experiment implemented in this case was to consider a linear (resistive) load in parallel with another resistance which is intermittently connected by means of a switch. Under these conditions, the (highly corrupted) generated load voltage is shown in Figure 6. Also in this figure, the estimated (re–constructed) voltage obtained by using the computed Fourier terms, is presented.

Figure 7 and 8 show the actual and the desired behavior of the output capacitor voltage and inductance current, respectively. Although the internal stability is also achieved in this experiment and in spite of the error between this actual and desired error, the usefulness (and robustness against the uncertainty on the estimated harmonics) is illustrated in Figures 9 and 10. In the first one the utility voltage is compared with the load voltage, making evident the remarkable improvement obtained in the power quality. This improvement is numerically corroborated in the second figure where the harmonic content, up to 32th harmonic, is shown. Here it can be noticed how the magnitude of the estimated and compensated harmonics is drastically reduced.

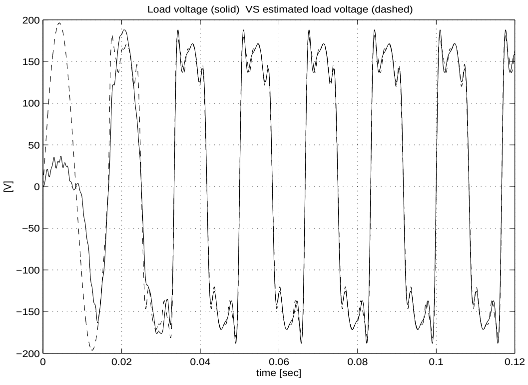


Figure 6: Load and estimated voltages: Unknown case

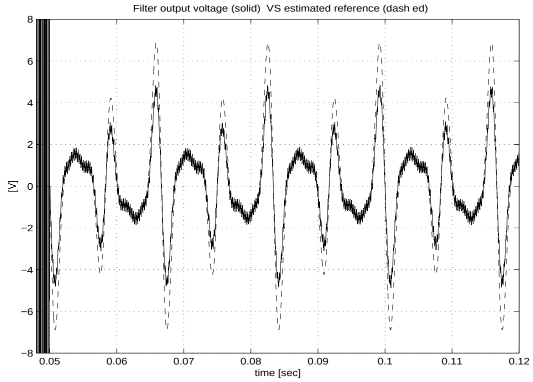


Figure 7: Actual and desired output capacitor voltage: Unknown case

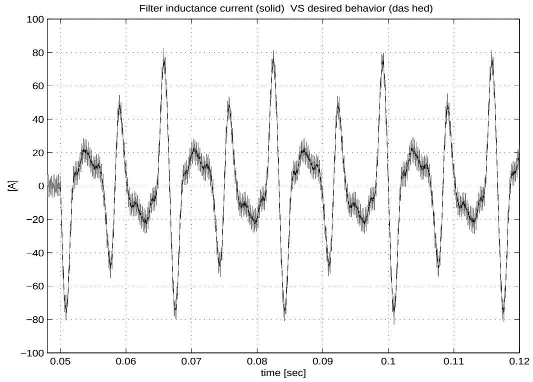


Figure 8: Actual and desired inductance current: Unknown case

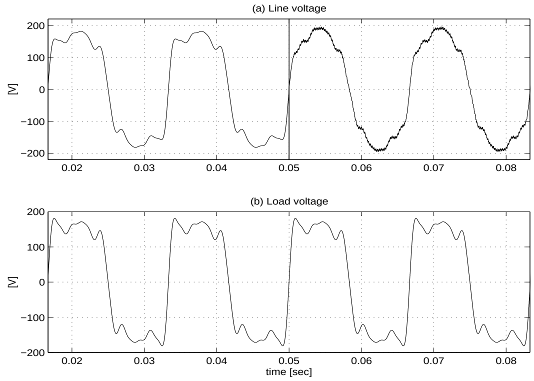
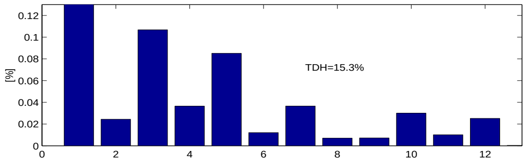


Figure 9: Utility and load voltages: Unknown case

(a) Frequency spectrum of the line voltage with a fundament al of 101.1%



(b) Frequency spectrum of the load voltage with a fundament al of 98.3%

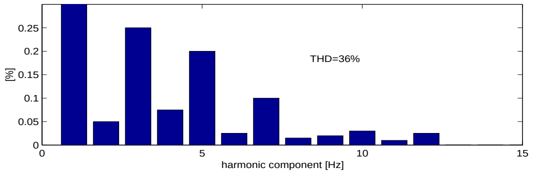


Figure 10: Harmonic content of utility voltage: Unknown case

5 Conclusions

In this paper the problem of compensating the distortion produced by the presence of voltage harmonics in the utility is approached. A control law that guarantee perfect cancellation with global stability is proposed. The control law is developed by exploiting the passivity properties of the average model of a full–bridge inverter equipped with a LC filter and connected to the network via a current transformer. From a theoretical point of view, the proposed controller has the advantage, with respect other passivity–based controllers, of not dealing directly with the problem of unstable internal dynamic of the systems. From a practical perspective, the usefulness of the presented scheme was illustrated by digital simulations where the switches dynamics were included and also the uncertainty on the harmonics estimation was taken into account.

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