STATE VARIABLE METHOD FOR A SINGLE-PHASE SHUNT ACTIVE POWER FILTER

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Abstract: The paper proposes a computer aided analysis for a single-phase shunt active power filter, used to improve the power transfer in an electrical distribution system. The necessary description for the most used variant of the electrical circuit is used to represent the behavior of the active filter by state variable method, needed to implement a MatLab simulation. Finally, obtained results and conclusions are presented.

Keyword: power factor correction, active power filter, MatLab simulation.

1. INTRODUCTION

In recent years, much attention has been paid to the problems of the harmonics generated by nonlinear loads connected to the electrical distribution system. As a solution of these, active power filters are investigated. These are switching power converters that correct the waveforms of the current (shunt filters) or the voltage (series filters).

Computer simulations are commonly used in research to analyze the behavior of new circuits, which lead to improve understanding of the circuit. There are two basic tools for the computer analysis of the electrical circuits [1]: circuit-orientated simulators and equation solvers. In the software package for circuit-oriented simulators, users need to supply the circuit topology and the component values. The simulator generates the equations and solves these. On the other hand, for the equation solvers, we must write the equations for all possible state in which the circuit may operate. Then, we must establish the logic that determines the circuit state and the corresponding set of differential equations based on the circuit topology. These equations can solve using high-levels programming languages, such as C, Pascal, or by software packages specialized in mathematics calculus such as MatLab.

We propose in this paper to present a computer simulation for a single-phase shunt active filter. In this direction, we explain the basically notions belonging to Power Electronic, needed to understand the problem. Then, by an analogy with dc-dc Boost converter, the electrical circuit has been represented by state-variable method. Also,

some problems related to time discretisation are explained. Finally, some results obtained by MatLab simulation and conclusions are exposed.

2. SHUNT ACTIVE POWER FILTER PRESENTATION

When the power generator produces the voltage

$$u_{ac}(t) = U_{ac} \cdot \sin \omega t , \qquad (1)$$

the desired current absorbed from ac network has a similar form

$$i_{ac}^*(t) = U_{ac} / R \cdot \sin \omega t , \qquad (2)$$

where R represent the consumers of active power. This value can vary in time, because the number of consumers is changing an their absorbed power also.

Fig. 1 explains the functions of a shunt active filter [2,3,4] from the electrical network's point of view. It was represented the current, $i_{nl}(t)$, absorbed by a nonlinear load and its first harmonic, $i_{nl1}(t)$, in phase with the system voltage. Shunt active power filter should introduces a component

$$i_{af}^* = i_{nl1} - i_{nl} , \qquad (3)$$

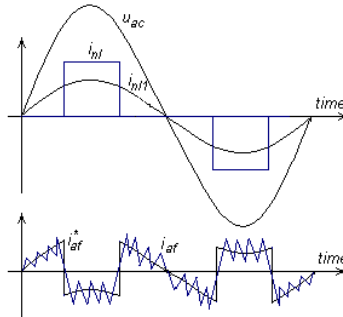but, in fact, introduces a component, i_{af} , that approximates by linear segments the desired one.

Fig. 1. Explanatory waveforms for a shunt active power filter

Fig. 2 represents the block scheme of a single-phase shunt active power filter in the most known variant. A full-bridge voltage source inverter with current control forms the power block. "First harmonic calculation" block on basis of the information about the current absorbed by the nonlinear load, i_{nl}, and the electrical network voltage, u_{ac}, calculates the first harmonic of the nonlinear load, i_{nl1}. In order to keeps constant the voltage across the capacitor C, this value is multiplied with

$$k(t) = 1 + LPF \{ U_{Crefaf} - u_{Caf}(t) \} \qquad (4)$$

where $u_{Caf}(t)$ is the voltage across the capacitor of the active filter, U_{Crefaf} is its reference and LPF{…} represents a low-pass filter. During an ordinarily working process, we have

$$k(t) \approx 1 \qquad (5)$$

and

$$i_{ref} = i_{nl1} \cdot k \approx i_{nl1} \qquad (6)$$

The error current

$$i_{er} = i_{ref} - i_{ac} \qquad (7)$$

is used to obtain signals for "Switches Command". A well-known strategy is hysteresis control that can be applied by the laws

$$SA1 = \begin{cases} ON & when & i_{er} > I_{er}^{+} \\ OFF & when & i_{er} < I_{er}^{-} \\ unchangend & when & I_{er}^{-} < i_{er} < I_{er}^{+} \end{cases}, \qquad (8)$$

$$SA2 = |SA1 \qquad\qquad (9)$$

$$SB2 = \begin{cases} ON & when & u_{ac} > 0 \\ OFF & when & u_{ac} < 0 \end{cases}, \qquad (10)$$

$$SB1 = |SB2, \qquad\qquad (11)$$

where $I_{er}^{+} > 0$, $I_{er}^{-} < 0$ represent the thresholds of the hysteresis comparator and the operator "$|...$" indicates the negation of the logical state.
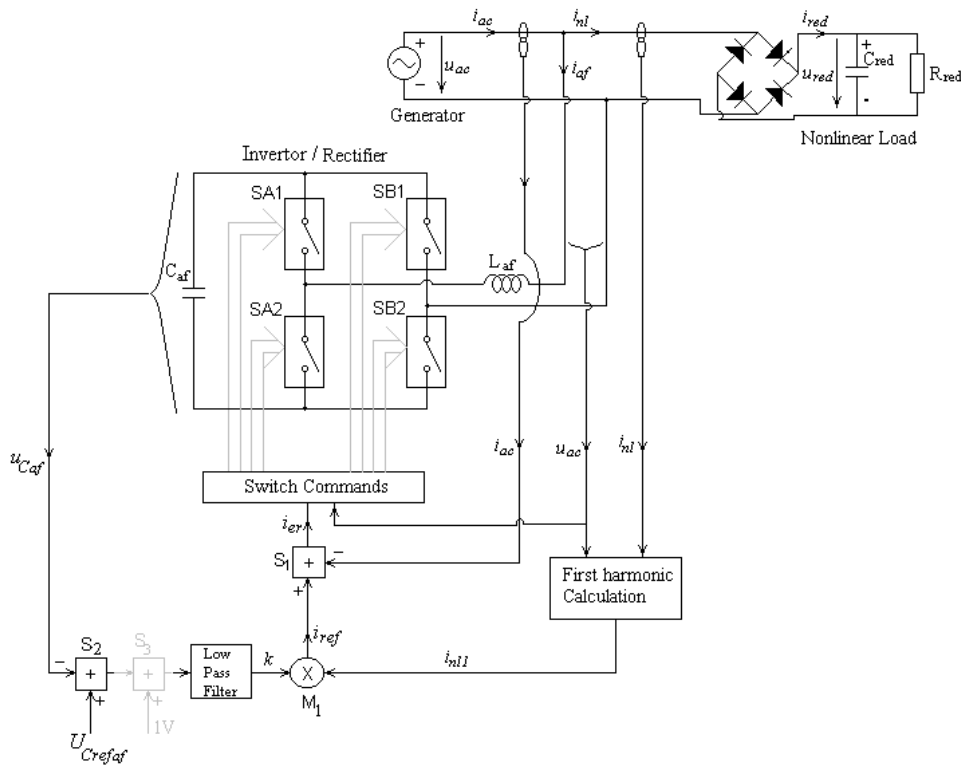

Fig. 2. Block scheme for a shunt active power filter

3. REPRESENTATION BY EQUATION OF ACTIVE FILTER

The simulation time can be divided in equal intervals Δt and the evaluations are done at discrete moments i: $t_i = i * \Delta t$. Supposing that at the moment (i-1), there are known the state variables, we shall write equations to determine these variables at the current moment (i). If N_{itper} is the number of the iterations comprised into a period of ac network, T_{ac}, than

$$T_{ac} = N_{itper} \cdot \Delta t . \qquad\qquad (12)$$

To express the state variable's equations of the inverter, we need to look its scheme redrawn in Fig. 3 [4]. It was consider some losses elements: R_{Laf} for inductance, R_{Cred} for capacitor, R_{laf} for switches. The equivalent voltage on C_{af} is expressed as

$$u_{Cafe} = u_{Caf} \cdot s . \qquad\qquad (13)$$
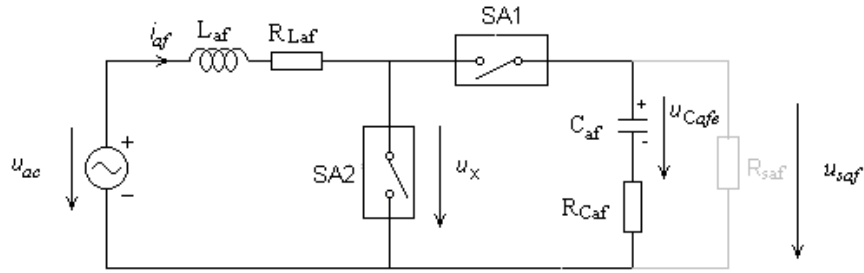
Fig. 3. The inverter of the active filter redrawn as a Boost converter

where

$$s = sign(u_{ac}) = \begin{cases} 1 & when & u_{ac} > 0 \\ -1 & when & u_{ac} < 0 \end{cases}.$$ (14)

The state-variable vector x contains the current inductor i_{af} and the capacitor voltage u_C:

$$x = \begin{bmatrix} i_{af} \\ u_{Cafe} \end{bmatrix} = \begin{bmatrix} i_{af} \\ s \cdot u_{Caf} \end{bmatrix}.$$ (15)

During each circuit state, the following state equation is valid:

$$\dot{x} = Ax + Bu_{af},$$ (16)

where

$$\dot{x} = \frac{dx}{dt} = \begin{bmatrix} \dfrac{di_{af}}{dt} \\ \dfrac{du_{Cafe}}{dt} \end{bmatrix},$$ (17)

A is matrix and B vector.

Also, for each circuit state, the output voltage is given by equation:

$$u_{saf} = s \cdot C \cdot x$$ (18)

When the switch is on, the next relations are obtained:

$$A = A_1 = \begin{bmatrix} -\dfrac{R_{Laf}}{L_{af}} & 0 \\ 0 & -\dfrac{1}{C_{af}(R_{saf} + R_{Caf})} \end{bmatrix}, B = B_1 = \begin{bmatrix} \dfrac{1}{L_{af}} \\ 0 \end{bmatrix}, C = C_1 = \begin{bmatrix} 0 & \dfrac{R_{saf}}{R_{saf} + R_{Caf}} \end{bmatrix}.$$ (19)

When the switch is off, we have:

$$A = A_2 = \begin{bmatrix} -\dfrac{R_{Laf}(R_{saf} + R_{Caf}) + R_{saf}R_{Caf}}{L(R_{saf} + r_C)} & -\dfrac{R_{saf}}{L_{af}(R_{saf} + R_{Caf})} \\ \dfrac{R_{saf}}{C_{af}(R_{saf} + R_{Caf})} & -\dfrac{1}{C_{af}(R_{saf} + R_{Caf})} \end{bmatrix}, B = B_2 = \begin{bmatrix} \dfrac{1}{L_{af}} \\ 0 \end{bmatrix},$$

$$C = C_2 = \begin{bmatrix} \dfrac{R_{af}R_{Caf}}{R_{saf} + R_{Caf}} & \dfrac{R_{saf}}{R_{saf} + R_{Caf}} \end{bmatrix}.$$ (20)

Assuming that the Δt interval is very short, the derivative can be approximated by finite differences, so that at (i) moment

$$\dot{x}(i) = \frac{dx(i)}{dt} = \begin{bmatrix} \dfrac{di_{af}(i \cdot \Delta t)}{dt} \\ \dfrac{du_{Cafe}(i \cdot \Delta t)}{dt} \end{bmatrix} \cong \begin{bmatrix} \dfrac{\Delta i_{af}(i \cdot \Delta t)}{\Delta t} \\ \dfrac{\Delta u_{Cafe}(i \cdot \Delta t)}{\Delta t} \end{bmatrix} = \begin{bmatrix} \dfrac{i_{af}(i \cdot \Delta t) - i_{af}((i-1) \cdot \Delta t)}{\Delta t} \\ \dfrac{u_{Cafe}(i \cdot \Delta t) - u_{Cafe}((i-1) \cdot \Delta t)}{\Delta t} \end{bmatrix}. \quad (21)$$

The state variable equation in the discrete form,

$$\dot{x}(i) = A \cdot x(i-1) + Bu_{ac}((i-1) \cdot \Delta t), \quad (22)$$

allows to calculate $\dot{x}(i)$.

To determine the state variables at (i) moment, the next equation is used

$$x(i) = \dot{x}(i) \cdot \Delta t + x(i-1), \quad (23)$$

so that it can be identified

$$\begin{bmatrix} i_{af}(i \cdot \Delta t) \\ s \cdot u_{Caf}(i \cdot \Delta t) \end{bmatrix} = x(i). \quad (24)$$

4. SIMULATION RESULTS

We verified the behaviour of a shunt active power filter, according to the presented equations and Fig, 2, in the next conditions:
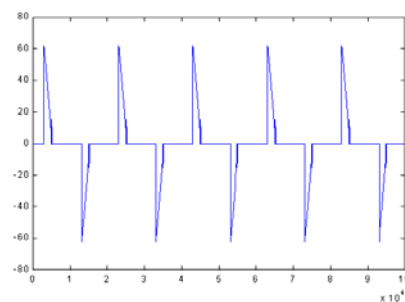
- $u_{ac}(t) = 310 \cdot \sin(2\pi \cdot 50 \cdot t)$;
- $N_{itper} = 20000$, $I_{er}^{+} = -I_{er}^{-} = 1A$, $U_{Cref} = 400V$, $k_{ucaf} = 0.01$;
- $R_{red} = 40\Omega$, $C_{red} = 1000\mu F$, $L_{af} = 0.1mH$, $R_{Laf} = 0.1\Omega$, $C_{af} = 1000\mu F$, $R_{Caf} = 0.1\Omega$, $R_{saf} = 1Meg\Omega$..

Fig. 5 shows some waveforms obtained by MatLab simulation [5].
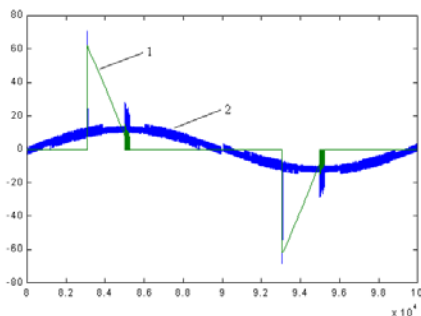
In these conditions, it was constated that in the active filter increases the power factor from 0.53 to 0.95.
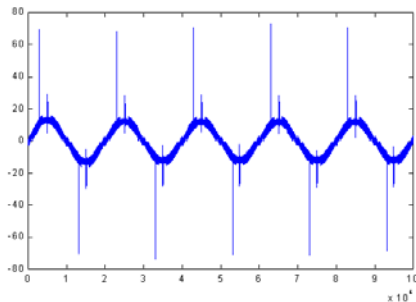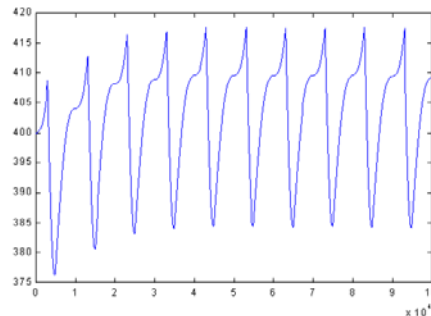
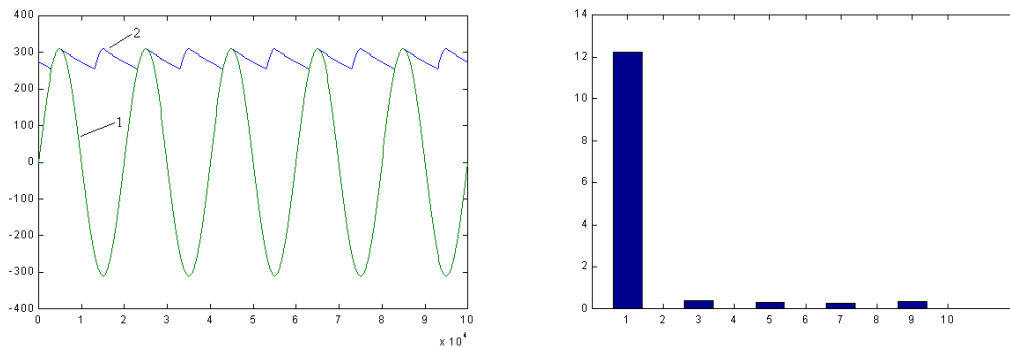a) absorbed current from ac network   b) absorbed current of rectifier

c) details for rectifier's (1) and input (2) currents   d) active filter's capacitor voltage

e) input (1) and rectifier's (2) output voltages   f) input current spectrum

Fig.5. Results obtained by MatLab simulation

5. CONCLUSIONS

This paper has proposed a computer aided simulation of a shunt active power filter using equation solvers. In this direction, the basically notions about shunt active filters have been exposed. Then, the behavior of the active filter was described using state variable method; the equations has been written and adapted starting from a Boost dc-dc converter. Also, the problems related to time discretesation were analyzed.

By this method, the simulation time is reduced from some hours, in case of PSpice simulation, to some minutes, in case of MatLab simulation. Also, using this method with the equation solvers, appear the possibility to introduce the digital signal processing for the study of the active power filters.

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