

Binary Controlled Static VAR Compensator, Based on Electronically Switched Capacitors

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Abstract. A binary control strategy for reactive power compensation, based on a chain of branches using unidirectional power switches is presented. This strategy allows, with an adequate number of compensating branches, a fine and precise control of reactive power in electric systems. The amount of reactive power is evaluated by storing the value of instantaneous line current during the "zero-crossing" of the mains voltage. Other characteristics of this control strategy are: 1) it does not generate harmonics; 2) it can compensate reactive power in an almost continuous form; and 3) inrush problems during connection and/or disconnection are avoided. The paper explains the control strategy proposed, the way it works and some results obtained under operation.

I. INTRODUCTION

To compensate reactive power, Static Var Compensators (SVC), which use a thyristor controlled reactor are widely used, because they allow a soft and continuous variation in the control of power factor [1-3]. However, this kind of compensator presents the problem of harmonic generation. On the other hand, capacitor banks cannot be controlled continuously, and besides they present inrush problems during connection and disconnection [4,5]. To avoid this kind of problems, a new solution for continuous reactive power control, without harmonic generation or inrush problems is proposed. This topology has the

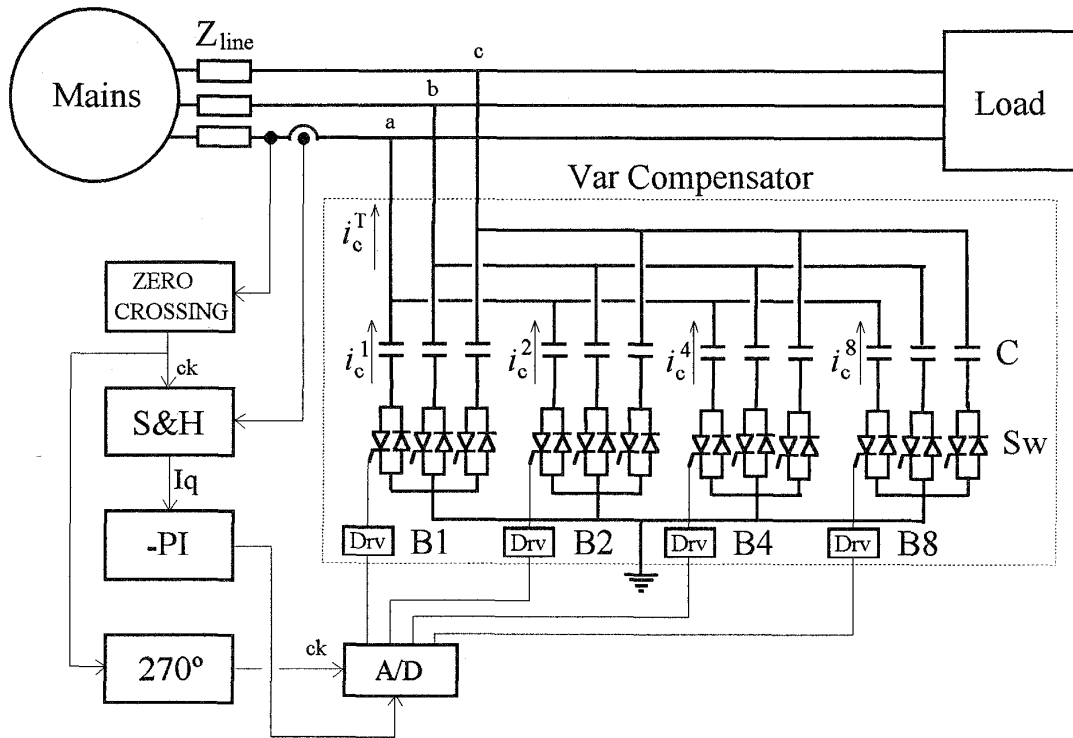


Fig. 1. Var compensator proposed (four-bit example)

following distinctive characteristics: 1) it does not generate harmonics; 2) it is much simpler and cheaper, compared with other topologies using electronic var compensators; 3) it can compensate reactive power cycle by cycle; and 4) inrush problems during connection and disconnection are avoided. The form in which capacitors are connected and disconnected are always with initial conditions which satisfy "zero current" and "zero voltage" requirements.

Each branch is implemented with one thyristor, one diode, and one capacitor. The strategy allows, with an adequate number of compensating branches, a fine and precise control of reactive power in electric systems. The amount of reactive power is evaluated through the value of instantaneous line current during the "zero-crossing" of the mains voltage. Other characteristics of this control strategy are: 1) it does not generate harmonics; 2) it can compensate reactive power in an almost continuous form; and 3) inrush problems during connection

and/or disconnection are avoided. The paper explains the control strategy proposed, the way it works and some results obtained under operation.

The three-phase var compensator of figure 1 has four branches named B1, B2, B4 and B8. Each branch has a particular capacitor value with the following characteristic: the branch B2 duplicates the capacitor value of B1. In the same form, B4 duplicates de value of B2, and B8 duplicates the corresponding value of B4. Then, if for example the capacitor value of B1 is 100 μF , then B2 will be 200 μF , B4 will be 400 μF , and B8 will be 800 μF . In this form, The var compensator will be able to compensate reactive power starting from 0 μF , until 1,500 μF , with steps of 100 μF . The system can also have eight or more branches to reduce the size of the step, with each additional branch scaled in a binary form. To make this device work properly, an appropriate control strategy is required.

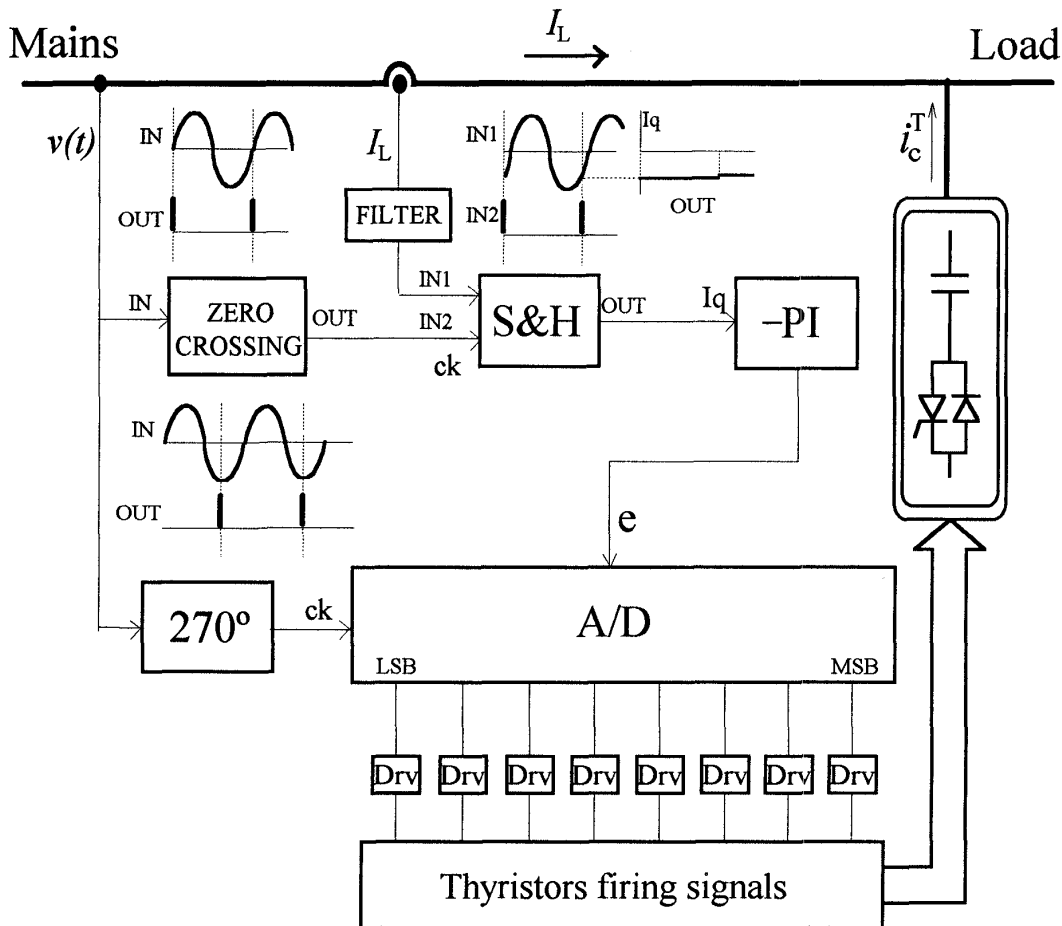


Figure 2. Control block for one phase (eight-bit system)

II. THE PROPOSED CONTROL SYSTEM

The figure 2 shows the control strategy proposed for an eight-bit system. In this figure, the overall process for phase "a" is explained. As it can be seen, the control needs to know the amplitude of the reactive component of the line current, I_q . The following equation relates the reactive component with the line current:

$$i_L(t) = i_o(t) + i_p(t) + i_q(t) + i_h(t) \quad (1)$$

where:

i_o : dc component

i_p : active component (in-phase component)

i_q : reactive component (in-quadrature component)

i_h : harmonics component

Equation (1) can be expanded as shown in (2), yielding the following general equation for the line current:

$$\begin{aligned} i_L(t) = & I_o + I_p \cos(\omega t) + I_q \sin(\omega t) + \\ & + \sum_{j=1}^{\infty} I_{2j} \cos(2j\omega t + \phi_{2j}) \\ & + \sum I_{2k+1} \cos((2k+1)\omega t + \phi_{2k+1}) \end{aligned} \quad (2)$$

2.1 Filter design.

To isolate I_q from (2), a band-pass filter (BPF) using switched capacitor filters was implemented. This kind of filter does not need external capacitors or inductors, and its cut-off frequency depends only on the clock frequency f_{clk} . With this kind of device, a band-pass filter with $Q=10$, and $H_o=1$ was implemented, which has permitted to obtain a negligible phase-shift displacement, and also a negligible attenuation of the signal. The block diagram of the filter used to isolate the fundamental component (I_p+I_q) is shown in fig. 3.

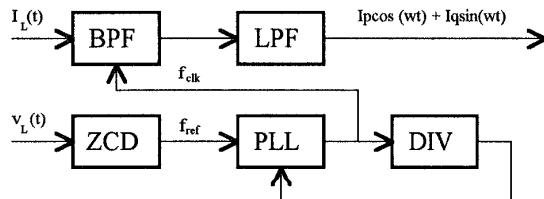


Figure 3. fundamental component filter

The clock frequency f_{clk} is obtained from the line voltage $v_L(t)$, and through a PLL (Phase Locked Loop). ZCD is the "zero cross detector" block, and LPF is a low pass filter, required for the switched capacitor device. After that, the line current I_L is used as an input signal for a "Sample and Hold" circuit (S&H). This "S&H" is synchronized with the phase-to-neutral mains voltage at $\omega t=0^\circ$ (zero crossing) to generate an output which is proportional to the amplitude of the reactive component of I_L . This output named I_q in figure 2 is a dc signal [6, 7]. This signal is integrated (PI control) and multiplied by $-I$, to get the control signal "e". This control signal contains the information of the amount of I_q required to compensate the load. As the branch of thyristors is scaled in a binary form, the signal "e" is transformed in a digital signal through an A/D converter. The eight outputs of the A/D converter are used as firing signals for the thyristors.

The clock signal of the A/D converter is a train of pulses synchronized at $\omega t=270^\circ$. This synchronization angle ensures that the thyristors will be switched-on when the mains supply reaches its maximum negative voltage. In this way, a soft connection is obtained, because the capacitors are charged at $v_c(t)=-V_m$. The current will increase starting from zero without distortion, following a natural sinusoidal waveform, and after a cycle is completed, the thyristor automatically will block, unless a new firing pulse is applied. In this form of operation, both connection and disconnection of the branch will be soft, and without distortion. Neither harmonics nor inrush currents are generated. The figure 4 shows the capacitor current when the thyristor is switched on using the aforementioned synchronization strategy. It can be noted that the current i_c does not present any distortion.

2.2 Adaptive control.

In practice, power capacitors have tolerance values which are ± 10 to 20 percent of the label value. To ensure a good performance, the control scheme adopted for power compensation, have to take in account this problem. To solve this problem, a self-tuning adaptive control will be adopted. This control will include a current sensing before and after the point where the compensator is connected. In this way, it will be possible to know the value of the capacitance, required to get the optimum control signal for the compensation of I_q .

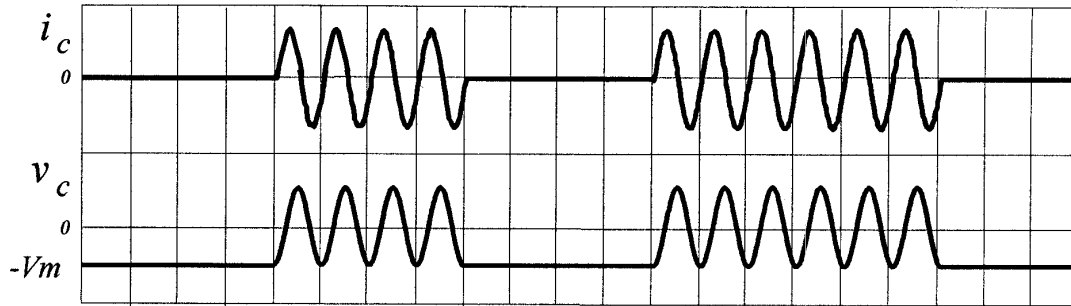


Figure 4. Capacitor current and voltage during connection and disconnection of one branch

III. SIMULATION RESULTS

The figure 5 shows the circuit used for simulations. The compensator has eight binary branches, and the control is in closed loop.

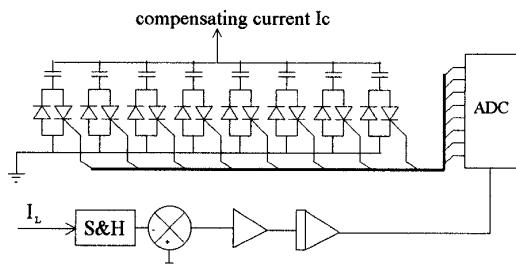


Figure 5. Circuit used for simulations

Under these conditions, a step variation is introduced. The step response is shown in figure 6, where 6 a) displays the output signal from the controller, 6 b) shows the instantaneous value of the magnitude of I_q , and 6 c) shows the total compensating current from phase "a" (i_c^T), which has been increased from 10 to 15 amps. In this simulation, the capacitor size in the LSB branch is $1 \mu\text{F}$, and in the MSB branch is $128 \mu\text{F}$. It can be noted that, despite the LSB branch is being switched on and off continuously, the steady-state after, and before the change in current, seems to be constant. The figure also shows that harmonics or inrush problems are not generated. The transitions during connection and disconnection are clean. The parameters of the compensator are $V_{\text{mains}}=380 \text{ V}_{\text{ff}}$, $Z_{\text{line}}=0.1+j0.01 \Omega$, $Z_{\text{load}}=2+j0.02 \Omega$.

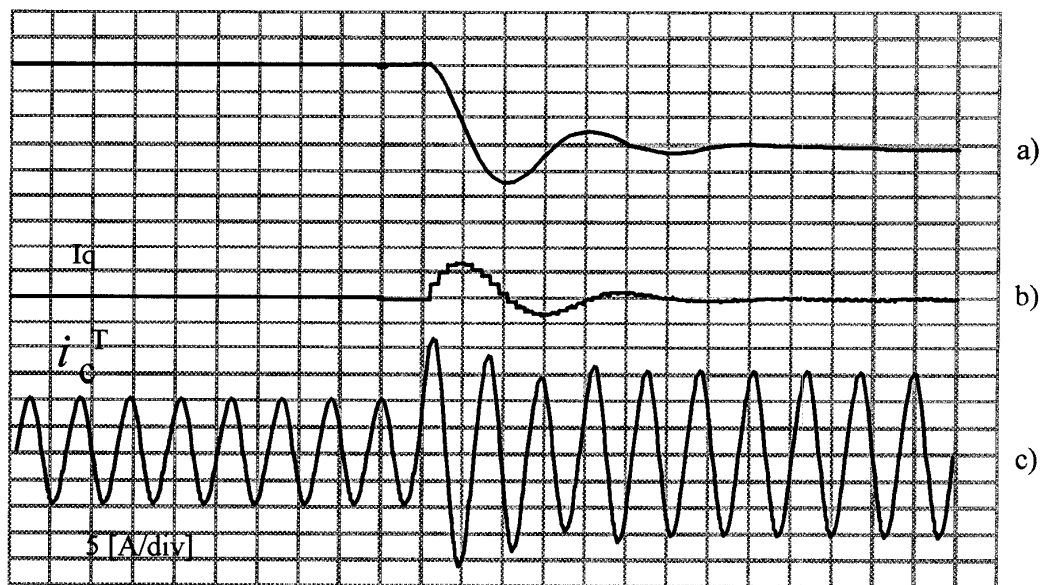


Fig. 6. Compensating current i_c^T for phase "a" (esc: 5 [A/div])

CONCLUSIONS

A novel topology for a var compensator, using unidirectional power switches, has been presented. It works in a binary form, by switching the capacitors on and off without distortion and/or inrush problems. The main characteristics of this new topology are: 1) it does not generate harmonics; 2) it is simpler compared to other electronic var compensators; 3) it can compensate reactive power cycle by cycle; 4) it does not require force commutated switches; and 5) inrush problems during connection and/or disconnection are avoided. The simulations showed that the aforementioned characteristics make feasible the implementation of such a var compensator. The care it needs for proper operation are: 1) to have the correct initial capacitor voltage, and b) to wait the right time to switch-on the thyristor. Resonant problems can be avoided by jumping the dangerous steps in the binary chain of capacitors.

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