New Topology for Harmonic-Free, Dynamic Var Compensator Using Unidirectional Power Switches

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Abstract.- This paper presents a new and simple topology for reactive power compensators. It is based on a branch of binary scaled capacitors, and a special and simple switching device, implemented with one thyristor, and one antiparallel diode. During the off state, the capacitors remain charged at the peak voltage. When connected, they are switched on when the line voltage reaches its peak value. The main characteristics of this new topology are: 1) it does not generate harmonics; 2) it is simpler and less expensive compared with other topologies using 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, allowing a dynamic compensation of reactive power. The paper analyzes the circuit proposed, the way it works and the results obtained under operation.

I. Introduction

To compensate reactive power, different strategies and topologies have been used, such as capacitor banks, Static Var Compensators (SVC) [1-3], and recently, Force Commutated Var Compensators (FCVC) which use PWM techniques [4, 5]. Nonetheless, most of them have some kind of drawback. The capacitor banks present inrush problems during connection and disconnection [6, 7], Static Var Compensators are harmonic polluters, and PWM Force Commutated Compensators are still too expensive and complicated. On the other hand, the older Synchronous Compensators have a slow dynamic response, and require a lot of maintenance.

Many solutions have been presented in the literature given above, to minimize those drawbacks, but only with partial success. The purpose of this work is to present a new topology for a var compensator, which eliminates the problems already mentioned. This topology has the 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; 4) it does not require force commutated switches; and 5) inrush problems during connection and disconnection are avoided. This last characteristic is the most important, because a dynamic operation of the switched capacitors becomes feasible. The form in which capacitors are connected and disconnected are always with initial conditions which satisfy "zero current" and "zero voltage" requirements. That means, no harmonic distortion during normal operation of cyclic commutation of the capacitors bank.

II. System Proposed

The figure 1 shows an example of the var compensator proposed. It has been implemented using a binary chain of capacitor branches with unidirectionally controlled power switches *"Sw"*, which are built with one thyristor and one anti-parallel diode. The simplicity of the proposed system is in both, power circuit and control firing circuit. The power circuit is simpler (and less expensive) because only one thyristor instead of two is used, and a reactor branch is not required. The control is simpler because all the thyristors involved are common cathode connection (wye configuration).

The three-phase var compensator of the example 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 new branch scaled in a binary form.

0-7803-4489-8/98/$10.00

To make this device work properly, a soft connection and disconnection of the branches is required, and the contribution of this work is to show a topology, and control strategy able to do this.

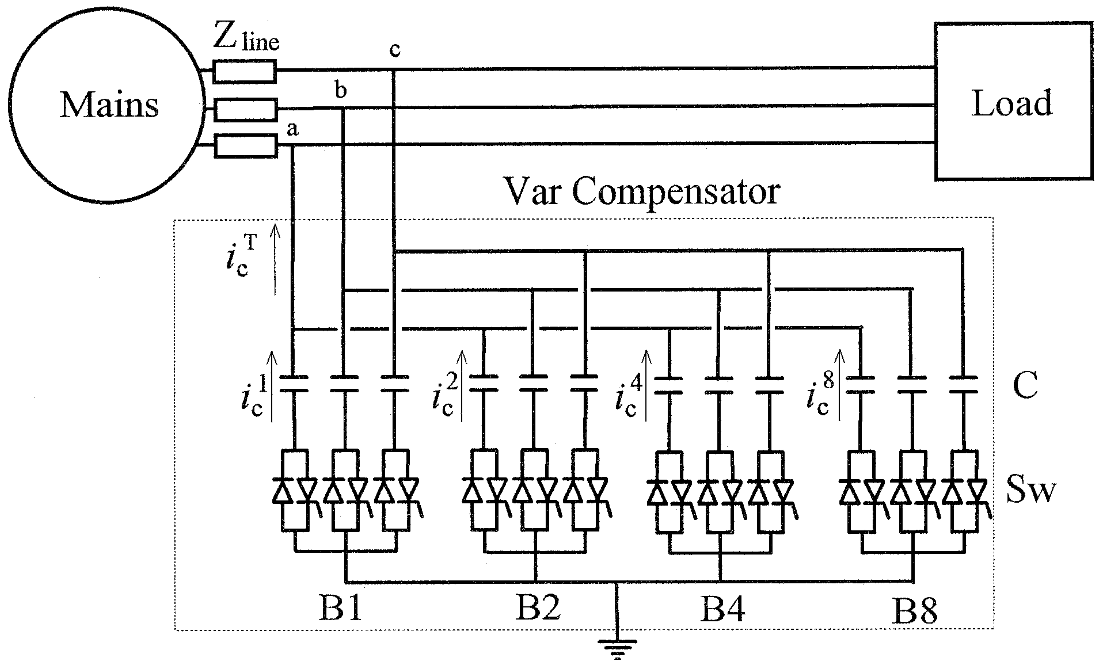

Figure 1. Var compensator proposed (four branches example)

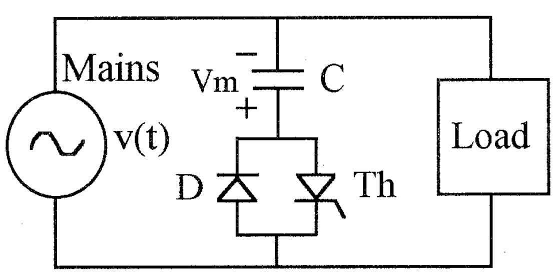

Figure 2. one branch of the circuit proposed

The figure 2 shows a branch for one phase of the circuit proposed in figure 1. When the thyristor ***Th*** is "off", the diode ***D*** keeps the capacitor ***C*** charged at the peak negative value of the mains supply (**-Vm**). The capacitor cannot be discharged because ***Th*** is off, and hence the branch is in "open circuit". To connect the branch, a firing pulse is applied at the thyristor gate, but only when the mains supply reaches its maximum negative voltage. In this way, a soft connection is obtained. The current will increase starting from zero without distortion, following a natural sinusoidal waveform, and after a cycle is completed, the capacitor voltage again will have the voltage **-Vm**, and 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. If the firing pulses, and the voltage **-Vm** are properly adjusted, neither harmonics nor inrush currents are generated. That is because two important facts are achieved: a) dv/dt at v=-Vm is zero, and b) anode-to-cathode thyristor voltage is equal to zero. Let us assume that $v(t) = V_m \sin \omega t$, is the mains voltage, V_c the initial capacitor voltage, and $v^{Th}(t)$ the thyristor anode-to-cathode voltage. The proper connection of the branch will be when $v^{Th}(t) = 0$:

$$v^{Th}(t) = v(t) - V_c = V_m \sin \omega t - V_c \tag{1}$$

as $V_c = -V_m$:

$$v^{Th}(t) = V_m \sin \omega t + V_m = V_m(1 + \sin \omega t) \tag{2}$$

then, $v^{Th}(t) = 0$ when $\sin \omega t = -1 \Rightarrow \omega t = 270°$.

At $\omega t = 270°$, the thyristor is switched on, and the capacitor C begins to discharge. At this point:

$\sin 270° = -\cos 0°$, and hence $v_c(t)$ for $\omega t \geq 270°$ will be: $v_c(t_0) = -V_m \cos \omega t_0$. Then the compensating capacitor current starting at t_0 will be:

$$i_c = C\frac{dv_c}{dt} = C \cdot V_m \frac{d}{dt}(-\cos \omega \cdot t_o) = C \cdot V_m \sin \omega \cdot t_o \tag{3}$$

This means the current starts from zero as a sinusoidal waveform without distortion and/or inrush problems. The figure 3 shows the capacitor current when the thyristor is switched on according with the aforementioned analysis. In this example, the thyristor is switched on during four cycles. Then is kept off during the next four cycles, and then is switched on again during six more cycles. It can be noted that the current i_C does not present any distortion, and is in agreement with the previous equations. The only requirement to accomplish this result is that the above initial conditions have to be strictly respected. Otherwise, inrush problems will appear. For this reason, a precise connection time, and initial capacitor voltage conditions are required.

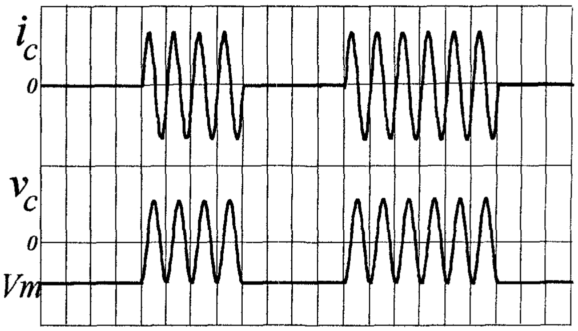

Figure 3. Capacitor current and voltage during connection and disconnection of the branch

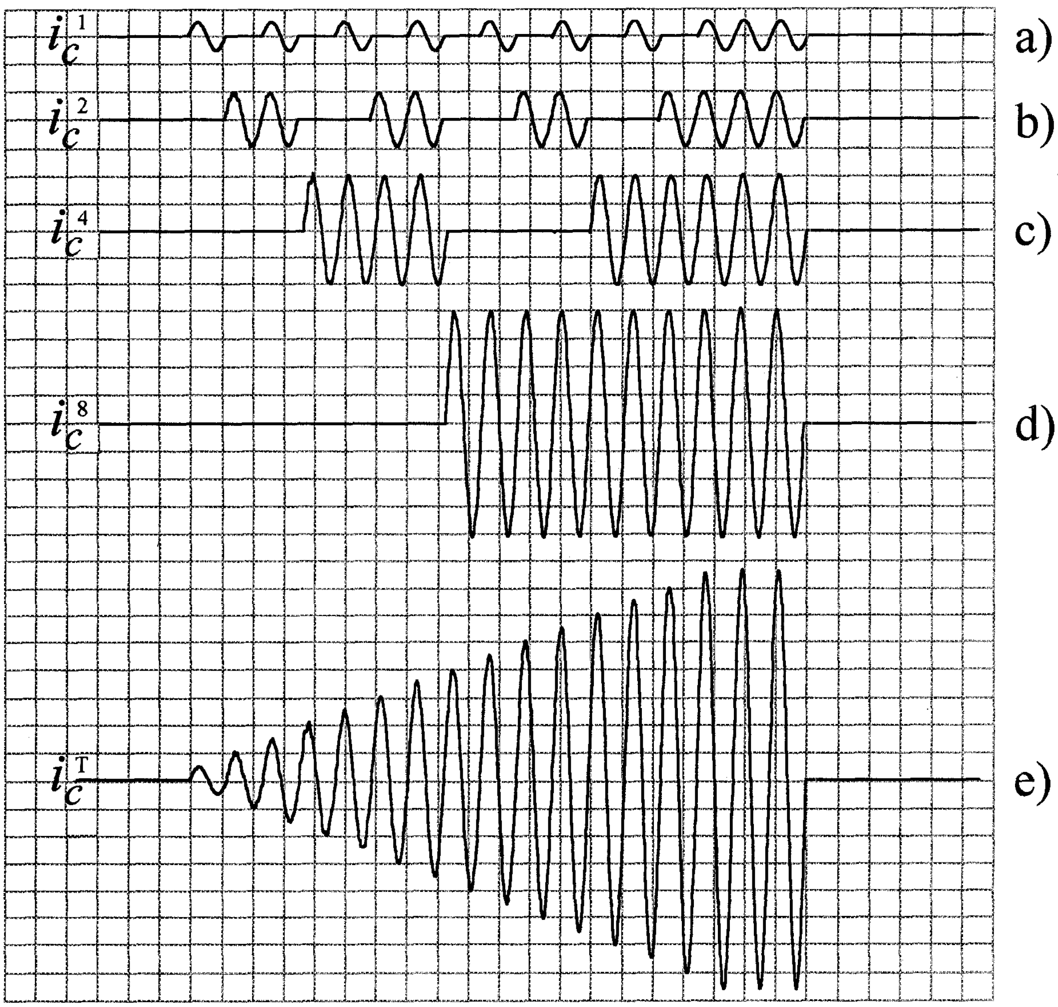

Figure 4. Compensating currents for phase "a" (esc: 5 [A/div])
a) current through B1 b) current through B2
c) current through B4 d) current through B8
e) total compensating current for phase "a" (B1+B2+B4+B8)

The compensator that has been presented can also operate in delta connection. However, the advantage of wye connection is that all the gates of the thyristors are referenced at the neutral point (common cathode for all the branches, and for the three phases). This means an important reduction in the complexity of the system. For example, for low voltage devices, galvanic isolation between power and control may not be required. The only disadvantage of the wye connection is that the neutral point cannot be avoided. Otherwise, the first thyristor which is switched on, will not start, and then an inrush problem will be generated when the thyristor of the following phase is fired. This happens because the three phases are not switched on at the same time, because they satisfy the aforementioned equations with 120° shift-phase.

III. Simulation Results

The Figure 4 shows the binary operation of the var compensator proposed in fig. 1. The total compensating current from phase "a" (i_C^T)., is being increased step by step. The capacitor currents from the branches B1 (i_C^1), B2 (i_C^2), B4 (i_C^4), and B8 (i_C^8) are shown in figures 4 a), b), c), and d) respectively. In figure 4 e), the total compensating current for the phase "a" (i_C^T) is displayed ($i_C^T=i_C^1+i_C^2+i_C^4+i_C^8$). It can be noted that harmonics or inrush problems are not generated, and that the current i_C^T seems to vary continuously. The transitions during connection and disconnection are quite clean. The parameters of the simulated compensator are V_{mains} = 380 V_{ff}, Z_{line} = 0.1+j0.01 Ω, Z_{load} = 2+j0.02 Ω, C(B1) = 30 μF, C(B2) = 60 μF, C(B4) = 120 μF, and C(B8) = 240 μF.

IV. Experimental Results

For laboratory experiments, a single-phase compensator, with six binary branches was implemented. It is shown in figure 5. The line voltage is 220 V, 50 [Hz]. The capacitor step is 1 μF, which allows compensation from 0 μF to 63 μF. Then, the maximum compensation number for this prototype will be 958 var. The load is a 350 Ω resistor.

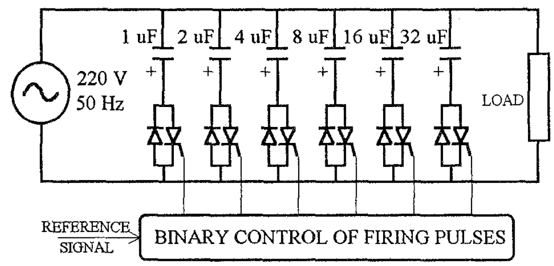

Figure 5. Experimental prototype

The control circuit is in open loop, and simply follows a reference signal from a variable resistor. This reference signal is transformed to a digital signal to produce the gating signals for the thyristors. The clock of the A/D converter is synchronized with the negative peak value of the mains source. In this form, the thyristors are switched on when ωt=270°. If the system requirement is to keep the power factor at some particular value (for example cosφ=1), then a closed-loop control will be required. As the purpose of this work is to show the operating characteristics of this compensator, closed-loop control is not required.

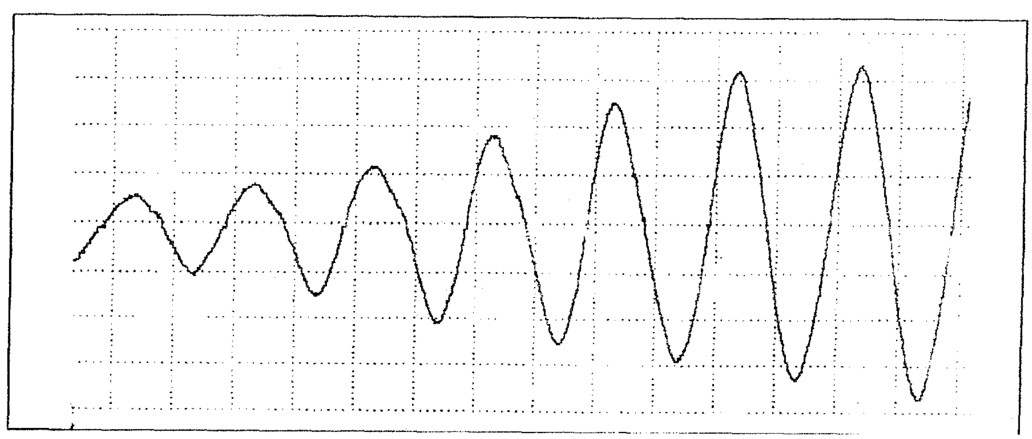

Figure 6. Experimental capacitor current i_C^T (1A/div)

The figure 6 shows the experimental results obtained with the prototype of figure 5. The oscillogram was obtained by manually increasing the "REFERENCE SIGNAL" of the "BINARY CONTROL OF FIRING PULSES". In this form, the capacitors are connected in a binary form, as shown in figure 4. It can be observed that inrush problems are negligible, even considering that capacitors are switched on and off in almost every cycle. The parameters of the circuit are those from figure 5.

V. CONCLUSIONS

A novel topology for a var compensator, using unidirectional power switches, has been presented. The main characteristics of this new topology are: 1) it does not generate harmonics; 2) it is simpler and less expensive, 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 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) it is required to have the correct initial capacitor voltage, and b) to wait the right time to switch-on the thyristors. But even in the case that these two conditions are not perfectly satisfied, in practice a small inductance in series with the capacitors may be added. Resonant problems can be avoided by jumping the dangerous steps in the binary chain of capacitors.

ACKNOWLEDGMENTS

The authors want to thank Conicyt for his financial support through Project Fondecyt number 1960572. The authors also want to thank Miss Yamille del Valle, and Mr. Marcos Orchard for their help in the implementation of an experimental prototype, and experiments.

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