Single phase AC Choppers with inductive load and improved efficiency

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***Abstract*— This paper describes two circuits improving commutation: the first circuit uses capacitors and the second circuit uses resistors. The functioning was proved by simulation, which shows a significant efficiency increase.**

I. INTRODUCTION

A.C. Choppers tend to replace A.C. phase control circuits with triacs or thyristors, because they have good performances. A.C. choppers with low switching frequency were presented in [1]. Along with the development of power semiconductors devices capable to work at high frequencies, the PWM techniques were used more and more [2]. In order to improve the power factor from the input of a.c. choppers, asymmetrical control techniques were described in [3]. A new asymmetrical PWM technique was introduced in [4], which improves the input power factor as well as eliminates, the harmonics of the load voltage, but the harmonics spectrum of the input current is rich . A chopper realized with IGBT's, which works at high switching frequency (5KHz) provided with un simple filter is presented in [5], which can obtain a relatively sinusoidal input current. The disadvantage of this technique results from the absence of dead times between these two IGBT's commands, which realize the switching function. In switching moments appears a cross-conduction, which determines a low efficiency. In this paper we analyze two power circuits, to improve switching and assure high efficiency of the chopper.

II. USING CAPACITORS TO IMPROVE THE COMMUTATION

Fig. 1 shows the proposed power circuit, which uses capacitors to improve switching. In order to minimize the power losses, these capacitors are connected in parallel with switching IGBT's only in commutation time, being connected in series with another IGBT. Fig. 2 presents the generation of the control signals and the load voltage waveform v_L. Switchers Q_1 and Q_2 are driven by the same control signals as in [5], the difference is that, at the entry into the conduction state, appears a dead time τ_b to avoid cross-conduction. The functioning of power circuit must be analyzed on 8 different intervals of time, in which the equivalent circuits from Fig. 3 are valid, if the drop voltage on conduction devices is neglected. Partition times of intervals are calculated with the following relations:

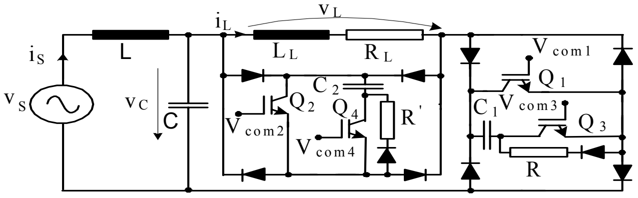

Fig.1 Power circuit of ac chopper which use capacitors to improve switching

$$\begin{cases} t_1 = KT-(D+1)\frac{T}{2}+\tau_b+\tau_1,\ t_2 = KT-(1-D)\frac{T}{2}-\tau_1, \\ t_3 = KT-(1-D)\frac{T}{2}, t_4 = t_3+\tau_b,\ t_5 = t_4+\tau_1, \\ t_6 = KT+(1-D)\frac{T}{2}-\tau_1, t_7 = t_6+\tau_1,\ t_8 = t_7+\tau_b,\ t_9 = t_8+\tau_1 \end{cases} \qquad (1)$$

On the first interval, $t\in[t_1,t_2]$ Q_1 is on and the load is connected to the power supply. The load voltage is given by,

$$v_L = v_S - L\frac{di_S}{dt} \quad t\in[t_1,t_3] \qquad (2)$$

The transistor Q_1 will discharge the capacitor C_1, through the resistor R connected in series with Q_1. On the second interval of time $t\in[t_2,t_3]$, Q_3 is turned on, which leads to the connection of C_1 in parallel with Q_1. The load remains connected to the power supply. At the end of this interval of time, Q_1 is turned off. On the third interval, $t\in[t_3,t_4]$, only Q_3 remains on. Through capacitor C_1 will flow the load current. Assuming that this current is constant, with the value I_{LK}, the capacitor voltage is:

$$v_{C1k} = \frac{1}{C_1}I_{LK}t,\quad t\in[t_3,t_4] \qquad (3)$$

and at the end of the interval, the capacitor voltage is:

$$V_{C1K} = \frac{1}{C_1}I_{LK}\tau_b \qquad (4)$$

On the fourth interval t∈[t$_4$,t$_5$], Q$_2$ is turned on and the load voltage is zero.

$$v_L = 0,\ \ t\in[t_4, t_7] \tag{5}$$

The resistance R' will discharge the capacitor C2, and the capacitor C will be connected in parallel with capacitor C$_1$.

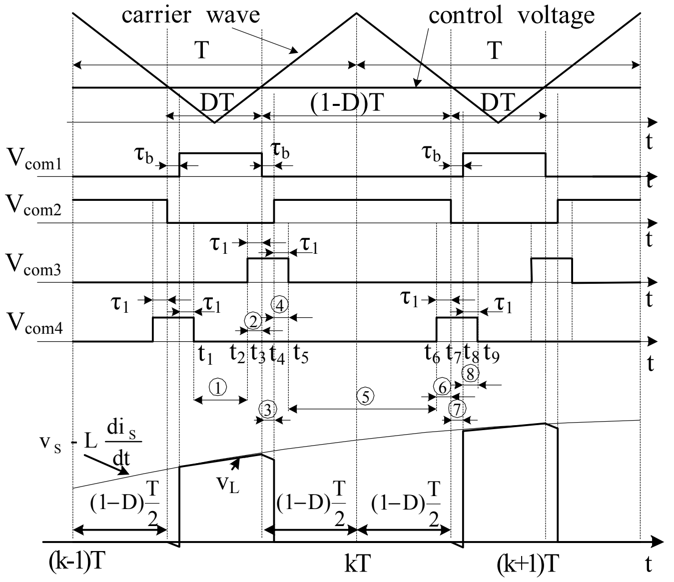

Fig.2. Generation of the control signals and load voltage waveform v$_L$

Assuming that in the moment t$_4$ the voltage on capacitor C has the value V$_{CK}$, after connection in parallel of the capacitors, the voltage on these will be:

$$V'_{C_1K} = V'_{CK} = \frac{CV_{CK} + C_1V_{C1K}}{C + C_1} = \frac{1}{C + C_1}(CV_{CK} + I_{LK}\tau_b) \tag{6}$$

The energy stored in capacitor C$_1$, in this moment is:

$$W_{C1K} = \frac{1}{2}C_1(V'_{C1K})^2 = \frac{1}{2}\frac{C_1}{(C + C_1)^2}(CV_{CK} + I_{LK}\tau_b)^2 \tag{7}$$

On the fifth interval, t∈[t$_5$,t$_6$], Q$_3$ is turned off and capacitor C accumulates energy through i$_S$ current. On the sixth interval, t∈[t$_6$,t$_7$] Q$_4$ is turned on and will connect C$_2$ in parallel with Q$_2$. On the seventh interval t∈[t$_7$,t$_8$], Q$_2$ in turned off. The capacitor C$_2$ accumulates energy through I$_{LK}$ current and at the end of the interval, the capacitor voltage is given by:

$$V_{C2K} = \frac{1}{C_2}I_{LK}\tau_b \tag{8}$$

Finally, on the eighth interval t∈[t$_8$,t$_9$], Q$_1$ is turned on, resistor R discharges the capacitor C$_1$, at the same time the capacitor C$_2$ will be connected in parallel with capacitor C. The final voltage on the capacitors, will be:

$$V''_{C2K} = V''_{CK} = \frac{1}{C + C_2}(CV_{CK} + I_{LK}\tau_b) \tag{9}$$

and the energy stored in capacitor C$_2$ is:

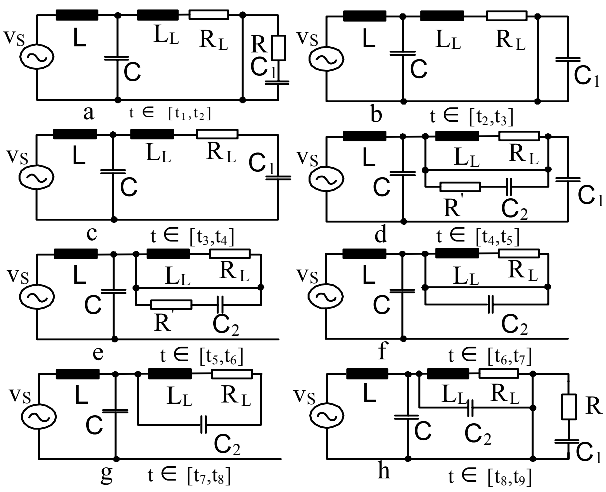

Fig.3 Equivalent circuits of the ac chopper which use capacitors to improve switching

$$W_{C2K} = \frac{1}{2}C_2(V''_{C2K})^2 = \frac{1}{2}\frac{C_2}{(C + C_2)^2}(CV_{CK} + I_{LK}\tau_b)^2 \tag{10}$$

The losses on the chopper are given by the losses in conduction and the losses on commutation of the electrical devices, as well as by the energies stored in the capacitors. If the f$_S$ is the a.c. voltage frequency of the power supply, the average power lost on discharge of the capacitors C$_1$ and C$_2$ can be calculated with the following relation:

$$P = f_S\left[\frac{C_1}{(C + C_1)^2} + \frac{C_2}{(C + C_2)^2}\right]\sum_{K=1}^{m}(CV_{CK} + I_{LK}\tau_b)^2 \tag{11}$$

Adopting equal values for both capacitors C$_1$ = C$_2$, we obtain:

$$P = \frac{2C_1f_S}{(C + C_1)^2}\sum_{K=1}^{m}(CV_{CK} + I_{LK}\tau_b)^2,\ \ k = \overline{1,m},\ \ m = \frac{T_S}{T} \tag{12}$$

Assuming that the voltage of the power supply, the current generated by the power supply and the load current are sinusoidal,

$$v_S = \hat{V}_S\sin\omega t,\ \ i_S = \hat{I}_S\sin(\omega t - \varphi_S),\ \ i_L = \hat{L}_L\sin(\omega t - \varphi_L) \tag{13}$$

we can write the following relations:

$$I_{LK} = \hat{I}_L \sin\left[(2K-1)\frac{\pi}{m} - \varphi_L\right],$$
$$V_{CK} = \hat{V}_S \sin(2K-1)\frac{\pi}{m} - \frac{2\pi L}{T_S}\hat{I}_S \cos\left[(2K-1)\frac{\pi}{m} - \varphi_S\right] \quad (14)$$

III. USING RESISTORS TO IMPROVE THE COMMUTATION

Fig. 4 shows the power circuit, which use resistors in order to improve commutation. As in the previous circuit, the resistors are connected only during commutation, and the control signal for IGBT's are generated in the same manners as in Fig. 2.

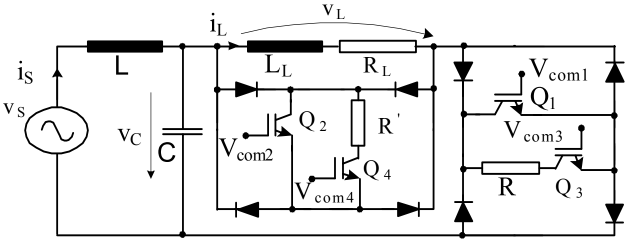

Fig.4. Power circuit of ac chopper which use resistors to improve switching

The functioning of the circuit must be analyzed on the same 8 time intervals, corresponding to the equivalent circuits in Fig. 5. On the first and the second time interval, $t\in[t_1,t_2]U[t_2,t_3]$ Q_1 is on, the load is connected to the power supply and the load voltage is given by (3). On the third interval $t\in[t_3,t_4]$, only Q_3 is on. We assume that the load current I_{LK} flowing through resistor R, is constant on this short interval. The voltage of the resistor and the average power transformed in to the caloric power by the resistor, are given by:

$$v_{RK} = R \cdot I_{LK}, \quad P'_{RK_{AVR}} = R \cdot I_{LK}^2 \frac{\tau_b}{T}, \quad t \in [t_3, t_4] \quad (15)$$

On the fourth interval $t\in[t_4,t_5]$, Q_2 is also turned on, the load voltage becomes zero, the capacitor C is connected in parallel with R and the average power transformed into caloric power by the resistor is:

$$P''_{RK_{AVR}} = \frac{V_{CK}^2}{R}\frac{\tau_1}{T}, \quad t \in [t_4, t_5] \quad (16)$$

.On the fifth and sixth interval $t\in[t_5,t_6]U[t_6,t_7]$, Q_2 is steal on, the load is steal connected in short-circuit, and the capacitor C is charged by the current i_S. On the seventh interval $t\in[t_7,t_8]$, only Q_4 is on, and the resistor R' is connected in parallel with the load.

$$v_{LK} = -R' I_{LK}, \quad t \in [t_7, t_8] \quad (17)$$

The averaged power transformed into caloric power by the resistor R' is:

$$P'_{R'K_{AVR}} = R' I_{LK}^2 \frac{\tau_b}{T} \quad t \in [t_7, t_8] \quad (18)$$

Finally, on the eight interval $t\in[t_8,t_9]$, Q_1 and Q_4 are on, the load is connected to the power supply, and the resistor R' is connected in parallel with the capacitor C. The average power is transformed into caloric power by the resistor:

$$P''_{R'K_{AVR}} = \frac{V_{CK}^2}{R'}\frac{\tau_1}{T}, \quad t \in [t_8, t_9] \quad (19)$$

The average power transformed into caloric power by the switching resistors R and R' is calculated by the relation:

$$P = \sum_{K=1}^{m}\left(P'_{RK_{AVR}} + P''_{RK_{AVR}} + P'_{R'K_{AVR}} + P''_{R'K_{AVR}}\right) = \frac{R+R'}{T}\sum_{K=1}^{m}\left(\tau_b I_{LK}^2 + \frac{1}{RR'}\tau_1 V_{CK}^2\right) \quad (20)$$

If R'=R and $\tau_b=\tau_1=\tau$, the relation (20) becomes:

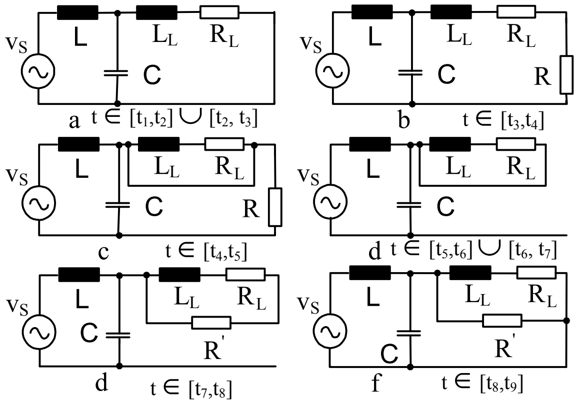

Fig.5 Equivalent circuits of the ac chopper which use resistors to improve switching

$$P = \frac{2R\tau}{T}\sum_{K=1}^{m}\left[I_{LK}^2 + \left(\frac{V_{CK}}{R}\right)^2\right] \quad (21)$$

The power control characteristic of the a.c. chopper express the fact that the ratio between the average load power P_{LAVR}, and the maximum load power transformed into caloric power by R_L, P_{LMAX} depends on the duty factor D. These powers are:

$$P_{L_{AVR}} = R_L \frac{\hat{I}_L^2}{2}, \quad P_{L_{MAX}} = \frac{R_L V_S^2}{R_L^2\left(1-\varpi^2 LC\right)^2 + \varpi^2\left(L + L_L - \varpi^2 L L_L C\right)^2} \quad (22)$$

The maximum load power is obtained when D = 1, so Q_1 is always in conduction, and Q_2 is always blocked. The relation gives the efficiency of the a.c. chopper:

$$\eta = \frac{R_L \hat{I}_L^2}{\hat{V}_S \hat{I}_S \cos\varphi_S} \qquad (23)$$

IV. SIMULATION RESULTS

The good functioning of the proposed circuits was checked by simulation. We considered a strong inductive load with R_L = 7Ω and L_L=32mH. We adopted a carrier frequency f = 1/T = 5KHz, so m = T_S/T = 100. Fig. 6 presents the waveform of the load voltage v_L for D = 0,6.

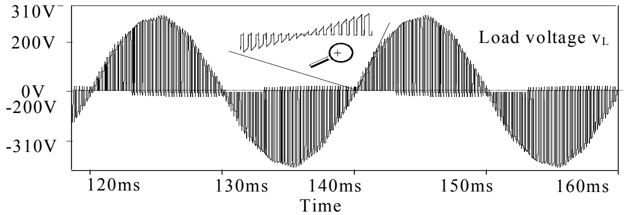

Fig.6 Load voltage waveform for D =0.6

Fig. 7 presents the waveforms of the current generated by the power supply and of the load current for three values of the duty factor D, when commutation is improved by the use of the capacitors. For dead times and the control superimposed time we adopt the values τ_b = 2μs, τ_1 = 1,5μs.

Fig.8 presents the normalized control power characteristic. We notice that, this characteristic is more linear than the one obtained in [5]. Improving commutation was necessary in order to increase efficiency.

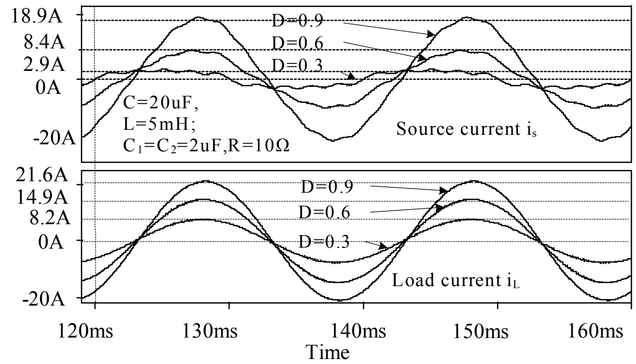

Fig.7 Waveforms of the source current i_S and lode current i_L with improve switching by capacitors.

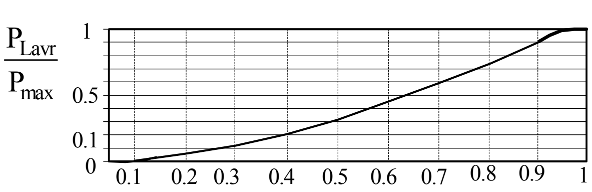

Fig.8. Control power characteristic

Simulations were made for the circuit in Fig.4, too. Thus, Fig. 9 presents the waveforms of the current generated by the power supply and the load current for three values of the duty factor D, when commutation is improved by the use of the resistor. The variation curve of the efficiency with the duty factor D obtained by simulation is presented in Fig. 10. We notice that, in the normal work zone, the efficiency is very good, varying between 0,85 and 0,95.

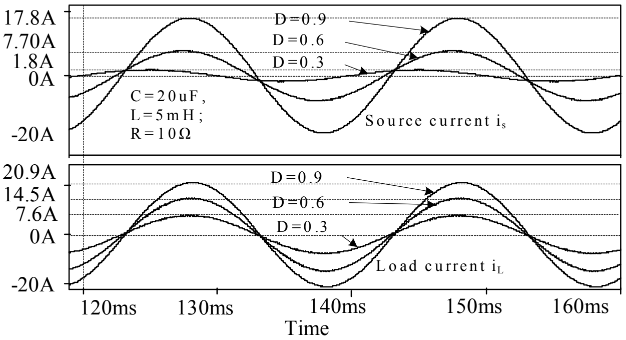

Fig.9 Waveforms of the source current i_S and lode current i_L with improve switching by resistors.

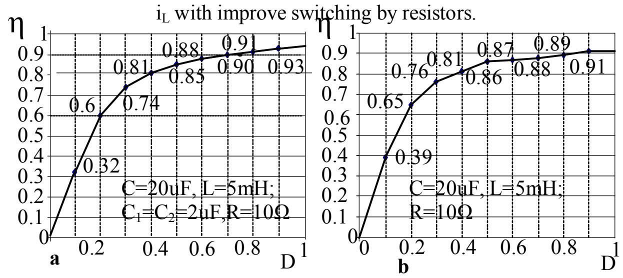

Fig.10 Efficiency variation with duty factor D with improve switching: a) capacitors b) resistors

V. CONCLUSIONS

The results of the simulation proved that by using the circuits for improving commutations, the waveforms of the current generated by the a.c power supply remain very good, practical sinusoidal while the efficiency increases significantly. The harmonics spectrum of the power supply current is lower if we use resistors. For high values of the duty factor D, efficiency id better when we use capacitors; for low values, efficiency is better then we use resistors. In both situations, the control characteristic is more linear.

REFERENCES

[1] G. N. Revankar, D.S.Trasi, ''Symmetrical Puls Width Modulated A.C.Chopper'', I.E.E.E. Trans on Ind. Electron. Contr. Instrum. Vol .IECI-24, 1977, pp 41-45.

[2] G. Choe, M. Park, ''An Improved PWM Technique for A.C. Chopper'', IEEE Trans. on Power Electronics, Vol.4, 1998, pp.496-505.

[3] D. Jang, G. Choe, '' Asymmetrical PWM Method for A.C. Chopper with Improved Input Power Factor'', I.E.E.E.- PESC Conf. Rec., 1991, pp 838-845.

[4] Jang Do-Hyum, Ghy-Ha Choe, M. Ehsani, ''Asymmetrical PWM Technique with Harmonic Elimination and Power Factor Control in A. C. Chopper'', I.E.E.E. Trans. on Power Electronics, Vol. 10, Nr. 2, March 1995, pp 175-184.

[5] M. Lucanu, O. Ursaru, C. Aghion, ''Single Phase A.C. Chopper with IGBT's '', Proc. Of the I.E.E.E. SCS2003, Iasi, Romania, pp.213-216.