MEMOIRS OF THE SCHOOL OF ENGINEERING, OKAYAMA UNIVERSITY, Vol. 2, No. 1, APRIL, 1967

Analysis of a Half-Controlled Single-Phase Bridge Circuit with Free-Wheeling Diode (II)

Toyoji HIMEI and Jyunichi INOUE

Department of Electrical Engineering

(Received December 28, 1966)

This paper is presented on the operation of the phase controlled single-phase bridge circuit with a free-wheeling diode, which has capacitance in parallel with the inductive load. Such circuit configuration is frequently met with, for instance, at the time when the more smoothness of d-c voltage is required, the higher reliability of SCR's firing is taken into account or load windings include some capacitance which is not negligible. The capacitance influences not only largely upon SCR's rush current but also significantly upon control characteristics of the circuit such as wave forms, pulsating ratio and power factor etc. Here, the various effects of the capacitance on the circuit performance are discussed.

§ 1. Introduction

Because of the features such as small size, small forward voltage drop, short turn-off time and large amplification, silicon controlled rectifiers (SCRs) have been used in many application fields, particularly in rectifier fields. Essentially by varying the firing angles of the SCRs, it is possible to control load voltage smoothly over the range between maximum available and zero. The operation, however, is much different from that of the conventional silicon rectifier diodes, which is larger pulsating ratio and reduced power factor etc.

A number of circuit configurations may be used for rectifier connections, among which bridge connections are particularly familiar[1] and have two different ways, that is; all rectifying devices are phase controlled (all SCRs bridge connection) and half the rectifying devices are made rectifier diodes, the others remaining SCRs (half-controlled bridge circuit). All SCRs bridge connection system is very useful when it is used as electric car rectifiers because of its possibility of regenerative braking. When the regenerative characteristic, however, is not necessary, it is usual for a free-wheeling diode to be connected in parallel with the load, which results in a small ripple voltage and reduced reactive power. A half-controlled bridge circuit is frequently used because this circuit operates as the same as that of the all SCRs bridge connection with a free-wheeling diode. What's more, it is extremely economical, since halves of SCRs are replaced with rectifier diodes. On the half-controlled bridge circuit, however, when the phase retard becomes larger than 90 degrees, so-called "half-waving" effect can take place[2], which results in losing control characteristic (this does not occur in the single-phase doubler connection). In order to avoid this phenomenon, it is a conventional procedure to connect a free-wheeling diode in parallel with the load. Since this procedure leads the operation of a-c side equal to having resistive load, all SCRs bridge connections and half-controlled bridge connections are regarded to operate under the same manner. Upon the above reason, analysis of the circuit operation of a half-controlled single-phase bridge circuit with a free-wheeling diode, which has the inductive load, has been the subject of the previous paper[3] in which the source impedance is taken negligible or only resistive.

It is very useful to take the source impedance pure resistive but in practice the transformer leakage reactance or stray reactance of the lead wire can sometimes become large to some degree which is not negligible. Further more, it frequently happens that the capacitance exists in parallel with the inductive load such as a smoothing condenser, a compensating condenser for the SCR's firing or the stray capacitance of the inductive load. In such case, the circuit operation becomes much different from that of the inductive load only. Resonance circuits are composed of between the capacitance and the source impedance or the load circuit. Consequently, control characteristics may come sometimes to lose the smoothness and also the wave form can come to get out of shape. Analysis of such circuit configuration which in future will be used more and more, has been presented in some references[4] but restricted to only "one sequence" of the operation modes (see Table 1), and not referred to the others. References on the SCR's circuit configuration have not yet been seen.

In this paper, the steady-state operation of a half-controlled single-phase bridge circuit with a free-wheeling diode which has capacitance in parallel with the inductive load, has been treated analytically. Here, the following characteristics have been discussed; control characteristics as functions of firing angle, pulsating ratio of d-c voltage and current, power factor, L-R-C resonance and the behavior of the counter emf load.

§ 2. Circuit Analysis

The circuit configuration, shown in Fig. 1, is the common cathode. Capacitance is connected in parallel with an inductive load. In order to simplify the analysis, it is assumed that

1) the forward voltage drops of SCRs and rectifier diodes are negligible,

2) the leakage currents of SCRs and rectifier diodes are negligible,

3) the turn-on and turn-off time of SCRs is negligible,

4) the commutating phenomena can take place only within the free-wheeling diode D_f and load branch, and

5) the wave form of the supply voltage is sinusoidal.

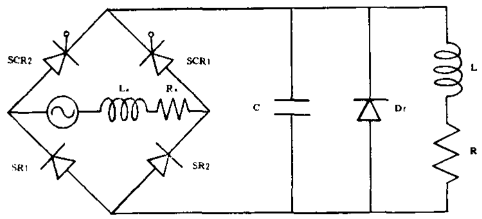


Fig. 1. Phase controlled single-phase bridge circuit with free-wheeling diode, which has capacitance in parallel with the inductive load.

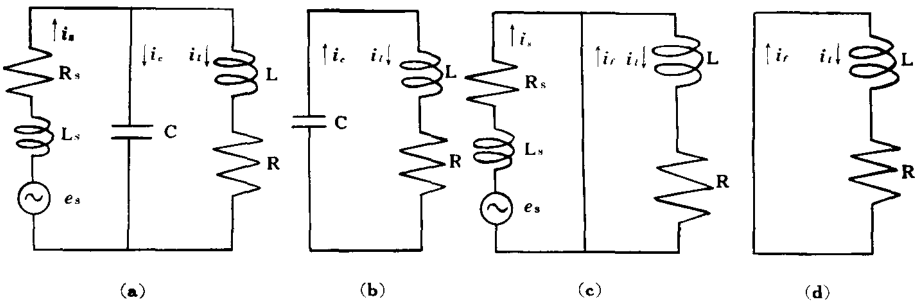


Fig. 2. Equivalent circuits according to the circuit operation.

The circuit operation of the a-c side can be divided into four operation modes, whose equivalent circuits are shown in Fig. 2 (a), (b), (c) and (d). The mode (a) corresponds to the so-called "rectifying period" when the energy flow is from the a-c side to the d-c side. In the mode (b), the a-c current is blocked but the load voltage is not zero. The mode (c) is the so-called "commutating period" and occurs just after one SCR has turned to conducting. The mode (d) expresses the period when the free-wheeling diode D_f is conducting. The circuit expressions corresponding with the operation modes are, in the mode (a)

$$E_m \sin(\omega t+\theta)=R_s i_s+L_s\frac{di_s}{dt}+\frac{1}{C}\int i_c dt \quad (1)$$

$$-\frac{1}{C}\int i_c dt+Ri_L+L\frac{di_L}{dt}=0 \quad (2)$$

$$i_C+i_L=0 \quad (3)$$

in the mode (b)

$$-\frac{1}{C}\int i_C dt+L\frac{di_L}{dt}+Ri_L=0 \quad (4)$$

$$i_C=-i_L \quad (5)$$

in the mode (c)

$$E_m \sin(\omega t+\theta)=R_s i_s+L_s\frac{di_s}{dt} \quad (6)$$

$$Ri_L+L\frac{di_L}{dt}=0 \quad (7)$$

$$i_s+i_f=i_L \quad (8)$$

Table 1. Classification of Sequences. (a), (b), (c) and (d) refers to Fig. 2. ①, ②, ③ and ④ designate the classification of sequences.

classification	sequence of operation modes \ operation modes	(c)		(a)		(b)		(a)		(b)		(c)		(d)	
①	sequence			→○		→○									
	boundary condition			$\omega t=\omega t_1(=0)$ $i_b=0$ $i_c=i_L$ $=I_{Lt_1}$ $=I_{Lt_0}$	$i_b=0$ $-i_c=i_L$ $=I_{Lt_2}$	$\omega t=\omega t_2$ $-i_c=i_L$ $=I_{Lt_2}$	$-i_c=i_L$ $=I_{Lt_3}$ $=I_{Lt_0}$	$\omega t=\omega t_3(=\pi)$							
②	sequence	→○		→○		→○								→○	
	boundary condition	$\omega t=0$ $i_b=0$ $i_f=i_L$ $=I_{Lt_0}$	$i_f=0$ $i_b=i_L$ $=I_{Lt_1}$	$\omega t=\omega t_1$ $i_c=0$ $i_b=i_L$ $=I_{Lt_1}$	$i_b=0$ $-i_c=i_L$ $=I_{Lt_2}$	$\omega t=\omega t_2$ $-i_c=i_L$ $=I_{Lt_2}$	$-i_c=i_L$ $=I_{Lt_3}$	$\omega t=\omega t_3$						$\omega t=\omega t_6(=\omega t_3)$ $i_f=i_L$ $=I_{Lt_3}$	$i_f=i_L$ $=I_{Lt_0}$ $\omega t=\pi$
③	sequence	→○		→○								→○		→○	
	boundary condition	$\omega t=0$ $i_b=0$ $i_f=i_L$ $=I_{Lt_0}$	$i_f=0$ $i_b=i_L$ $=I_{Lt_1}$	$\omega t=\omega t_1$ $i_c=0$ $i_b=i_L$ $=I_{Lt_1}$	$i_L=I_{Lt_2}$	$\omega t=\omega t_2$						$\omega t=\omega t_5(=\omega t_2)$ $i_L=I_{Lt_2}$	$i_b=0$ $i_f=i_L$ $=I_{Lt_5}$	$\omega t=\omega t_6$ $i_f=i_L$ $=I_{Lt_6}$	$i_f=i_L$ $=I_{Lt_0}$ $\omega t=\pi$
④	sequence	→○		→○		→○		→○		→○				→○	
	boundary condition	$\omega t=0$ $i_b=0$ $i_f=i_L$ $=I_{Lt_0}$	$i_f=0$ $i_b=i_L$ $=I_{Lt_1}$	$\omega t=\omega t_1$ $i_c=0$ $i_b=i_L$ $=I_{Lt_1}$	$i_c=0$ $-i_b=i_L$ $=I_{Lt_2}$	$\omega t=\omega t_2$ $-i_c=i_L$ $=I_{Lt_2}$	$-i_c=i_L$ $=I_{Lt_3}$	$\omega t=\omega t_3$ $i_b=0$ $-i_c=i_L$ $=I_{Lt_3}$	$i_b=0$ $-i_c=i_L$ $=I_{Lt_4}$	$\omega t=\omega t_4$ $-i_c=i_L$ $=I_{Lt_4}$	$-i_c=i_L$ $=I_{Lt_5}$	$\omega t=\omega t_5$		$\omega t=\omega t_6(=\omega t_5)$ $i_f=i_L$ $=I_{Lt_5}$	$i_f=i_L$ $=I_{Lt_0}$ $\omega t=\pi$

in the mode (d)

$$Ri_L + L\frac{di_L}{dt} = 0 \qquad (9)$$

$$i_f = i_L \qquad (10)$$

where E_m is the peak value of the source voltage, θ is the firing angle, i_s is the a-c current, i_L is the load d-c current, i_c is the capacitance current, i_f is the current through the free-wheeling diode D_f.

The sequences of the operation modes in a half cycle, that is, from the instant when one SCR is fired until the other will be fired, is classified, as shown in Table 1. In the operation of the classification ①, the d-c voltage does not come to zero in a half cycle and the free-wheeling diode does not conduct all the way. In the a-c side, the resonant current flows through L_s, R_s and C.

However, in the classification ②～④, since D_f conducts always once in a half cycle, commutating periods are in existence just after one SCR has turned to conducting. The d-c voltage is zero when D_f is conducting. Therefore, these classifications appear when capacitance is not very large.

Classification ② expresses the operation that added to ① with both the commutating period and the D_f-conducting period. For the purpose of comprehension, the wave forms of each branch of the classification ② are shown in Fig. 3.

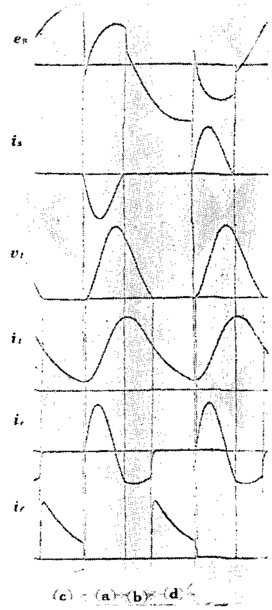


Fig. 3. Wave forms of each branch, corresponding to the classification ② (cf. Table 1).

Classification ③ expresses the operation that the a-c current flows like that of an inductive load, that is, i_s keeps flowing even after the source voltage drops to zero in the mode (a).

Classification ④ is, so to speak, the transition period operation, which suddenly appears as the firing angle θ increases in the state of the classification ②. If θ increases further more, this will shift to the classification ③. The a-c current flows discontinuously in a half cycle. Theoretically, discontinuous a-c currents may appear more than 2 times in a half cycle. This operation depends largely upon the SCR's grid input wave form. If one pulse input is added to the gates of SCRs, this phenomenon does not occur. Fig. 4 shows the wave forms of the classification ④; the a-c current, the capacitance current and the d-c voltage wave forms.

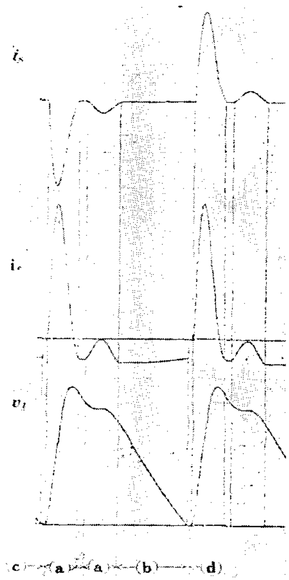


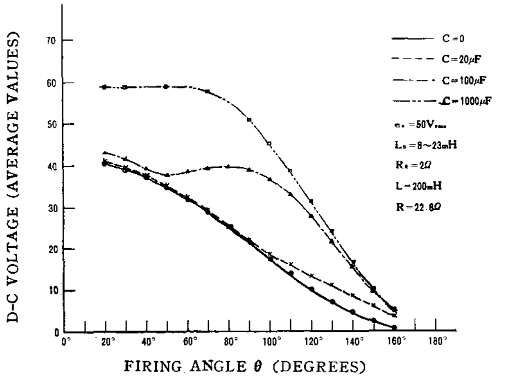
Fig. 4. Wave forms of the classification ④ (cf. Table 1).

§ 3. Control characteristics

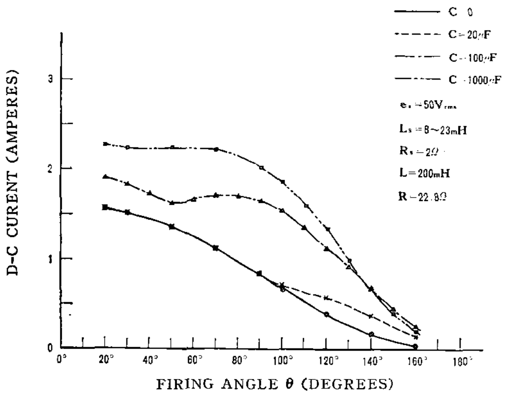
Control characteristics

The control characteristics of the d-c voltage, the d-c current and the a-c current as functions of the firing angles are shown in Fig. 5 (a), (b) and (c). Where, values of capacitance were changed while the other circuit constants kept unchanged. From the inspection, it can be seen that

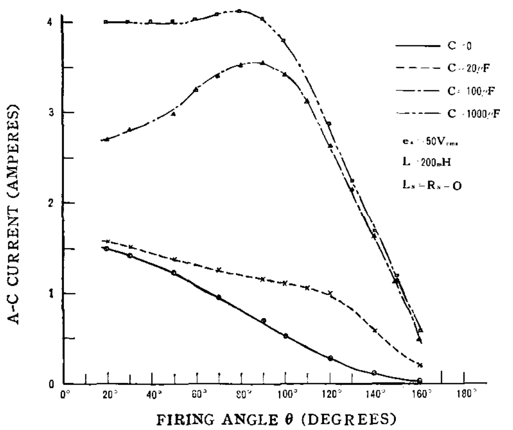
1) the output voltage and current increase



(a)



(b)



(c)

Fig. 5. Control characteristics.
(a); d-c voltage (average), (b); d-c current (average) and (c); a-c current (rms).

when capacitance is present.

2) the control characteristic curves are less smooth than that of the case that capacitance is not present. This reduction of smoothness originates in the transfer of the sequences of operation modes, as firing angles vary.

3) as capacitance will be large, the output grows large all over firing angles.

4) reasons of the increased output are: the load impedance becomes small when capacitance is present; in the a-c side, the presence of capacitance results more or less in the resonant current and so its peak value increases. It should be noted that if capacitance is connected for smoothing the d-c voltage, it is only the source impedance that suppresses the peak value of the capacitance charging current.

Control limitation

1) The controlled range will become somewhat limited when capacitance is present in the operation of the classification ①.

2) The d-c voltage is positive all the way in classification ①. When SCRs are not biased forward, they can not be fired. In the operation of the classification ①, the d-c voltage has some value. So if the a-c voltage is not larger than the d-c voltage, SCRs does not conduct in the succeeding half cycle.

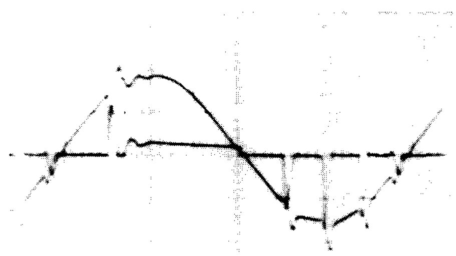


Photo 1. Wave forms of the a-c voltage and current. In the former half cycle, SCR's grid input is rectangular. In the latter half cycle, four pulses are added.

Input waveform

Although the presence of capacitance makes SCRs conduction initiate securely, the a-c current can flow oscillatory. This phenomenon results in the discontinuous a-c current. This operation, however, depends largely upon the SCR's grid input wave form. Photo 1 shows the bridge input a-c voltage and the a-c current wave forms. In the former half cycle, the rectangular grid input is provided to the SCR. In the latter, the pulse input is. In this photo, however, the pulses which were oscillated by the UJT pulse generator were added, and consequently four pulses appeared. Depending on input wave forms, the a-c current and the d-c output characteristics vary. Thus, in order to keep smoothness of the control characteristics, it is desirable that the grid input wave form is rectangular.

§ 4. Pulsation and Oscillation

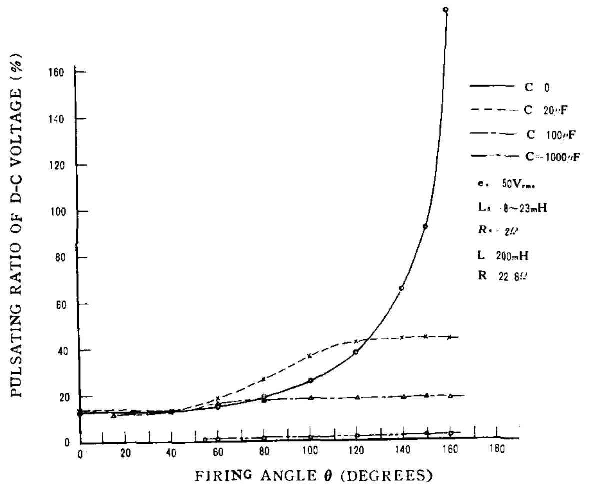
Pulsating ratio

Fig. 6 shows pulsating ratio of the d-c voltage and the d-c current. Capacitance influences upon the pulsating ratio as following.

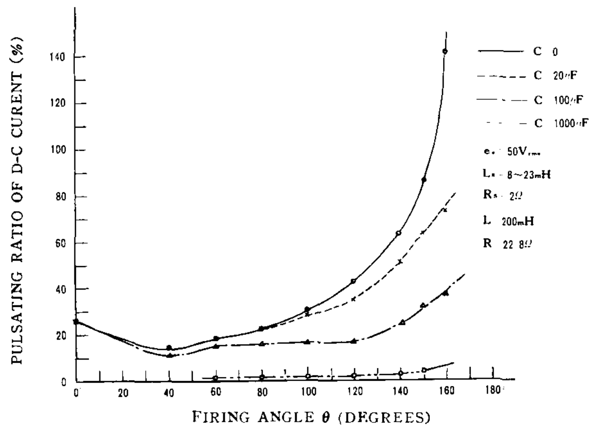
1) The pulsating ratio becomes smaller due to capacitance.

2) The larger capacitance, the smaller pulsating ratio.

3) In Fig, 6 it is also shown that the pulsating ratio of the d-c voltage grows larger under a certain condition than that of no capacitance. This results from the a-c oscillating current.



(a)



(b)

Fig. 6. Pulsating ratio.
(a); d-c voltage and (b); d-c current.

Smoothing inductance

If capacitance is used with inductance, to smooth the d-c voltage, the bridge a-c voltage and the load voltage becomes different in an instantaneous value. When the bridge d-c voltage reduces to zero, the load voltage is not necessarily zero, which means that a new operation mode takes place. So the smoothing inductance can not be taken as part of the source impedance. All SCRs bridge connection and the half-controlled bridge connection operate in different ways, because the function of the free-wheeling diode differs from that of no smoothing inductance. Thus, analysis of the circuit operation must be done respectively.

Fig. 7 shows the pulsating ratios of the d-c currents when the smoothing inductance was put into both d-c side and a-c side. It it clear that the operation modes and also their sequences are different.

§ 5. Power Factor

When SCRs are used to control the output voltage, the load current will lag the source voltage, and consequently the power factor will reduce more and more as the firing angle increases. Photo 2 shows the phase relation between the source voltage and current. Presence of capacitance will generally reduce the period of current conduction It can be seen from Fig. 8 that this results in the reduction of the power factor. From the inspection, when capacitance is 1, 000 μF, the reduction of the power factor varies smoothly as the firing angle increases. This is from the fact that the sequence of the operation modes is only of the classification ① all the way. It is noted that in this case, under 70 degrees of the firing angle, the control function is lost

§ 6. Counter emf

When counter emf load is connected, the current can flow through SCRs only when the a-c source voltage is greater than counter emf voltage. The range of the possible firing of SCRs will be limited more narrow than that of being without counter emf voltage. The output current flows through the energy subtracted from the source voltage by counter emf and diminishes to some degree, but the output voltage can grow larger (see photo 3 (a) and (b)). Further more, when the counter emf exceeds the voltage due to the energy trapped in the inductance, the d-c current will flow back from the d-c load to capacitance reversely and consequently will capacitance be charged. These phenomena are particular ones resulting from the presence of capacitance.

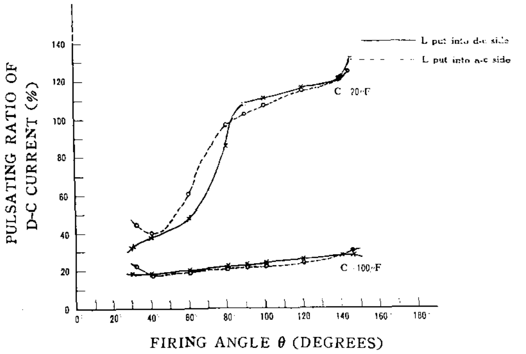


Fig. 7. Pulsating ratio when a smoothing inductance is added. solid line; when the inductance is added to the d-c side (as smoothing inductance).
dotted line; when the inductance is added to the a-c side.

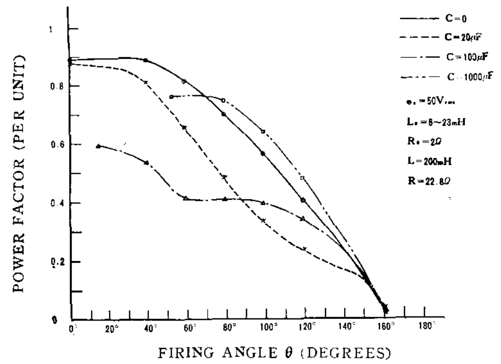


Fig. 8. Power factor, as functions of firing angle. Parameter is capacitance.

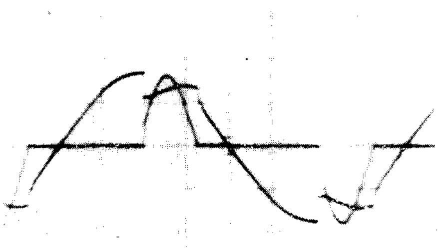


Photo 2. Wave forms of the bridge a-c voltage and the a-c current.

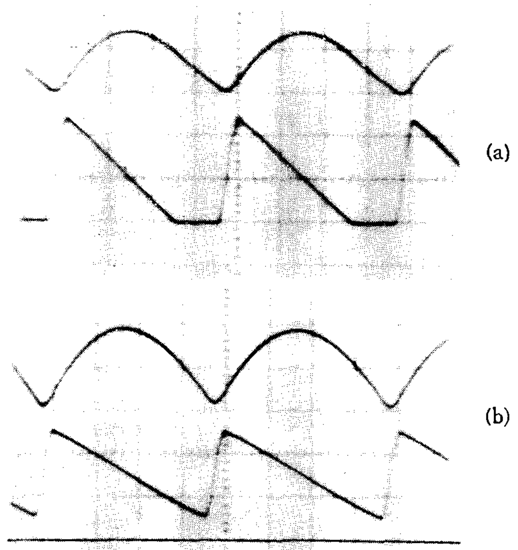


Photo 3. Wave forms of the d-c voltage and current. (a); without counter emf and (b); added counter emf. In each case, the upper trace is the d-c current and the lower trace is the d-c voltage.

§ 7. Conclusion

The circuit operation of the single-phase bridge connection with capacitance in parallel with the inductive load can be divided into four modes. The sequence of the operation modes can express all the performance. The presence of capacitance will result in the following,

1) the d-c voltage and current increases,
2) the control characteristics are not smooth,
3) pulsating ratio becomes small,
4) the power factor will not be always improved, and
5) the controlled range will be limited.

The authors are not in a position to tell the design details on SCRs rectifier connections, but it seems that it cannot be always expected to result in good contribution that capacitance is put into d-c side on purpose.

References

1) J. Schaefer: *Rectifier Circuits: Theory and Design*, (John Wiley, 1965)
2) D. W. Borst E. J. Diebold and F. W. Parrish: *Voltage Control by Means of Power Thyristors;* I. E. E. E. Transactions on Industry and General Applications, Vol. IGA-2, No. 2, Mar/Apr 1966
3) T. Himei, J. Inoue and K. Fukumori: *Analysis of a Half-Controlled Single-Phase Bridge Circuit with Free-Wheeling Diode* (1); Memoirs of The School of Engineering Okayama University, Vol. 1 No. 1, March, 1966.
4) for example, Text Book, "*Mercury-arc Rectifiers*" I. E. E. of Japan, 1953.