Self-load bank for UPS testing by circulating current method

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Abstract: For saving energy and reducing costs of the burn-in test of an uninterruptible power supply (UPS) system, the self-load bank by the circulating method is proposed. The AC/DC converter of the tested UPS itself is used as a nonlinear load, the tested current flow as a form of circulation, and the power of the tested load is controlled by a DC regulator also supplying the energy loss of the tested UPS. To test a linear load, a regulator is used to regulate the load characteristic. From the experimental results the energy saved in the burn-in test is approximately 80% of that lost by the conventional method, using a directly connected *RLC* or rectifier load.

1 Introduction

The priority for maintaining high operating reliability is essential for online UPS. Besides circuit design [1], the burn-in test of the UPS is an important consideration for maintaining high reliability prior to the UPS being taken over by users. The standard characteristic test for safety has been described in other literature [2, 3]. In this paper, energy savings and reduced test costs are proposed through the use of a self-load bank by circulating current for the burn-in test. In the conventional method, the *RLC* or rectifier load is directly connected for the burn-in test. It generally takes 24 to 72 hours to make the burn-in test with a full or half load. This dissipates a large amount of energy and increases the test costs of UPS.

Energy saving is the major purpose for reducing the test costs of the UPS. In the literature [4, 5] the energy feedback method was proposed by controlling the voltage magnitude and phase angle to decide the test load: *R*, *RL*, or *RC*. There is a disadvantage in that the frequency of the utility system must be equal to that of the UPS tested. For testing a nonsynchronised power supply [5], an AC/DC converter and a DC/AC inverter is used as an interface to synchronise the utility system and the tested UPS for parallel operation, therefore reducing absorbed energy from the utility system. The load characteristic is nonlinear.

In this paper, the self-load bank for UPS burn-in test by a circulating current method is proposed. Generally, an online UPS contains an AC/DC converter, a DC/AC inverter and battery. A typical burn-in test of the UPS is to operate the AC/DC converter and DC/AC inverter for about 24 to 72 hours before it is handed over to users. The backup time of the UPS is supplied by battery, not included in this burn-in test, but detailed in the literature [2, 3]. Usually, this backup time of the UPS supplied by the battery is very short, compared to the burn-in test supplied by the AC/DC converter. This means the dissipative energy in the backup time test is low. So in the process of the test, the load for testing the backup time of the UPS is directly connected to an *RLC* or rectifier load. Of course, the energy from the battery in the backup time test can be returned to the utility system by using the AC/DC converter and DC/AC inverter as a synchronising interface, for parallel operation with the utility system [5]. As a result, the method proposed in this paper uses the condition that the test UPS has an AC/DC converter and a DC/AC inverter.

Primarily, the AC/DC converter is used as a nonlinear load, the output of the tested on-line UPS is connected through an inductor to the input of the UPS, and a DC regulator is added to control the tested power and to compensate for the energy loss, which amounts to about 20% of the rated capacity of the UPS at full load. Therefore, completing the nonlinear load for the burn-in test, allowing different frequencies between the utility system and the tested UPS. This means that the proposed method can test the on-line UPS at any frequency output. Secondly, for testing a linear load, a load regulator is designed to simulate the linear load, *R*, *RL* and *RC*. The function of the load regulator is similar to an active filter compensator [6–8], with only minimal power loss in the circuit element. Finally, by using the proposed method, the process of the burn-in test of the online UPS can be performed with reduced energy dissipation and costs decreased. From the experimental results the amount of saved energy in the burn-in test of an online UPS is about 80%.

2 Block diagram of burn-in test system

The burn-in test system block diagram for the proposed method is enclosed by the dotted line shown in Fig. 1. The burn-in test system uses the AC/DC converter, which is a partial UPS, as a nonlinear test load. So the output terminal of the tested UPS is connected through a filter inductor L_a to the input terminal of the UPS. The tested load current is controlled by the DC regulator, voltage value V_{dc}, and the filter–inductor L_a. Output current waveforms I_o from the UPS can be regulated by the load regulator to simulate an approximate linear load *R*, *RL* and *RC*. The load regulator is controlled as a reac-

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tive compensator and will not absorb average power. Under these conditions, the output power of the tested UPS is the same as the input power of the UPS. The input power (input current I_s) is controlled by the direct

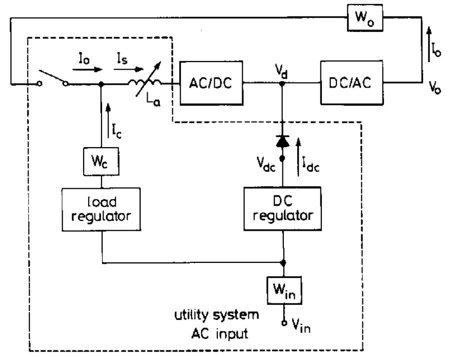

Fig. 1 *Block diagram of burn-in test system by means of circulating current method*

voltage V_{dc} and inductor L_a, meaning that the output power of the tested UPS can be controlled by V_{dc} and L_a.

As shown in Fig. 1, the burn-in test system uses the AC/DC converter of a partial UPS as a load, and the tested current takes a circulating form. The power of the tested load is supplied by the output of the DC/AC inverter of the UPS and is absorbed by the input of the AC/DC converter of the UPS. So the tested energy will not be dissipated and is circulated in the UPS. This process is called Self-Load bank. Due to the existence of losses from all the circuit elements, a UPS tested by the circulating current method for the burn-in test must be supplied with the lost energy to maintain the voltage V_{dc} at a constant value. So the DC regulator is used, both to control the output power of the tested UPS, and to supply the loss energy of the tested UPS. In the same manner, the load regulator will lose some energy, but this will be compensated by a rectifier circuit described in Section 4.

3 Basic principle of AC/DC load

An AC/DC converter is adopted to supply the direct voltage to the DC/AC inverter of the UPS. The types of AC/DC converter are various [9]; in this paper, the phase-controlled rectifier is used as an example in the tested UPS. The technology of the phase controlled AC/DC converter is well documented. Two possible operation modes, discontinuous and continuous, are described in the literature [10–12], for the phase controlled AC/DC converter. The single-phase half-controlled rectifier operated in discontinuous condition, as shown in Fig. 2, is mentioned as follows. Assume

$$v_s = \sqrt{(2)}\,|V_s|\sin\omega t$$

$$m = V_d/[\sqrt{(2)}\,|V_s|]$$

If the output current i_d is discontinuous, i_d goes to zero before $\omega t = \pi + \delta$. After the pulse of gate current i_g is applied, thyristor S_1 and diode D_4 in Fig. 2 are conducting, then

$$i_d(t) = \frac{1}{\omega L_f}\int_{\delta}^{\omega t} [\sqrt{(2)}\,|V_s|\sin\omega t - V_d]\,d(\omega t) \qquad \delta \leqslant \omega t \leqslant \pi + \delta \quad (1)$$

From eqn. 1, eqn. 2 is developed as

$$i_d(t) = \frac{\sqrt{(2)}\,|V_s|}{\omega L_f}[\cos\delta - \cos\omega t - m(\omega t - \delta)] \qquad \delta \leqslant \omega t \leqslant \pi + \delta \quad (2)$$

From Fig. 3, the current falls to zero at instant $\omega t = \delta + \gamma$, so $i_d(t) = 0$, then

$$\cos\delta - \cos(\delta + \gamma) - m\gamma = 0 \quad (3)$$

The average value of the rectifier current is

$$I_d = \frac{1}{\pi}\int_{\delta}^{\delta+\gamma} i_d\,d(\omega t)$$
$$= \frac{\sqrt{(2)}\,|V_s|}{\pi\omega L_f}[\gamma\cos\delta + \sin\delta - \sin(\delta + \gamma) - m\gamma^2/2] \qquad \delta \leqslant \omega t \leqslant \pi + \delta \quad (4)$$

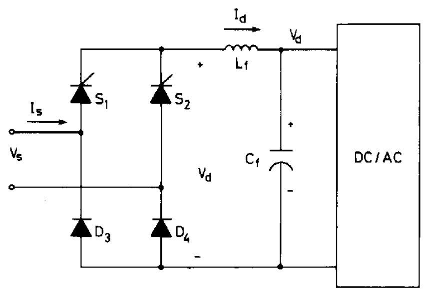

Fig. 2 *Half-controlled single-phase AD/DC converter*

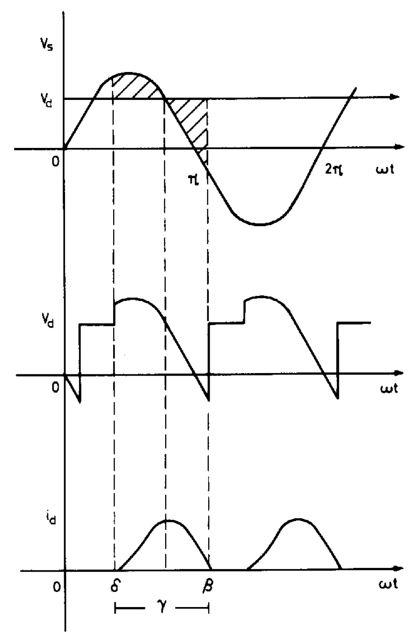

Fig. 3 *Waveforms of current and voltage in circuit of Fig. 2 in discontinuous mode*

The RMS value of the output current I_{dr} is given by

$$I_{dr} = \left(\frac{1}{\pi}\int_{\delta}^{\delta+\gamma} i_d^2\, d(\omega t)\right)^{1/2} \quad (5)$$

Due to the RMS input current I_{sr} being equal to the RMS value of the output current I_{dr}, the input power factor is calculated as

$$PF = VI_d/|V_s|I_{sr} = \sqrt{(2)}mI_d/I_{dr} \quad (6)$$

From eqn. 2, the current $i_d(t)$ of the AC/DC can be controlled by the filter inductor L_f and the fire angle δ. The firing angle δ is regulated by the feedback output voltage V_d. If the output voltage can be regulated to keep a constant value, the firing angle δ and the current $i_d(t)$ will consequently produce the constant value. Similarly, the three-phase phase-controlled AC/DC converter can also use the same principle to control its input current for the tested power control.

4 Self-load bank analysis

Fig. 4 shows the sample block diagram of the self-load bank test system for the burn-in test by the circulating

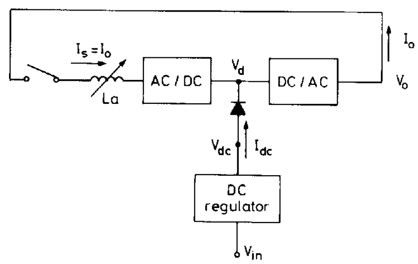

Fig. 4 *Example block diagram of self-load bank test system*

current method. The load of the UPS is the internal phase controlled AC/DC converter of the UPS, and the load is nonlinear. The tested current forms a circulating current form. If all the circuit elements were ideal, and therefore did not lose any energy, the output current of the UPS would not be interrupted, and would circulate continuously. But as all of the circuit elements will lose some energy the efficiency of the tested UPS is less than 1. So the DC regulator is used to compensate the loss energy of the tested UPS in this proposed method, and from Section 3 the input current $i_s(t)$ of the AC/DC converter of the tested UPS can be controlled by the filter inductor and output voltage V_d. The DC regulator does not only supply the loss energy of the UPS but also controls the tested current of the UPS. The voltage V_{dc} is regulated by the DC regulator for controlling the output current of the tested UPS. The control range of V_{dc} will be kept between $V_{d,max}$ and $V_{d,min}$. $V_{d,max}$ is the maximum control voltage of the AC/DC converter of the tested UPS, and if V_d is higher than $V_{d,max}$ the firing angle δ cannot be fired and the input current I_s falls to zero. $V_{d,min}$ is the minimum value of voltage of the tested UPS, and if V_d is lower than $V_{d,min}$, the UPS will be detected and turned off. For extending the range of the tested current of the UPS, the filter inductor can be used to regulate the tested current. But the filter inductor L_f is inherent in the UPS and cannot be regulated. So a regulating inductor L_a is connected in series between the output and input terminal of the tested UPS. Now let I_{base} be assumed to be

$$I_{base} = \sqrt{(2)}|V_s|/\omega(L_f + L_a) \quad (7)$$

The variation of normalised average current, normalised RMS current, and power factor with capacitor voltage m ($m_1 = 0.55$, $m_2 = 0.6$, $m_3 = 0.65$, $m_4 = 0.7$, $m_5 = 0.75$, $m_6 = 0.8$), conduction angle γ, and firing angle δ in a half-controlled AC/DC converter are shown in Fig. 5.

In the preceding description, the circulating current test method uses the AC/DC converter of the UPS itself as a nonlinear load, the DC regulator supplies the loss energy and controls the tested current. In this proposed method for the burn-in test of the UPS, a large amount of energy is saved, dissipated in the conventional test method connected directly by R, RL, RC and rectifier load. The function of the DC regulator is to compensate for the loss of energy of the UPS and to control the tested power by its output voltage V_{dc}, so the utility AC-source V_{in} supply to the DC regulator and the tested UPS alternating output voltage V_0 will allow for different frequencies.

5 Load regulator

The burn-in test of the UPS uses the circulating current method for saving energy and decreasing the test costs. The load of the AC/DC converter in this tested UPS is only a nonlinear load. For testing a linear load, R, RL and RC, the load regulator is designed to simulate a linear load. The load regulator is a compensator to make the output current I_o of the tested UPS a linear load, changing the load characteristic for the burn-in test. The simple block diagram of the entire test system is shown in Fig. 6. Fig. 7 shows the load regulator which is a current-controlled PWM type inverter [6–8]. To compensate the output current of the tested UPS for an R, RL, and RC load, the compensatory current $i_c(t)$ can be calculated by

$$P_o = V_o I_o \cos\theta \quad (8)$$

where P_o is the test power absorbed by the AC/DC converter load. The regulated current $i_o(t)$ can be calculated to form any R, RL, or RC load. Assume

$$v_o(t) = |V_o| \sin \omega t \quad (9)$$

$$i_o(t) = |I_o| \sin(\omega t \pm \theta) \quad (10)$$

then

$$i_c(t) = i_s(t) - i_o(t) \quad (11)$$

The calculated block diagram of the load regulator is shown in Fig. 8. The only function of this load regulator is to compensate the reactive power. Therefore the power factor of the output current I_o will be limited depending on the test power P_o. Normalising the test power P_o, V_o and I_o, the power factor is

$$PF = \cos\theta = P_{o,pu}/(V_{o,pu} I_{o,pu}) \quad (12)$$

where $V_{o,pu} = 1$ and $I_{o,pu} = 1$. So the minimum power factor PF_{min} of the output current of the UPS is regulated by the load regulator, and can be given as

$$PF_{min} = \cos\theta \geqslant P_{o,pu} \quad (13)$$

Since the load regulator compensates only the reactive power, it will not dissipate the average energy if the power switch is in ideal conditions without loss. But it is impossible that the load regulator will not dissipate the switch loss, so a rectifier circuit is added to compensate the loss of the load regulator, connected in parallel with the capacitor C_i of the load regulator shown in Fig. 7. In this test system, the UPS output voltage is 110 V. 155 V is supplied to the secondary isolation transformer T_r, for compensating the load regulator loss, and the rated capacity of the isolation transformer is about 20% of that of the load regulator.

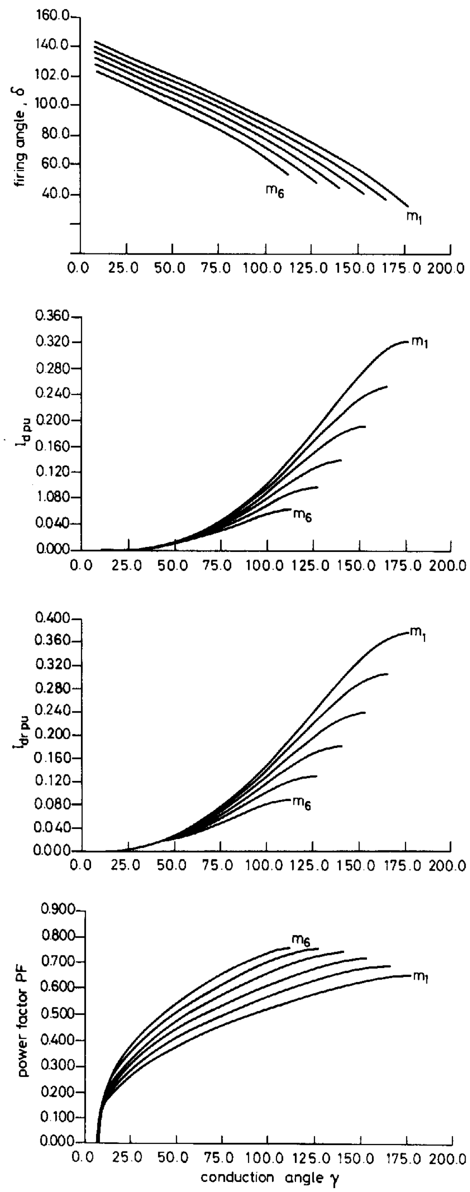

Fig. 5 *Variation of fixing angle, normalised average current, normalised RMS current, and power factor with capacitor voltage m and conduction angle γ in half-controlled AC/DC converter*

$m_1 = 0.55, m_2 = 0.6, m_3 = 0.65, m_4 = 0.7, m_5 = 0.75, m_6 = 0.8$
$I_{base} = \sqrt{(2)}|V_s|/\omega(L_a + L_f)$

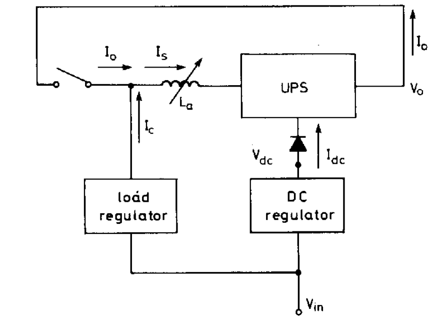

Fig. 6 *Simple block diagram of entire burn-in test system*

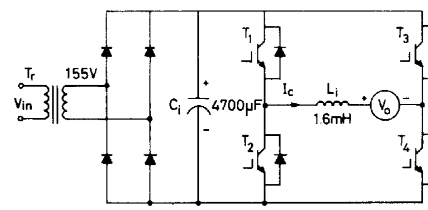

Fig. 7 *Load regulator*

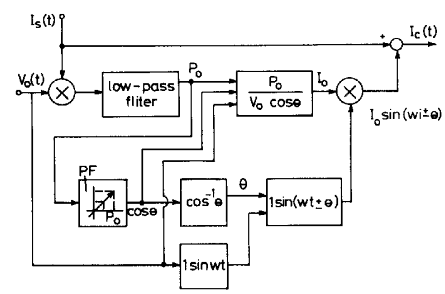

Fig. 8 *Calculated block diagram of load regulator*

6 Experimental results and discussions

The self-load bank by circulating current method for the burn-in test of the online UPS is assembled as shown in Fig. 1. A single-phase online UPS (3 kVA 110 V 60 Hz) is implemented for the burn-in test. Fig. 9 shows the waveforms of V_o, I_o, V_d and I_{dc} when the AC/DC converter of the UPS is only used as the tested load and the load regulator is turned off, this means that the tested load is nonlinear. When the load regulator is turned on, the *R*, *RL* and *RC* circuit characteristics are simulated as a linear load. Fig. 10 shows the waveforms of V_o, I_o, I_c, I_s, V_d and I_{dc} simulated by the $R(PF = 1)$ load. Figs. 11 and 12 show the waveforms of V_o, I_o, I_c and I_s simulated by the $RL(PF = 0.86)$ and $RC(PF = 0.9)$ loads, respectively. From the foregoing test conditions, the UPS output power W_o, the compensatory power W_c of the load regulator, and the total dissipative power W_{in} from the utility system are indicated in Table 1. It is obvious that the absorbed energy from the utility system is approximately equal to the loss energy of the UPS. The energy saved in the method described compared to the conventional one is about 80%. This means that the input power from the utility system in the conventional method will be the sum of W_o and W_{in} at every test condition. So the advantages of the proposed method for the burn-in test include

(i) Reduced test costs due to energy saving
(ii) Space saving due to the self-load bank
(iii) Lower power demands from the utility system
(iv) Reduced need for cooling equipment, necessary with dissipative loads
(v) Any output frequency of UPS can be tested with the local utility system.

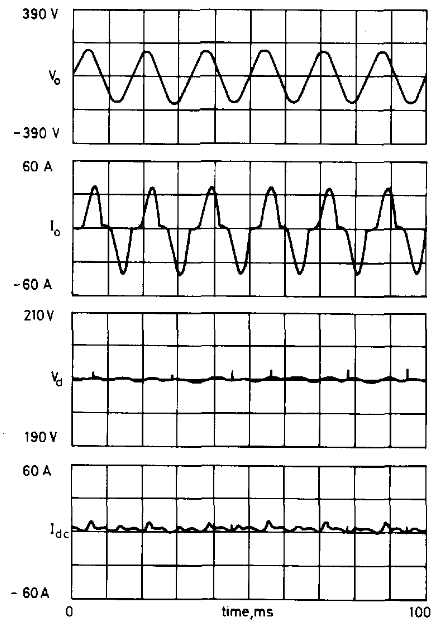

Fig. 9 *Waveforms of currents and voltage without load regulator*

Table 1: Results of burn-in test

Load regulator	Load characteristic	W_o	W_c	W_{in}	V_d	L_s
		kw	kw	kw	V	mH
Turn off	Nonlinear	1.78	0	0.41	200	2.66
Turn on	*R* (*PF* = 1)	1.78	0	0.47	200	2.66
Turn on	*RL* (*PF* = 0.86)	1.78	0	0.45	200	2.66
Turn on	*RC* (*PF* = 0.9)	1.78	0	0.49	200	2.66

The burn-in test of a single-phase online UPS can be completed as described. Similarly, the three-phase online UPS with a phase-controlled AC/DC converter also can be tested by using this proposed method for the burn-in test. Three regulating inductors, a DC regulator and a three-phase load regulator would be needed for this test.

6 Conclusions

The proposed method for the burn-in test system of the single-phase online UPS needs a regulating inductor, a DC regulator for controlling the tested current and a load regulator to simulate the linear load. The characteristics of the tested load is both nonlinear and linear. The test system can be operated at any output frequency of the tested UPS, with the local utility system to supply the DC regulator and load regulator. From the experimental results, the burn-in test system is easy to construct and control, giving an energy saving of about 80% in the burn-in test for the online UPS.

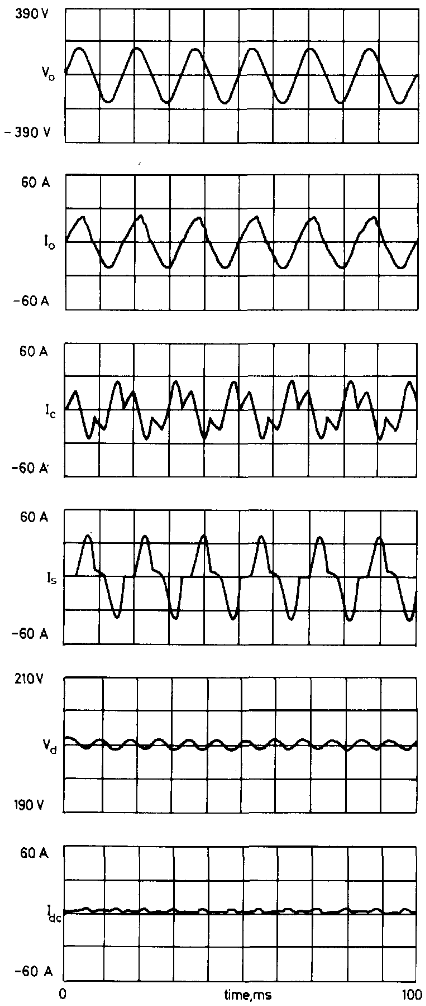

Fig. 10 *Waveforms of currents and voltage with load regulator in R (PF = 1) condition*

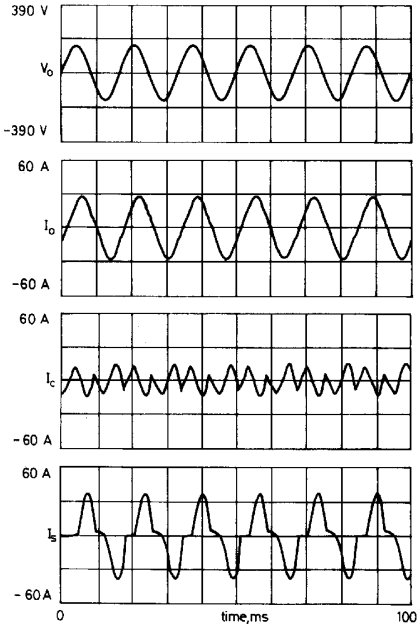

Fig. 11 *Waveforms of currents and voltage with load regulator in RL (PF = 0.86) condition*

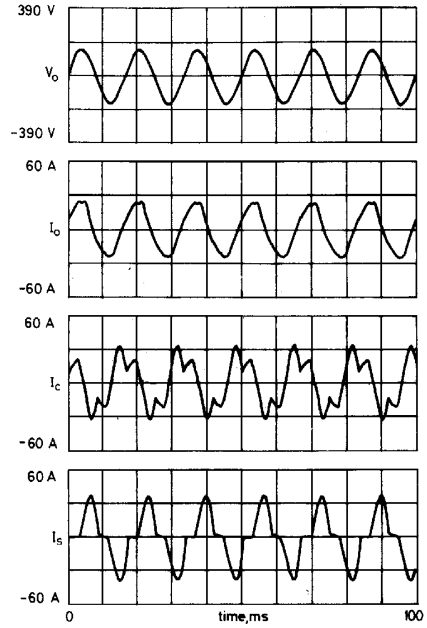

Fig. 12 *Waveforms of currents and voltage with load regulator in RC (PF = 0.9) condition*

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