Abstract—This paper reports experiment on the previously proposed instantaneous value voltage control of a single-phase ac chopper. The proposed control method is based on a modified carrier SPWM and instantaneous value voltage and current feedback control system. The validation of the proposed method is confirmed by experimental results.

Index Terms—AC chopper, automatic voltage regulation, instantaneous value voltage control, pulse-width modulation.

I. INTRODUCTION

Recently, the studies of AC chopper for ac voltage control have been increased because it has many advantages such as high input power factor, sinusoidal output voltage with small low-pass filter requirement and fast response.

The applications of ac chopper for automatic voltage regulator (AVR) or line conditioning have been proposed based on series voltage compensating technique using auxiliary series transformer connected between supply and load [1]-[3]. The ac chopper-based AVR system can be depicted as shown by Fig. 1. If a single-polarity ac chopper is used the output voltage can only be regulated against one direction supply voltage change i.e. under- or overvoltage while a reversible polarity ac chopper can provide voltage regulation for both supply over- and undervoltage. AC chopper based AVR without series transformer that is capable of compensating for both under- and overvoltage has also been proposed using the buck-boost type ac chopper [4].

Recently, concern about power quality, especially the voltage sags and swells, has been largely increased, due to the proliferation of sensitive equipment such as adjustable speed drives, programmable logic controller and process control equipment. The ac chopper based AVRs are considered as alternative solutions to these problems. However, the sudden change in supply voltage magnitude as in cases of voltage sags and swells requires that the AVR should have dynamic response as fast as the inverter-based voltage sag correcting devices currently available. To address this requirement a fast peak voltage detecting technique has been used in the feedback control of the output voltage of the ac choppers [1], [2] and [4]. This technique has limitations of dynamic response and waveform quality under low power factor and non-linear load condition.

II. PROPOSED INSTANTANEOUS-VALUE VOLTAGE CONTROL OF AC CHOPPER

A. Configuration of a single-phase ac chopper

For a single-phase ac chopper, four switches are used in the main circuit as shown in Fig. 2 [1]. The output voltage can be controlled by the duty ratio of the chopping pulse. Typical gate signals of the four switches and the chopped output voltage before filtering are shown in Fig. 3. Let the input supply voltage is defined as follows:

\[ V_s(t) = V_m \cos(\omega t) \]  

where \( \omega \) and \( V_m \) are the angular frequency and magnitude of the supply voltage, respectively.

The author has proposed a novel instantaneous value voltage control for a single-phase ac chopper in [5]. The proposed control method was based on the modified carrier SPWM and instantaneous value feedback of the output voltage and current signals. The simulation results confirmed that the proposed method provided very fast dynamic response against both sudden supply voltage and load change. The proposed control method also demonstrated nearly sinusoidal output waveform even under nonlinear load.

In this paper, the details and results of the experiment of the proposed instantaneous value control method of the ac chopper are reported.
where \( D \) and \( \omega_s \) are the duty ratio and angular switching frequency, respectively. The first term in the righ-hand side of (2) is the fundamental component and the second term is the harmonic content distributing around the switching frequency.

For a high switching frequency, the harmonic content can be filtered out using appropriated small-size low-pass filter. In steady-state, the filtered output voltage of the ac chopper can be approximately expressed as follows:

\[
v_s = D V_m \cos(\omega t) + \sum_{k=1}^{\infty} \frac{V_m \sin k \omega_s \pi}{k \pi} \cos \left( k \omega_s + \omega \right) t + \phi_1,
\]

where \( \phi_1 \) denotes the fundamental phase delay due to the low-pass filter.

As a result of (3), the amplitude of the output voltage is linearly controlled by the duty ratio of the PWM signal.

In the recent works, the amplitude of the output voltage is regulated by feedback control of the instantaneous peak value of the output voltage using PI controller [1], [2] and [4]. The controller output which is a dc signal is then compared to the sawtooth carrier pulse to make PWM signals for the four switches. Owing to the delay in the detection of the peak value of the output voltage, the control of the ac chopper output voltage cannot be achieved with fast response. Furthermore, the feedback system is based on dc signals, which do not reflect the wave-shape quality of the output voltage and the variation of the supply voltage. The control system is thus susceptible to non-linearity of the load current and magnitude change of the power supply.

B. Sine-amplitude modulated sawtooth signal generator

Fig. 4 illustrates a simplified schematic diagram of the sawtooth carrier pulse generator. This circuit uses a non-inverting integrator in stead of an inverting integrator as in the previously proposed circuit [5], however the principle of operation is the same.

The absolute-value of the supply voltage signal is used as the input of the integrator circuit. If the supply voltage is defined by (1), it can be shown as in (4) that the output voltage at \( t+T \) instant is equal to the amplitude of the supply voltage at \( t+T/2 \) instant [5].

\[
v_s(t + T) = V_m \cos \omega(t + T/2),
\]

where, \( T \) is the period of the sawtooth signal. From (4), the amplitude of the sawtooth pulse varies with the amplitude of the \( T/2 \)-second delayed supply voltage. Because the magnitude of the sawtooth pulse is very low around the zero-crossing of the supply voltage, this could lead to fully-on of the switches and makes it unable to control the output voltage around the zero crossing of the supply voltage. To correct this, small dc voltage is added to the integrator input to increase the slope of the triangle pulse around zero-crossing.

Fig.5 illustrates the experimental results of the modified sawtooth signal comparing to the sinusoidal control signal and the resultant PWM signal. As can be seen from the figure, a constant duty ratio PWM waveform is obtained in the same manner as the conventional dc-sawtooth comparison method. The advantage of this method is that the output voltage is independent of the supply voltage as long as the duty ratio is less than a unit.

C. Instantaneous-value voltage control

The equivalent circuits of AC chopper during active
mode of operation, i.e., the switch S1 is “ON” and the switch S3 is “OFF”, and during freewheeling, i.e., the switch S1 is “OFF” and the switch S3 is “ON” are illustrated by Fig. 6 (a) and (b), respectively. For simplicity, the effect of deadtime is ignored. In Fig. 6, the load is modeled as a current source disturbance $I_o$. Using the state-variable averaging method described in [8], the output voltage can be expressed by

$$V_o(s) = \frac{D V_1(s) - (sL_f + R_f)I_o(s)}{L_f C_f s^2 + R_f C_f s + 1}$$

where $R_f$, $C_f$, and $L_f$ are the resistance, capacitance, and inductance of the low-pass filter, respectively.

The block diagram of the AC chopper is illustrated in Fig. 7. The effect of the output current disturbance can be cancelled out by disturbance observer. The closed loop control system of the output voltage is now proposed as shown in Fig. 8. If the parameters of the model match with those of the actual system, the effect of output current disturbance will be rejected and the closed loop transfer function can be found as

$$\frac{V_o(s)}{V_s(s)} = \frac{K_p s + K_d + 1}{L_f C_f s^2 + (K_p + R_f C_f) s + K_p + 1}$$

where $K_p$ and $K_d$ are the derivative and proportional gain of the PD controller, respectively.

The poles of the closed-loop control system are

$$s_{1,2} = -\zeta \omega_n \pm j \omega_n \sqrt{1 - \zeta^2},$$

where

$$\omega_n = \frac{\sqrt{K_p + 1}}{L_f C_f},$$

and

$$\zeta = \frac{1}{2} \left( K_D + R_f C_f \right) \frac{1}{\sqrt{(K_p + 1) L_f C_f}}$$

are the natural frequency and damping factor of the closed-loop system, respectively.

The desired closed-loop control characteristics can be specified by properly selecting the gains $K_d$ and $K_p$.

### III. EXPERIMENTAL RESULTS

Fig. 7 illustrates the configuration of the ac chopper for experiment. The important parameters of the system are summarized in the Table I. The experiments have been carried out to evaluate the performance of the proposed method. Additionally, the experiment results using conventional average-value control method will be used for comparison.

#### A. Step response

The experimental result with the proposed instantaneous-value control system is illustrated in Fig. 10. The output voltage follows the reference control signal precisely and has very fast dynamic response.
B. Effect of non-linear load

The non-linear load is made of a full-wave rectifier with LC filter and resistive load. To illustrate the effect of non-linear load, the output voltage without the proposed control method is shown in Fig. 11. The steady-state experimental result with the proposed instantaneous-value control system is illustrated in Fig. 12. Nearly sinusoidal output voltage is obtained.

C. Effect of load change

The experimental result on step load change is shown in Fig. 13. The output voltage is not affected by the change of the load.

D. Effect of supply voltage change

Fig. 13 illustrates the experimental results when the ac supply has voltage dip to 70% of its nominal voltage for 5 cycles. Fig. 14 illustrates the experimental results when the ac supply has voltage swell to 110% of its nominal voltage for 5 cycles. With the proposed control method the output voltage is nearly unaffected with the suddenly supply voltage change. These results demonstrate the robustness of the proposed modulation method.

IV. CONCLUSIONS

In this paper, the validity of the proposed instantaneous value voltage control for a single-phase ac chopper has been confirmed experimentally. The proposed control method provides fast step response, nearly sinusoidal voltage waveform.
under non-linear load condition and robustness against the supply voltage dips.

The proposed modulation and control system can enhance the function and performance of ac chopper-based AVR system to be able to compete with high performance inverter-based voltage sag mitigating devices. Though the experiment was carried out only with a buck-type ac chopper, this control scheme can also be used for other type of ac chopper as well.

REFERENCES


