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Control of buck-boost chopper type AC voltage regulator

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Abstract
Traditional AC voltage regulator used servo-motor position regulation or thyristor phase controlled method which had low dynamic response speed or large amount of harmonic components. However, these drawbacks can be overcome by using Pulse Width Modulation chopper techniques in AC voltage regulation. Buck-Boost Chopper type AC voltage regulator, derived from the DC chopper modulated method, is a kind of direct AC-AC voltage converter and has many advantages: such as fast response speed, low harmonics and high power factor. It adopts high switching frequency AC chopper techniques and can do wide range step less AC voltage regulation. The steady-state equivalent circuit of the Buck-Boost chopper type AC voltage regulator, as well as the theoretical analysis method of the input power factor and the output voltage is presented in this paper. In addition, in order to solve the problems caused by the sags or swells of the input voltage, the output voltage controller is designed. The proposed voltage controller uses output peak voltage as feedback signal and adopts PI control strategy to regulate the output voltage. Digital simulation results coincide with the theoretical analysis and show that the Buck-Boost chopper type voltage regulator has a unit input power factor and that the designed voltage controller can stabilize the output voltage with fast dynamic speed when input voltage fluctuations occur.

Keywords: AC chopper, Voltage Regulator, Pulse Width Modulation, Feed forward and Feedback Control, Power Factor, Voltage Fluctuations

1. Introduction
AC voltage regulation is an important part of power conversion. There are some types of AC /AC converter to regulate the input voltage to a lower or higher output voltage. A winding transformer is widely used in voltage regulation fields such as power system, motor speed control and so on. However, because the winding ratio is changed by servomotor or by manual regulation, it has low regulation speed. There are also other researches, which use thyristor phase controlled circuit to do voltage regulation. These converters have been widely used as a soft-starter and a speed regulator of pumps and fans. Although it has a higher regulating speed than winding transformer, the low input power factor and the large amount of the low-order harmonic current are the major problems. The size of the passive filter becomes larger. Furthermore, these shortcomings affect the power quality. The reactive and harmonic currents generated by the thyristor commutation also produce extra power loss on the transmission lines.

Using high switching frequency AC chopper can solve these problems. A Chopper type voltage transformer adopts PWM control techniques and the above problems are improved when it is operated in chopping mode. The input voltage is chopped into segments and changing the duty ratio of the control signal regulates the output voltage. The advantages are nearly sinusoidal input-output currents voltage waveforms, improved power factor, reduced harmonic current, a fast response speed and a smaller input filter size. It can protect sensitive equipment such as computer or communication equipment; it can also be used to solve power quality problems caused by line voltage sags and swells.

In order to reduce the power loss, researches have been conducted to reduce the number of the switching devices. Three switches and four switches AC chopper were discussed in previously presented papers. Different working principles have also been presented to ensure the safety of the converter. The switching patterns are critical and an alternate path has to be established in dead time. DC regenerative snubber capacitor is used to realize the safe commutation and enhance efficiency. Although there are various researches that focus on the topology of the AC chopper converter, little attention has been given to the theoretical analysis of the input power factor. In addition, because most of the previous proposed control methods are open loop control, voltage regulation performance is restrained. To solve the problems caused by the input voltage fluctuation, the output voltage closed loop feedback control system is proposed for a better dynamic performance. The remainder of this paper is divided into four sections. First, the circuit description and working principles are discussed in section II. Then, the theoretical analysis method of the input power factor and output voltage are presented is section III. Based on the theoretical analysis, the output voltage controller design is shown in section IV. Digital simulation is conducted in section V to the proposed analysis method and the voltage controller performance. This paper ends with concluding remarks.

2. Circuit Configuration and Principle of Operation
The basic circuit configuration of the proposed converter is shown in Fig.1. This circuit has the following characteristics: it can operate directly from the single-phase line and regulate the output voltage higher or lower steplessly. Furthermore, the input voltage phase synchronous circuit is unnecessary in this scheme. As a result, the circuit is simplified and the cost is reduced. The input filter, consisting of inductor L_i and capacitor C_i, absorbs the harmonic currents. The switches S_1 and S_2 are bi-directional. The used bi-directional switch

module is composed of two insulated gate bipolar transistors (IGBT). This bi-directional switch structure make the two IGBT share the common the driver circuit, thus the circuit hardware design is simplified. The used IGBT has inner anti-parallel diode, which provide freewheeling currents path when the reverse voltage is encountered. The inductor *L* is used to store and transfer the energy to the output side. The switch *S*1 is used periodically to connect and disconnect the inductor *L* to the supply, i.e., it regulates the power delivered to the inductor *L*. The switch S_2 provides a freewheeling path for the inductor current to discharge the stored energy of the inductance L when the switch S_1 is turned off. These switches are controlled by PWM signals with constant duty ratio. C_1, C_2 and R_1, R_2 are the snubber capacitors and resistors respectively. The snubber circuits are connected in parallel with the bi-directional switches. The output filter capacitor C_0 reduces the output voltage ripple.

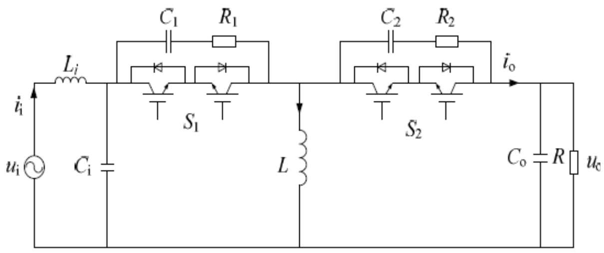

Fig 1: Buck-Boost chopper type AC voltage regulator

The switches S_1 and S_2 work in complementary mode. The switching pattern of the control signals is shown in Fig.2.The operation is divided into three modes: active mode, freewheeling mode and dead-time mode. The active mode is defined when the switch *S*1 is turned on. During the active mode, the inductor current is forced to flow through the voltage source via the modulated switch *S*1 during its on-state periods and the inductor storages the energy. The freewheeling mode is defined when the modulated switch S_1 is turned off. The inductor current paths can be formed by the direction of the load current. In freewheeling mode, the load current freewheels and the inductor *L* discharges the energy through the switch S_2 with the help of its body diodes according to the direction of the load current.
Finally, the dead-time mode is defined when the switches S_1 and S_2 are both turned off. The dead-time t_d shown in Fig.2 is short, only about several microseconds. The snubber circuits can absorb the bidirectional turn-off spike energy due to line stray inductance.

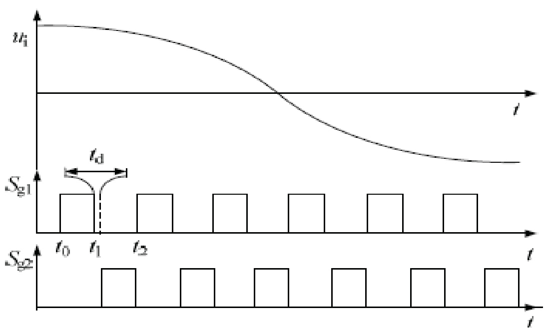

Fig 2: Switching patterns of the PWM signals

3. Analysis

To facilitate the analytical procedure, the following assumptions are made: First, all components are assumed ideal. In addition, because the switching frequency f_S is much higher than the line frequency *f*, the high frequency input harmonic currents can be absorbed by small input filter. The input power factor is assumed not to be affected by the input filter. In switching period, the input voltage u_i and the output voltage u_o are considered to be constant. When $u_i > 0$, the waveforms of inductor voltage u_L and current i_L are shown in Fig.3. The inductor voltage u_L is u_i during the active mode, or $-u_o$ during the freewheeling mode. In dead-time mode, the inductor voltage u_L is u_i or $-u_o$ according to the direction of i_L.

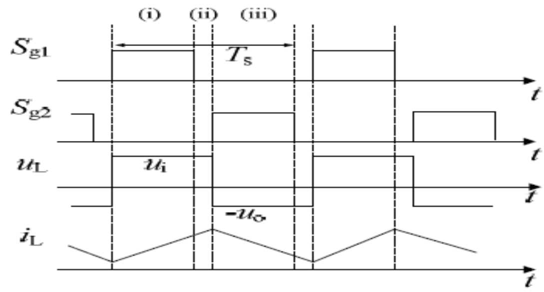

Fig 3: Waveforms of the inductor voltage u_L and current i_L

In ideal condition, the inductor voltage of u_L can be expressed

$$u_L = \begin{cases} u_i & s_1 \text{ is on} \\ -u_0 & s_1 \text{ is off} \end{cases}$$

In the average model, the average inductor voltage during one switching period can be given by:

$$u_L(t) = Du_i(t) - (1-D)u_0(t) \qquad \text{… (1)}$$

Where u_i (t) and u_0 (t) are the average AC input voltage and output voltage during the switching period, respectively, and *D* is the duty ratio. Because the switching frequency is much higher than the line frequency, it is possible to approximately give the average inductor voltage as follows:

$$u_L(\mathrm{t}) = \mathrm{L}\frac{di_L(t)}{dt} \qquad \text{… (2)}$$

Where $i_L(t)$ is the average inductor current during the switching period? The inductor current produces the output current during the freewheeling mode, and the inductor current is caused by the input current during the active mode. Hence, the following relations are obtained:

$$i_i(\mathrm{t}) = \mathrm{D}i_L(\mathrm{t}) \qquad \text{… (3)}$$

$$i_o(\mathrm{t}) = (1\text{-D})i_L(\mathrm{t}) \qquad \text{… (4)}$$

Where *ii* (t) and *io* (t) are the average input and output current Respectively. From (1) and (2), the following equation is Obtained.

$$\mathrm{D}\,u_i(\mathrm{t}) = \mathrm{L}\frac{di_L(t)}{dt} + (1\text{-D})u_o(\mathrm{t}) \qquad \text{… (5)}$$

Substituting (3) in (5), yields

$$\frac{D}{1-D}u_i(\mathrm{t}) = \frac{L}{D(1-D)}\frac{di_i(t)}{dt} + u_o(\mathrm{t}) \qquad \text{… (6)}$$

Equation (6) represents the steady-state equivalent circuit for the chopper type voltage regulator. The equivalent circuit is shown in Fig.4.

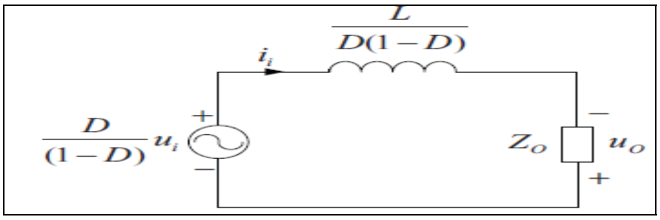

Fig 4: steady state equivalent circuit of Buck-Boost chopper type voltage regulator

Where Z_0 is the equivalent resistance of load R in parallel with the output filter capacitor C_0. Let

$$Z = Z_O + j\frac{\omega L}{D(1-D)} \quad \ldots (7)$$

Where Z is the total impedance of the equivalent circuit and is the angular frequency of the line voltage. According to the Kirchhoff's laws, the input current is:

$$i_i = \frac{DU_i}{(1-D)Z} \quad \ldots (8)$$

And the output voltage is

$$U_o = -\frac{DZ_o}{(1-D)Z}U_i \quad \ldots (9)$$

The input power factor angle of the converter is:

$$\varnothing = \text{arc } t_g(\frac{U_i}{I_i}) = \text{arc } t_g(\frac{(1-D)Z}{Z}) \quad \ldots (10)$$

4. Voltage Controller

Voltage sags or swells are caused by the disturbances or faults in power systems. The input voltage fluctuation also affects the output voltage. From (9) the output voltage can be regulated by the duty ratio of the PWM control signals. The voltage controller, which uses the output peak-voltage as the feedback signal, is designed to keep the stability of the output voltage in case of input voltage fluctuation. The peak-voltage detector and control system structure diagram is shown in Fig.5.

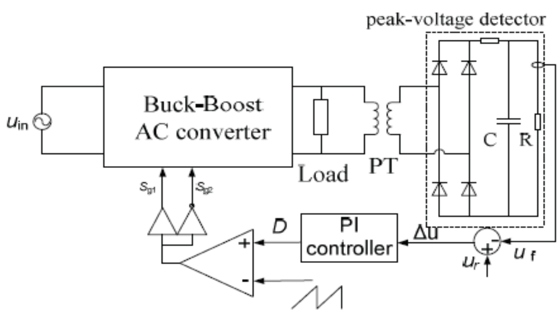

Fig 5: The peak-voltage detector and control system

Where u_f is the detected output peak-voltage and u_r is the reference value of output peak-voltage. The circuit detects the output peak-voltage with diodes rectifier, capacitor and resistor. When the input voltage decreases, the capacitor discharges through the resistor, and when increased, the capacitor is charged directly.

The controller input Δu is expressed as:

$$\Delta u = u_r - u_f$$

The controller output is duty ratio D. When the input voltage fluctuation happens, the detected output peak-voltage u_f needs to be regulated to a constant reference value u_r with fast response speed. The proportional-integral (PI) controller satisfying these performance requirements is used as follows:

$$D = k_p\Delta u + k_i\int \Delta u \, dt$$

Where k_p and k_i are proportional and integral gains respectively. The integral part of the designed controller makes the steady-state output voltage error zero.

5. Simulation Experiment

To show the feasibility of the proposed analysis method and control strategy, the simulation model of the proposed voltage regulator is setup using Matlab/Simulink software. When the load is pure resistive R_L=100 and the duty ratio D=0.4, the waveforms of the input voltage, input current, output voltage, output current and inductor current are shown in Fig.7.

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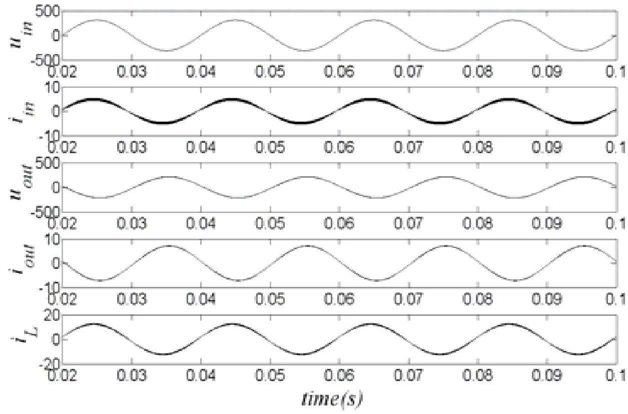

Fig 7: Waveforms of input voltage, input current, output voltage, output current and inductor current when D=0.4

The input current is almost in phase with the input voltage. Unlike the thyristor phase controlled converter, the output voltage wave is sinusoidal and the harmonics are highly reduced. With duty ratio ranging from 0.2 to 0.7, the simulation results of input power factor are shown in Fig.8.) And simulation results of output voltage root-mean- square (rms) value are shown in Fig.9.

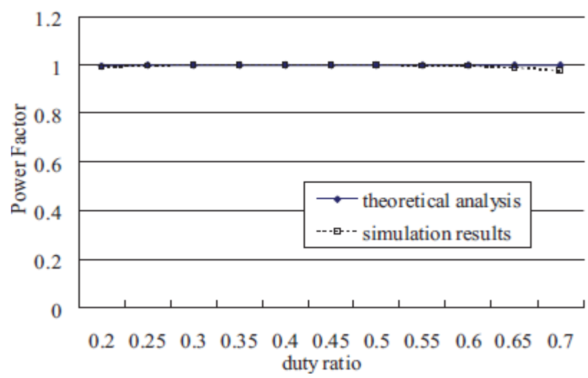

Fig 8: Variation of input power factor under different duty ratio

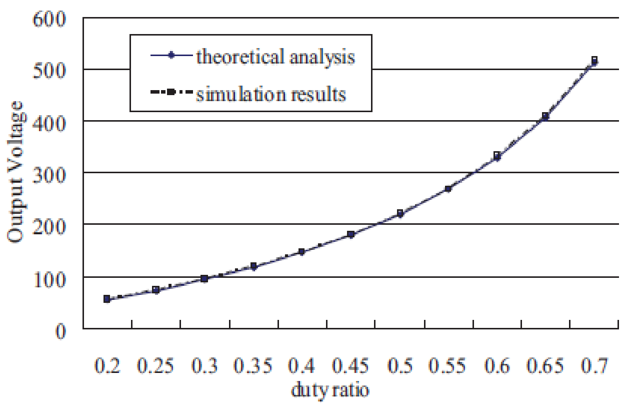

Fig 9: Variation of output voltage under different duty ratio

According to the diagram, the simulation results are consistent with the theoretical analysis. The chopper type AC voltage regulator has a high input power factor and can reach the unit power factor in working zone. Fig.10 shows the simulation results of the output voltage when voltage sags or swells of 20% in the input voltage occur. The voltage controller can regulate the output voltage and suppress the voltage fluctuation with fast speed. According to Fig.11, when the output peak voltage is 100V, the total harmonic distortion (THD) of output voltage is only 1.62%. The output voltage has little harmonic components.

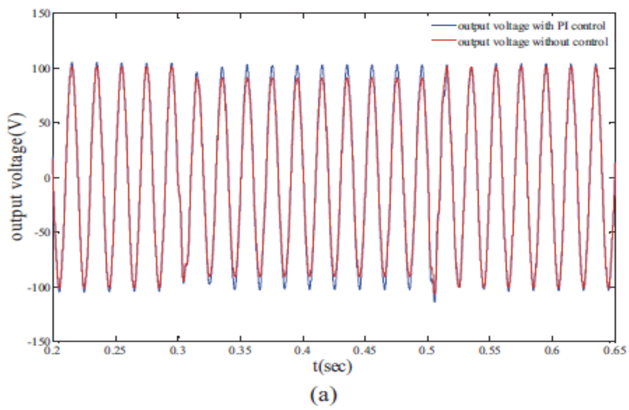

Fig 10 (a): voltage sags of 20% in the input voltage

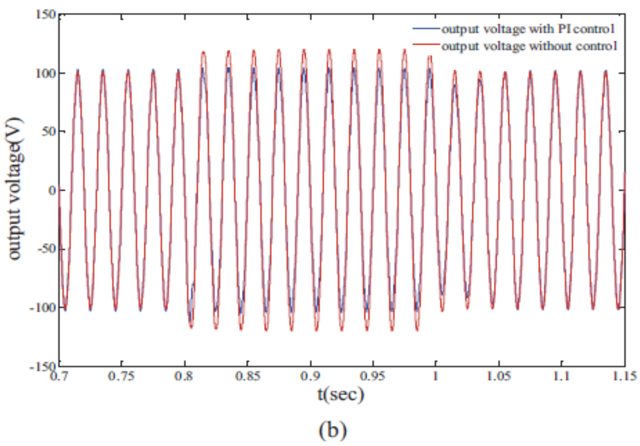

Fig 10 (b): voltage swells of 20% in the input voltage

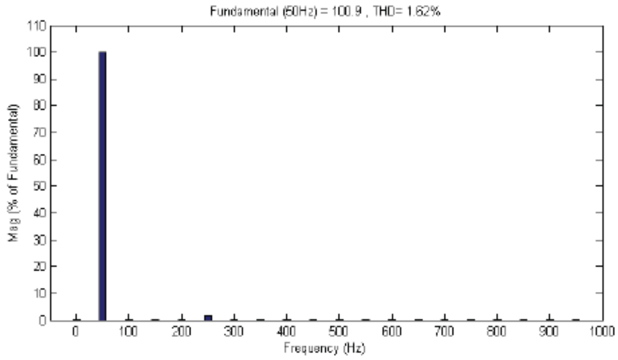

Fig 11: Spectrum analysis of the output voltage

6. Conclusion

The Buck-Boost chopper type AC voltage regulator has many advantages compared to the winding transformer and thyristor phase controlled voltage regulator. The analysis method of the input power factor and the output voltage is presented. The simulation results coincide with the theoretical analysis and show that the chopper type voltage regulator has a unit input power factor, and that the output voltage can be regulated higher or lower steplessly. Compared with other plans, the input current is in a sinusoidal waveform with less harmonic components. The output voltage control system is designed using PI control method and the peak-voltage detector. The simulation results show that the voltage controller has a good dynamic performance when input voltage swells or sags occur. The Buck-Boost chopper type AC voltage regulator can improve the PF and reduce the power loss caused by the reactive and harmonic currents. In addition, it has significant meaning in protecting the voltage sensitive load against the line voltage swells and wags.

7. Reference

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