High precision Automatic Voltage Regulator by using series transformer

Zhang Lei, Hwa-Chun Lee, Tae-Uk Jung, Hae-Kon Nam, Soon-Ryul Nam, Sung-Jun Park,
Chonnam Univ, Chonnam Univ, Kyungnam Univ, Chonnam Univ, Chonnam Univ, Chonnam Univ

직렬 변압기를 이용한 고정밀 자동전압조절기

장뢰, 이화춘, 정태욱, 남해곤, 남순열, 박성준
전남대, 전남대, 경남대, 전남대, 전남대, 전남대

Abstract

Now there are two types Non-contact compensation AC automatic voltage regulator (A.V.R). One is transformer compensation regulator, whose principle is the combination of multiple compensation transformers, do the compensation by turning on and off the connections of the transformer through the multi-full bridge circuit. This method removed the mechanical drive and contacts, which increases the life and the dynamic performance of the A.V.R. However, the compensation is multilevel, and it needs many compensation transformers and switches, the circuit is complex, the compensation precision is low. Another type is PWM switch AC regulator, whose principle is getting the AC voltage from the input, then induce the AC compensation voltage through commutating and high frequency PWM transforming, and phase tracking. Here the compensation is step-less, the compensation precision is high, and the response is fast. But the circuit is complex, and it needs an inverse compensation transformer, which is difficult to realize high-power applications. In this paper, it shows an Automatic Voltage Regulator which use high frequency PWM inverter do compensation. This A.V.R has the function as the custom-power, which make the performance of the power supply in a high level.

1. Introduction

An ac automatic voltage regulator can provide a well-regulated voltage source, and is becoming more and more important due to the rapid decrease in the quality of power systems. Generally, there are many different structures to implement an A.V.R, including a conventional transformer with mechanical or electrical tap changer, an adjustable transformer driven by motor, a saturated reactor, a regulative series transformer controlled by a dc-to-ac inverter which is supplied by a diode rectifier or a switching mode rectifier, a high-frequency ac-to-ac electronic transformer with or without a high-frequency transformer, and so on. The adjustable transformer or saturated reactor-based A.V.R has some disadvantages, including the use of bulky transformers and/or a slower response than switching-based structures. In contrast to this, the high-frequency switching-based AVR has the merit of a smaller size as it uses high-frequency switching technology. However, it normally allows only unidirectional ability of voltage regulating (voltage sag or voltage swell), and it is not suitable for a large-scale system. Thus, the regulative series transformer controlled by a dc-to-ac inverter seems to be a good choice as it manages only the fluctuation part of the source voltage, and has a smaller size than the topology that is processing the full-load power. Fig. 1 shows the circuit configuration of this type of AVR.

The AVR which is showed in this paper can be used to deal with both directions of voltage regulation, and it has merits including a higher switching efficiency, a simple circuit structure, and a simple control algorithm.

2. Automatic Voltage Regulator using high frequency PWM inverter

The Principle circuit of Non-contact compensation AC Power Supply using PWM high frequency inverter is shown in Fig.1, in which the compensation voltage is produced by full-bridge inverter, and the inverter uses high frequency SPWM modulation. The output voltage of the single phase full-bridge inverter u_{ab} goes through the transformer T_r, which transforms u_{ab} to compensation voltage u_{co} and output it in the secondary winding of T_r. The secondary winding of transformer T_r is in series in the main circuit to compensate the commercial power, and make sure the output voltage u_o is stable. In the circuit the filter is low-pass filter, which is used to filtering the high frequency harmonic wave of the output. The PWM controller can use single-chip to produce and control the PWM signal, and control the switches of the inverter. The voltage sensor is used to detect the input and output voltage.

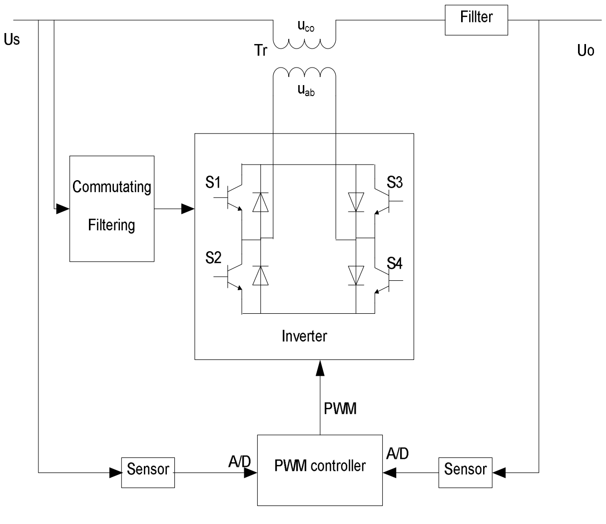

Fig. 1 Main topology of the A.V.R

The resistance of the transformer secondary winding and internal resistance of commercial power make up of line impedance Z, and u_r is reference voltage, the control circuit is showed in Fig.2, so following the control principle in Fig.2, if use

u_s-Zi_s-u_r as the modulation voltage, it can make the output of inverter be proportional to the changes of commercial power voltage and load voltage.

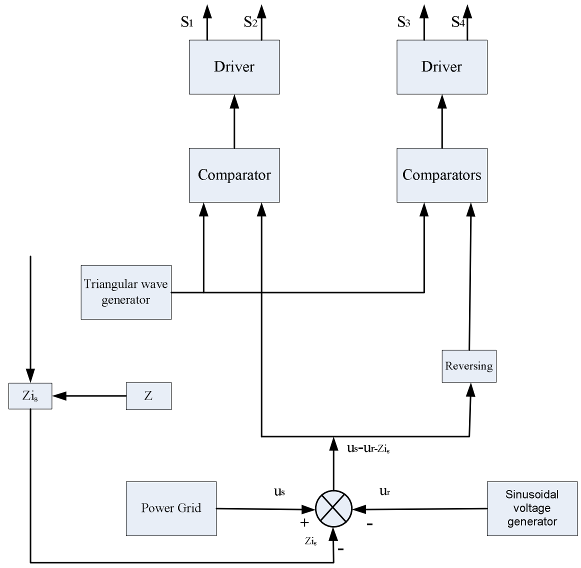

Fig. 2 Block diagram of control circuit

2.1 Harmonic Analysis of the inverter output voltage

Assuming the DC input voltage of the inverter is U_d, the peak voltage value of carrier triangular wave is U_c, the value of modulation rate M is

$$M = \frac{\sqrt{2}(U_s - ZI_s - U_r)}{U_c} \tag{1}$$

In this equation: U_s, I_s, U_r is the SRM of commercial power voltage u_s, commercial power current i_s and reference voltage u_r.

Carrier rate: $N=\frac{f_c}{f_s}$, f_c is the frequency of triangular wave, f_s is the frequency of commercial power voltage.

SPWM waveform is showed in Fig.3. From this figure it can be known that the double Fourier series of inverter output voltage u_{ab} is shown in the following equation.

$$u_{ab} = u_a - u_b = MU_d \sin \omega t + \frac{2U_d}{\pi} \sum_{m=1}^{\infty} \sum_{n=\pm1,\pm3}^{\pm\infty} \frac{J_n(mM\pi)}{m} \cdot \cos m\pi \cdot \sin[(mN+n)\omega t] \tag{2}$$

The ratio of transformer T_r is ξ, so the expression of compotation voltage u_{co} is:

$$u_{co} = \xi MU_d \sin \omega t + \xi \frac{2U_d}{\pi} \sum_{m=1}^{\infty} \sum_{n=\pm1,\pm3}^{\infty} \frac{J_n(mMn\pi)}{m} \cdot \cos m\pi \cdot \sin[(mN+n)\omega t] \tag{3}$$

So it can be known: carrier rate is the more, the frequency of harmonic is the higher, and the filtering is the easer.

2.2 Compensation Analysis containing the line impedance

Because of the voltage drop of the inverter switches, switch dead-time, resistance and the inductance influence of the transformer T_r, which can make the compensation voltage u_{co} reduced. But this impact is not large, and the relation between this impact and the changing of load is not big, so we can compensate it by increasing the ratio of the transformer T_r.

From Fig.1, thinking about line impedance Z, in the state that the $u_s > u_r$, the formula of the output voltage is:

$$u_o = u_s - Zi_s - u_{co} \tag{4}$$

Assuming that there is no harmonic in commercial power voltage, commercial power input power factor is cosφ=1, so: $u_s = \sqrt{2}\ U_s \sin\omega t$, $i_s = \sqrt{2}\ I_s \sin\omega t$, substitute the formula (3) and value of u_s, i_s to the formula (4):

$$u_o = \sqrt{2}U_s \sin \omega t - \sqrt{2}ZI_s \sin \omega t - \xi MU_d \sin \omega t - \frac{2\xi U_d}{\pi} \sum_{m=1}^{\infty} \sum_{n=\pm1,\pm3}^{\pm\infty} \frac{J_n(mM\pi)}{m} \cos m\pi \cdot \sin[(mN+n)\omega t] \tag{5}$$

Using the low-pass filter in the circuit filtering the high frequency harmonic of the u_{co}, the above formula is:

$$u_o = \sqrt{2}U_s \sin \omega t - \sqrt{2}ZI_s \sin \omega t - \xi MU_d \sin \omega t \tag{6}$$

Substituting the value of M in formula (1) and $\xi = \frac{U_c}{U_d}$ to the formula (6);

$$u_o = \sqrt{2}U_s \sin \omega t - \sqrt{2}ZI_s \sin \omega t - \sqrt{2}(U_s - ZI_s - U_r) \cdot \sin \omega t$$
$$= \sqrt{2}U_r \sin \omega t$$

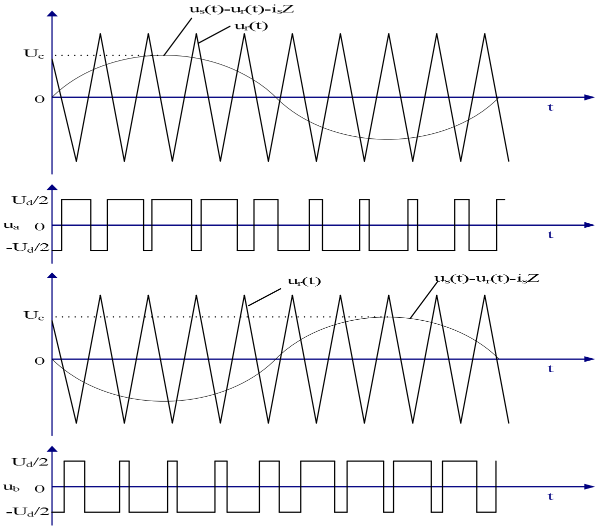

Fig.3 SPWM wave

This AC regulator has 6 operative modes:

(1) $u_s > u_r + Zi_s$, $u_{co} = u_s - Zi_s - u_r$, this time output voltage $u_o = u_s - (u_s - Zi_s - u_r) = u_r$

(2) $u_s < u_r + Zi_s$, $u_{co} = u_s - Zi_s - u_r$. The output voltage $u_o = u_s - (u_s - Zi_s - u_r) = u_r$

(3) $u_s = u_r$, this time $u_{co} = -Zi_s$, output voltage $u_o = u_s - Zi_s = u_r$

(4) No-load ($i_s = 0$), $u_s > u_r$, $u_{co} = u_s - u_r$, output voltage $u_o = u_s - (u_s - u_r) = u_r$

(5) No-load (is=0), $u_s < u_r$, $u_{co} = -u_s + u_r$, output voltage $u_o = u_s + (-u_s + u_r) = u_r$

(6) No-load ($i_s = 0$), us=u_r, $u_{co} = 0$, no compensation.

When the commercial power voltage u_s or the load changes, the output voltage of the SPWM high frequency inverter which is modulated by the instantaneous value of (u_s-u_r-Zi_s) can compensate the changes of the output voltage u_o, and keep $u_o = u_r$.

2.3 The compensation for the harmonic in the commercial power voltage

Assuming the value of the commercial power is unchanged, but it contains harmonic

$$\sqrt{2}\sum_{n=2}^{\infty} U_{sn} \sin \omega t$$

That is

$$u_s = \sqrt{2}U_{s1} \sin \omega t + \sum_{n=2}^{\infty} U_{sn} \sin n\omega t, \qquad u_{s1} = u_{r0}$$

In order to simplify the derivation, let i_s=0, the voltage of modulation wave is:

$$\begin{aligned} u_s - Zi_s - u_r &= \sqrt{2}u_{s1} \sin \omega t + \sum_{n=2}^{\infty} \sqrt{2}u_{sn} \sin n\omega t - \sqrt{2}U_{r0} \sin \omega t \\ &= \sum_{n=2}^{\infty} \sqrt{2}u_{sn} \sin n\omega t \end{aligned} \tag{7}$$

Modulation ratio: $M_n = \frac{\sqrt{2}U_{sn}}{U_c}$, the compensation voltage uco is:

$$u_{co} = \sum_{n=2}^{\infty} \xi M_n U_d \sin n\omega t + \xi \frac{2U_d}{\pi} \sum_{m'=1}^{\infty} \sum_{n'=\pm1,\pm3}^{\pm\infty} \frac{J_n'(m'' Mn\pi)}{m''} \tag{8}$$

$$\square \cos m'' \pi \square \sin[(m'' N + n')n' \omega t]$$

Substituting the value of us, is and uco' into the formula (4), use low pass filter filtering the higher frequency harmonic, and substitute $M_n = \frac{\sqrt{2}U_{sn}}{U_c}$, $\xi = \frac{U_c}{U_d}$ into u_{co}'

$$\begin{aligned} u_o &= \sqrt{2}U_{s1} \sin \omega t + \sum_{n=2}^{\infty} \sqrt{2}U_{sn} \sin n\omega t - \sum_{n=2}^{\infty} \sqrt{2}U_{sn} \sin n\omega t \\ &= \sqrt{2}U_{s1} \sin \omega t = \sqrt{2}U_r \sin \omega t \end{aligned} \tag{9}$$

From equation (9), it can be known: when the commercial power u_s contains harmonic, the SPWM high frequency inverter output voltage u_{co} which use the instantaneous value of (u_s-u_r-Zi_s) as modulation wave can compensate the harmonic in u_s, in particular the low harmonic.

Furthermore from the physical perspective, because the control circuit do comparison of the instantaneous value of the commercial power and sine wave reference voltage, and use the difference of these two values as modulation wave do compensation, the commercial power u_s is sine wave, when $u_s > u_r$, it is negative compensation, that is u_s-u_{co}; when $u_s < u_r$, it is positive compensation, that is u_s+u_{co}. When the commercial power contains harmonic which contain flickering and sharp pulse, $u_s > u_r$ part is negative compensation, and $u_s < u_r$ part is positive compensation. The sketch map of the compensation principle is Fig.4. From Fig.4, it can be known: when the commercial power wave changes, which can be compensated by PWM inverter theoretically.

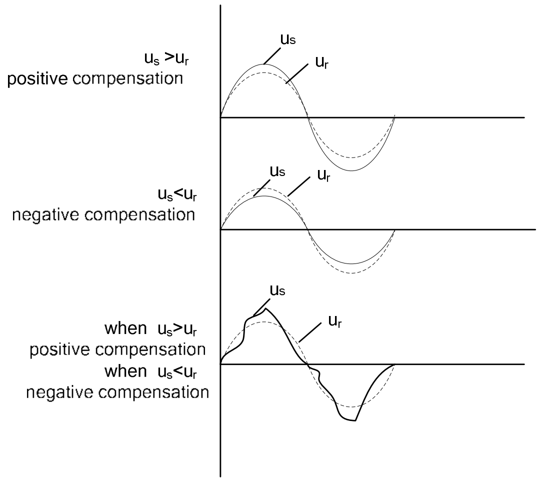

Fig.4 Compensation principle sketch map

The value change of u_s, the harmonic or flickering and sharp pulse, which can be compensated by instantaneous value of the SPWM inverter and the waveform of output voltage u_o after compensation, is close to stability power supply.

3. Simulation results

Fig.5 and Fig.6 are the voltage waveforms before and after compensation. Through these two waveforms it can be known: the THD of the waveform before compensation in Fig.5 is large and there is dissymmetry in the fundamental wave. The waveform after compensation is a perfect sine wave, and the dissymmetry is eliminated.

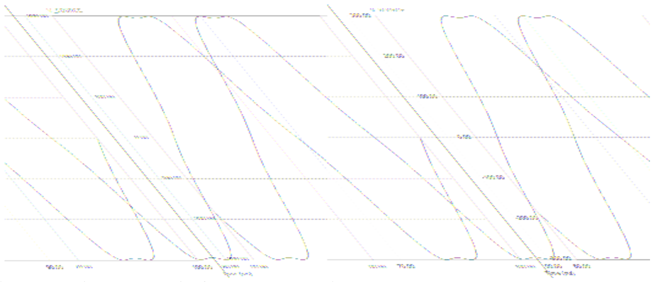

Fig. 5 Voltage wave before compensation

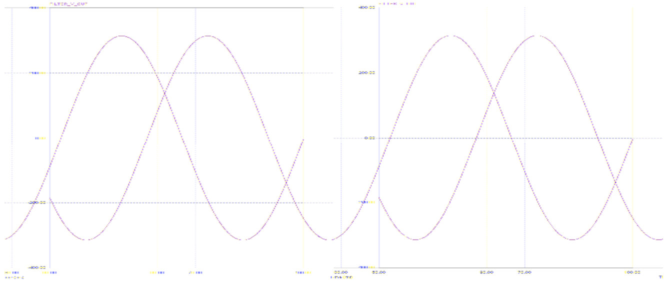

Fig. 6 Voltage wave after compensation

Conclusion

Through the simulation and experiment it shows that this ac regulator using PWM inverter can compensate voltage changes of the commercial power and it also compensate the harmonic wave and the flickering, which can improve the power quality. It is a promising AC stabilified-voltage power.

Reference

[1] S. J. Jeon and G. H. Cho, "A series-parallel compensated uninterruptible power supply with sinusoidal input current and sinusoidal output voltage," in Proc. IEEE PESC'97, 1997, pp. 297–303.

[2] T.Jauch, A.Kara, M.Rahmani, D.Westermann. " Power Quality Ensured by Dynamic Voltage Correction." ABB Review. 19'38, (4): 25-36

[3] P.R. Gray and R.G. Meyer, "Analysis and design of analog integrated circuits", New York: Wiley & Sons, Inc., 1993.

[4] H. Zhao, Q. M. J. Wu, and A.Kawamura, "An accurate approach of nonlinearity compensation for VSI inverter output voltage," IEEE Trans. Power Electron., vol. 19, no. 14, pp. 1029-1035, Jul.2004.