Series Compensated Step-down AC Voltage Regulator using AC Chopper with Transformer

H.J Ryoo†, J.S Kim* and G.H Rim**

Abstract - This paper describes a step-down AC voltage regulator using an AC chopper and auxiliary transformer, which is a series connected to the main input. The detail design of the AC regulator, logic and PWM pattern of the AC chopper is described and the three-phase AC regulator using two single-phase AC choppers with a three transformer configuration is proposed for three-phase application. The proposed three-phase system has the advantages of lower system cost due to reduced switch number and gate driver circuit as well as advantages of decreased size and weight because it uses a series compensated scheme. The proposed AC regulator has many benefits such as fast voltage control, high efficiency and simple control logic. Experimental results indicate that it can be used as a step-down AC voltage regulator for power saving purposes very efficiently.

Keywords: series compensation, AC chopper, AC voltage regulator

1. Introduction

Recently, studies on the PWM AC chopper have increased because it offers numerous advantages such as sinusoidal input current with unit power factor, rapid dynamics, and significant reduction in the filter size [1, 2]. One of the problems occurring when we use the PWM AC chopper is that the switching pattern of the AC chopper is critical and an alternative path has to be provided for the current when all switches are turned off. To solve this problem, many topologies are proposed by using additional bypass capacitors or RC snubbers [1, 2].

As the PWM AC chopper can be operated with high reliability without any problem of commutation, series compensation schemes using the AC chopper with a series transformer connected to the main input are proposed for line conditioning and AVR application [3].

In this paper, a novel single-phase and three-phase step down AC voltage regulator using AC choppers with series transformers for the purpose of 10-20% voltage decrease are studied. The operation principles of proposed topologies and the design procedure of prototypes are explained.

To verify the performance of the proposed scheme, detail experiments are performed and experimental results indicate that the proposed AC regulator offers good performance.

2. Series Compensated Single-phase Step Down AC Voltage Regulator

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2.1 Principle of Operation

Fig. 1 shows the 20kVA series compensated single-phase AC voltage regulator scheme using an AC chopper with a series transformer.

The current flow of AC chopper used in the series compensated scheme is somewhat different from that of a normal AC chopper. As a bi-directional current path is always possible, the PWM switching pattern is necessary. For the positive half cycle of input voltage, each of the operation modes is explained as follows in Fig. 2.

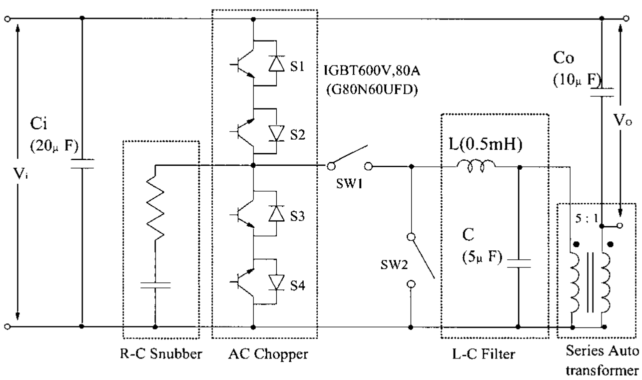


Fig. 1 Single-phase AC voltage regulator using AC chopper with series transformer (20kVA)

1) t1 period (powering mode: S1, S3, S4 is on, S2 is off)

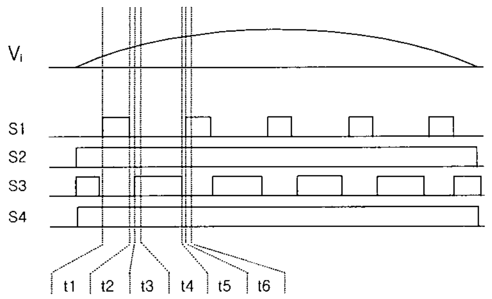
In this period of operation, the chopper side current flowing into the transformer due to load current is regenerated and depressed by input voltage through S2 and anti-parallel diode D1. Fig. 2 (a) describes the current flowing of this powering mode.

2) t2 period (powering mode: S2 and S4 is on, S1 and S3 is off)

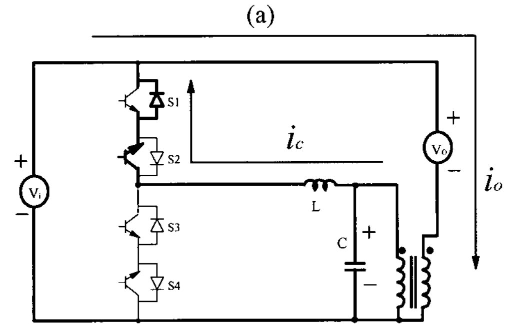
It is the dead time period of S1 and S3. The current flowing is identical to that of the t1 period and is shown in Fig. 2 (a).

3) t3 period (transient mode: S2, S3, S4 is on, S1 is off)

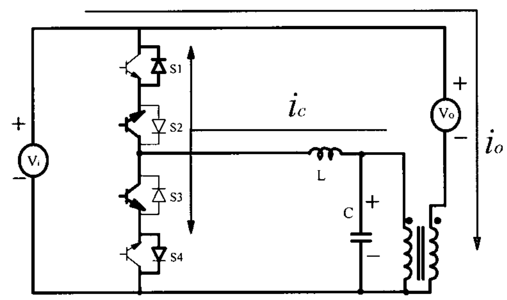
As S3 is on, the chopper current is beginning to flow through S3 and D4 and current flowing into main input through S2 and D1 is quickly decreased. Fig. 2 (b) shows this transient mode of operation. The moment S2 and D1 are turned off, the operation mode is changed to freewheeling mode, which is shown in Fig. 2 (c).



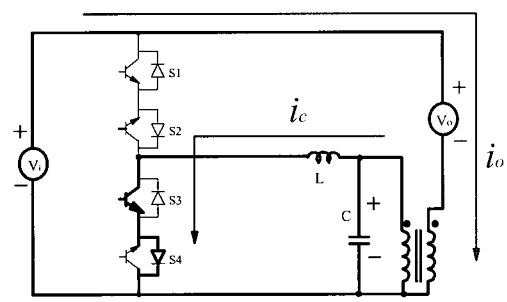
(a)



(b)



(c)



(d)

Fig. 2 Operation modes of step-down AC voltage regulator (a) Operation modes of positive half cycle. (b) Powering mode. (c) Transient mode. (d) Freewheeling mode.

4) t4 period (freewheeling mode: S2, S3, S4 is on, S1 is off)

Chopper current is freewheeled through S3 and D4.

5) t5 period (transient mode: S2, S4 is on, S1 and S3 is off)

As S3 is turned off, the current flowing into S3 and D4 is bypassed to S2 and D1 and regenerating current is increased.

6) t6 period (powering mode: S1, S3, S4 is on, S2 is off)

As S1 is turned on, regenerated current is increased until S3 is fully turned off. After that it is returned to t1 period.

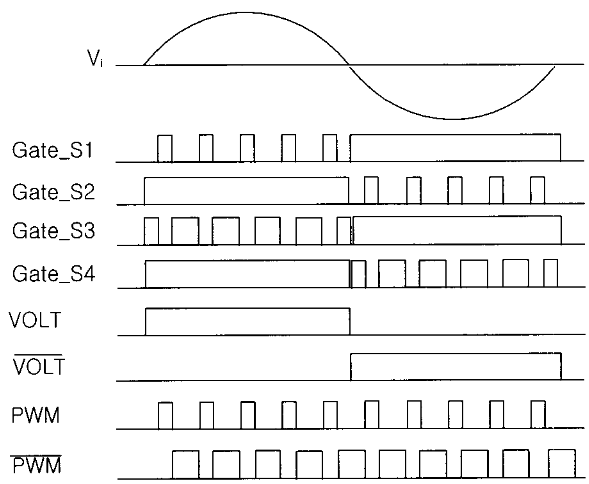


Fig. 3 Generation of PWM switching pattern for safe operation of AC chopper.

In the same manner, the operation mode of the negative half cycle can be explained.

2.2 Considerations for safe operation

When we make the switching pattern of the AC chopper, there are some considerations essential for safe operation.

First, it is important to ensure the freewheeling path in order to flow current freely independent on the polarity of applied voltage. If all the switches are on, short circuit is generated and if all the switches are off, voltage spike across the AC switch damages IGBTs in AC chopper application. To solve this problem, the switching pattern of Fig. 3 should be used for ensuring current path of the dead time period by freewheeling switch. However, it is impossible to force the current in the dead time period of zero crossing point along the path of the input voltage. In this paper, to solve this problem, a simple RC snubber is used as shown in Fig. 1.

In this case, the power loss of the RC snubber is not greatly increased because it only makes the bypass circuit during the dead time of zero crossing point of input voltage.

Second, when main power is applied while connecting the load, the IGBT switch can be damaged due to the high voltage generated in the chopper side caused by current flowing into the primary winding.

To avoid this problem, AC magnetic switch SW1 and SW2 are used as shown in Fig. 1.

Fig. 4 indicates the initial sequence logic to protect IGBTs from high voltage generated before the gate circuit is not stabilized.

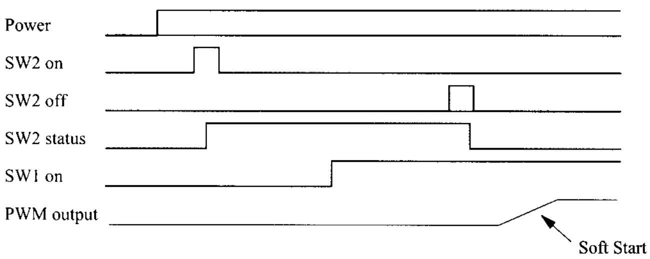


Fig. 4 Initial sequence logic for AC chopper

2.3 Experimental Results

To verify the performance of the proposed step down AC voltage regulator, a 20kVA single-phase prototype is designed and tested. Table 1 shows the detail specification of the prototype AC regulator.

Table 1 Specification Of Single-phase AC Voltage Regulator

Input	220V ±10%, 20KVA
Output	220V-15% (187V) ~ 220V adjustable, 20kVA
Transformer	Primary (AC chopper side): 220V, 25A Secondary (output side): 55V, 100A Type: autotransformer
AC chopper	IGBT: G80N60UFD (600V, 80A, Fairchild) Rated Output: 6 kVA Switching Frequency: 15kHz
Filter	Input Capacitor: 20 μF Output Capacitor: 10 μ F L-C filter: 0.5mH, 5 μF

Fig. 5 depicts the input and output voltage waveforms when output voltage reference is fixed as 187V, and detail waveforms are shown in Fig. 6 at rated load. Fig. 7 indicates the waveforms of voltage and current at initial sequence.

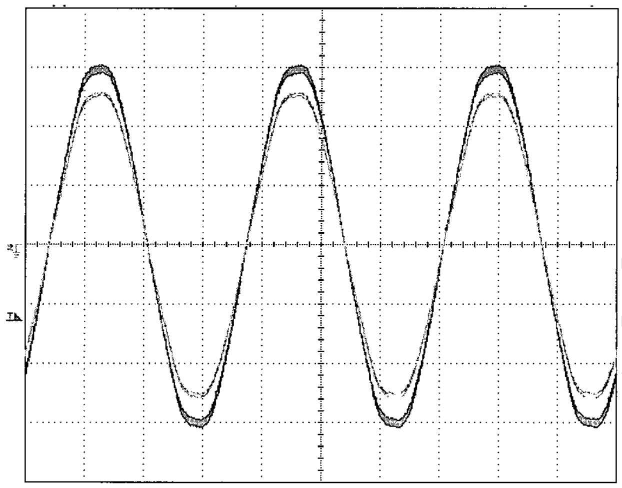


Fig. 5 Waveforms of input voltage and output voltage. (Input: 220VAC,output: 187VAC,100V/div., 5ms/div.)

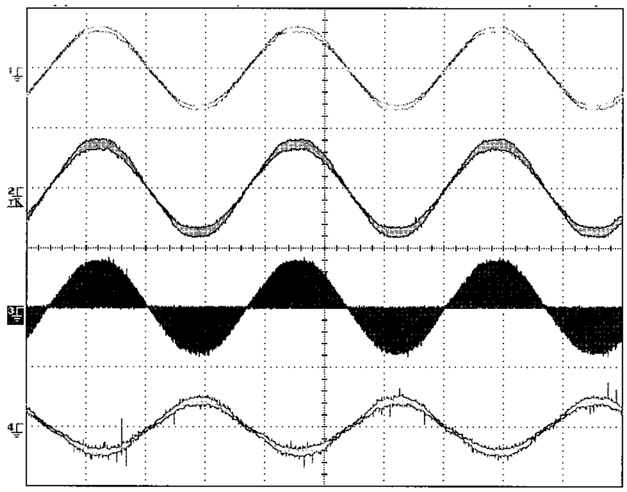


Fig. 6 Waveforms of each part at rated load. (1: input voltage, 2: output voltage, 3: AC chopper voltage, 4: AC chopper current, 400V/div., 50A/div., 5ms/div.)

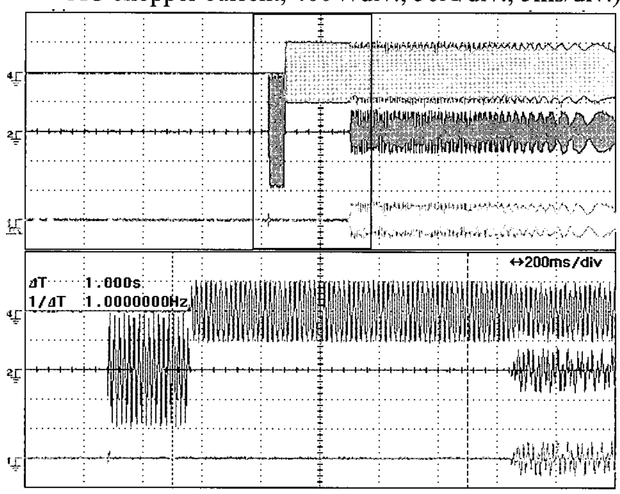


Fig. 7 Waveforms of voltage and current at initial sequence. (Top: current of primary winding, medium: voltage at primary winding, bottom: voltage at AC chopper, 500V/div.)

3. Series Compensated Three-phase Step Down AC Voltage Regulator

3.1 Principle of Operation

A novel three-phase step down AC voltage regulator that has a reduced number of switches using two AC choppers with three single-phase transformers based on series compensated single-phase step down AC voltage regulator. Detail configuration of three-phase AC scheme is shown in Fig. 8.

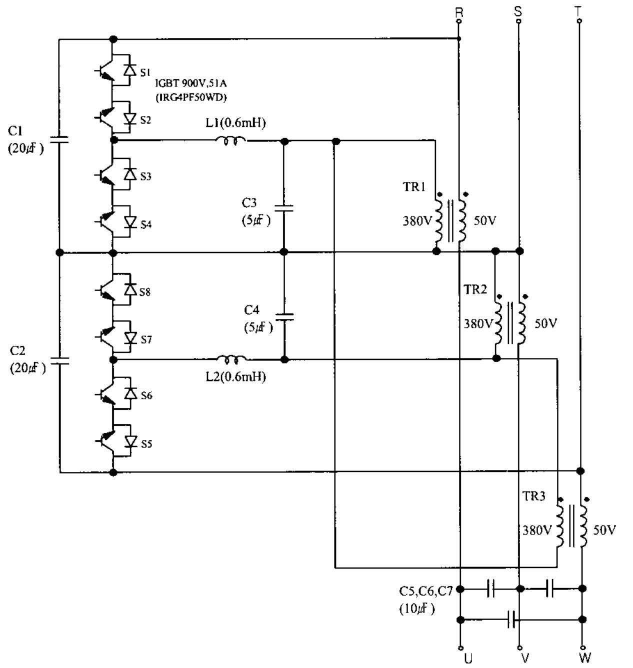


Fig. 8 A novel three-phase step-down AC voltage regulator using two AC choppers with three single-phase transformers

However the operation principles of the three-phase AC voltage regulator are based on that of a single-phase AC voltage regulator. Three-phase voltage compensation is generated from two AC choppers based on three-phase equivalent circuit theory.

The three-phase AC regulator shown in Fig. 8 can be analyzed using a simple equivalent circuit, which is presented in Fig. 9.

From the equivalent circuit of Fig. 9 and Kirchihoff's law, the following equations are obtained.

$$V_{RS} + V_{ST} + V_{RT} = 0 \tag{1}$$

$$\begin{aligned} V_{UV} &= V_{RS} + nV_{ST} + nV_{RS} \\ V_{VW} &= V_{ST} + nV_{TR} - nV_{ST} \\ V_{WU} &= V_{TR} - nV_{RS} - nV_{TR} \end{aligned} \tag{2}$$

where $n = \frac{1}{r}$, r = *transformer ratio*

The vector diagram of the proposed three-phase AC regulator is shown in Fig. 10.

If we assume the phase difference between V_{RS} and V_{UV} as α, the following equation can be obtained, as seen in Fig. 9.

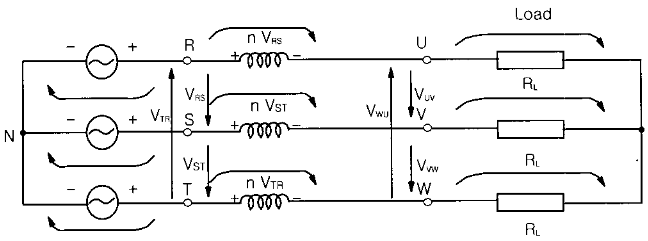


Fig. 9 Equivalent circuit of the three-phase voltage regulator

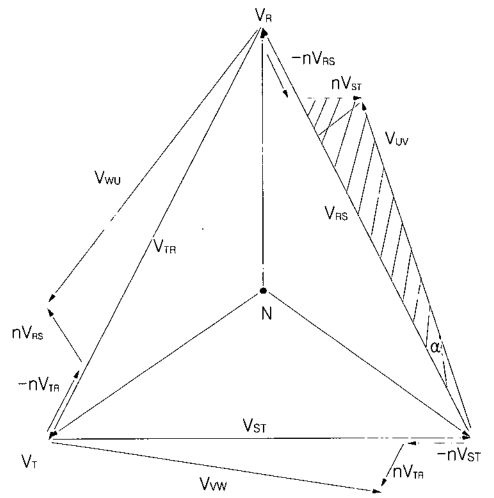


Fig. 10 Vector diagram of the three-phase voltage regulation

$$\begin{aligned} V_{RS} &= nV_{RS} + nV_{ST}\cos\frac{\pi}{3} + V_{UV}\cos\alpha \\ V_{UV}\sin\alpha &= nV_{ST}\sin\frac{\pi}{3} \end{aligned} \tag{3}$$

If input three-phase voltages are balanced and the quantity of each phase voltage is simplified as equation (4), we can extract a magnitude relationship between input voltage and output voltage.

$$\begin{aligned} V_{RS} &= V_{ST} = V_{TR} = V_i \\ V_{UV} &= V_{VW} = V_{WU} = V_o \end{aligned} \tag{4}$$

From equations (3) and (4), equation (5) is obtained.

$$V_o\cos\alpha = \frac{(2r-3)V_i}{2r}, V_o\sin\alpha = V_i\frac{\sqrt{3}}{2r} \tag{5}$$

From equation (5), the phase difference α and magnitude relationship between input voltage and output voltage can be obtained as follows.

$$\alpha = \tan^{-1}(\frac{\sqrt{3}}{2r-3}), \frac{V_o}{V_i} = \frac{\sqrt{3}}{2r} \cdot \frac{1}{\sin\alpha} \qquad (6)$$

3.2 Experimental results

A 60kVA three-phase prototype, which is described in Table II is designed and tested.

Fig. 11 and Fig. 12 show the performance of the proposed three-phase AC regulator. From experimental waveforms, it is confirmed that the phase of compensated voltage is different from input and output voltages as shown in Fig. 10.

Table 2 Specification Of Three-phase AC Voltage Regulator

Input	3Φ 380V ±10%, 60KVA
Output	3Φ380V-15% (323V) ~ 380V adjustable, 60kVA
Transformer	Primary (AC chopper side): 380V, 25A ×3 Secondary (output side): 50V, 100A ×3
AC chopper	IGBT: IRG4PF50WD (900V,51A, IR) Rated Output: 9 kVA × 3 Switching frequency: 15kHz
Filter	Input Capacitor: 20 μF Output Capacitor: 10 μ F L-C filter: 0.5mH, 5 μF

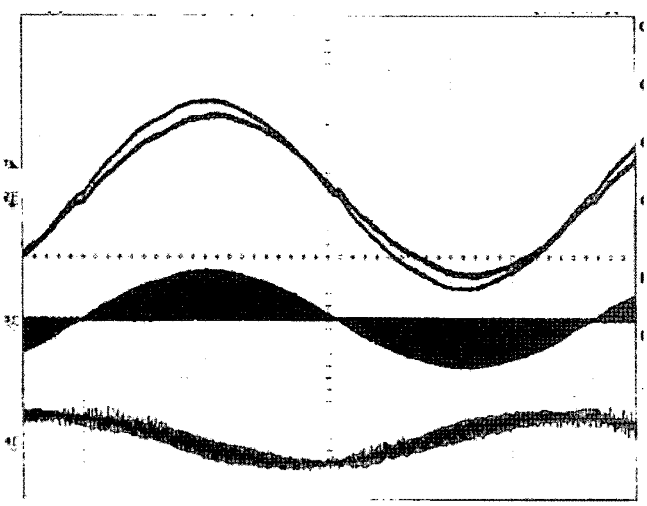


Fig. 11 Waveforms of each part at rated load. (1: V_{RS}, 2: V_{UV}, 3: AC chopper voltage, 4: AC chopper current, 2ms/div., 350V/div., 20A/div.)

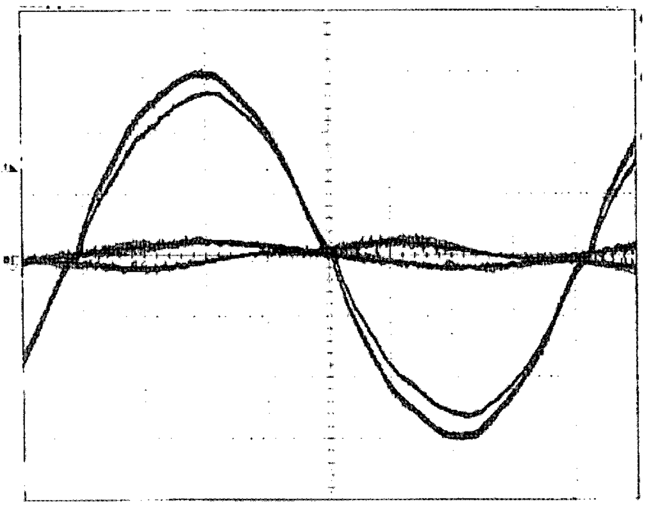


Fig. 12 Waveforms of input, output and compensated voltages. (1: V_{RS}, 2: V_{UV}, 3: compensated voltage nV_{RS}, 4: compensated voltage nV_{UV},2ms/div., 185V/div.)

4. Conclusions

In this paper, a novel single-phase and three-phase step down AC voltage regulator using AC choppers with series transformer is proposed. It can be used for power saving purposes of three-phase AC loads such as in the case of street lighting by decreasing the supply voltage 10-20% when high luminous intensity is not required.

Furthermore it can be modified as automatic voltage regulator or power line conditioner with input transformer.

Detail design and principles are explained and experimental results show that the proposed AC regulator has good performance.

Acknowledgements

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