### Dynamic Voltage Regulator based on PWM AC Chopper Converter: Topology and control

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*Abstract:* - This article presents a novel topology of dynamic voltage regulator using transformer and PWM AC chopper. The proposed voltage regulator employs an ac chopper converter to generate compensation voltage and uses the transformer to isolate the power converter from the load. When input voltage sags and swells occur, the output voltage can be regulated by changing the duty ratio of the PWM control signals. The transformer is connected in series with the load. Thus, the load voltage can be kept stable when input voltage fluctuations occur. For this purpose, a feedforward feedback digital controller has been designed to perform the close-loop control. The proposed converter and control strategy present the advantages of fast dynamic response and effective compensation to the voltage fluctuations. Simulations are made to investigate the performances of the proposed converter. The simulation results show that the designed voltage regulator has fast transient response, and can suppress the load voltage fluctuations effectively. The prototype is also setup. The simulation results have been validated by the experiment.

*Key-Words:* AC chopper, Voltage Regulator, Pulse Width Modulation, Feedforward and Feedback Control, Voltage Sags, Voltage Swells

#### **1** Introduction

The voltage sags (under-voltage) and swells (overvoltage) are common problems that affect the power quality. In modern industry, the dynamic voltage regulator is of greatest importance since it affects the normal working sate of the equipment and the industry process.

Voltage sag is a decrease to between 0.1 and 0.9 of the nominal voltage in rms voltage at power frequency for durations of 0.5 cycles to 1 minute. Voltage sags are usually caused by starting of the large load, fault or short circuit, or faults in power systems and have great impacts on normal work conditions of the equipments and instruments. If the voltage sags exceed two to three cycles, the manufacturing systems using of sensitive electronic equipments are prone to be affected, especially in semiconductor industry. On the other hand, the voltage swell is an increase to between 1.1 and 1.8 of the nominal voltage in rms voltage at the power frequency durations from 0.5 to 1 minute. Voltage swells are usually caused by switching the capacitor, lighting or disconnection of heavy load. These power quality problems have great influences on the customers such as equipment stalling, industrial process shutdown and important data loss.[1,2] These problems also lead to great financial losses

and the wastage of resources. The increasing market competition and costs have made the industries realize the significance and necessity of improving power quality.

Several voltage regulation techniques have been published in the literatures. The tap-changing transformers are used in power distribution systems as the voltage regulator.[3,4] However, this method has significant shortcomings. Because a large number of thyristor need to be used to change the transformer ratio of the tap-changing. The complex operation will limit the dynamic response speed. There are some approaches based on conventional rectifier/inverter technology, and some are based on energy storage devices, which make them more expensive and complex.[5,6]

Considering these problems, ac chopper converter is adopted in this design. This chopper converter has some advantages such as simple topology, high input power factor, fast dynamics and small size filter. It has been widely used in automatic voltage regulators [7-9], soft-starter and speed regulator of the inductor motor [10-12], light dimmer [13,14] and so on.

Three switches [15,16] and four switches [17-20] AC chopper converter are presented in the previous presented papers. In these researches, the switching patterns are critical. DC regenerative snubber capacitor[7,13,17] was used to realize safe commutation and enhance efficiency.

In this paper, a new topology of dynamic voltage regulator for critical loads in electric distribution systems is discussed. The proposed topology employs a PWM ac chopper converter along with a transformer. A buck type ac chopper converter and the corresponding commutation strategy are employed to compensate the load voltage without snubber circuits. This topology can change the polarity of the compensation voltage. As a result, compared with the previous voltage sags compensator, this topology can not only compensate the voltage sags but also the voltage swells. The proposed plan does not use bulk capacitors or inductors for energy storage and provides fast dynamic response at low cost.

In previous researches [12,15], peak voltage or rms voltage were used as the controller input to regulate the output voltage of the ac chopper. These signals change only one time in each period of the input voltage. Thus, the low dynamic response speed is the major problem. In order to keep the output voltage stable, a voltage feedforward and feedback control strategy is employed. This control strategy adopts instantaneous voltage as the controller input. The output voltage can be stabilized and the dynamic response speed is improved.

During disturbances such as voltage sags or voltage swells, the proposed scheme compensates the power source voltage and helps in keeping the voltage at the terminals of the critical load stable. This paper discusses a design example of the proposed system. A prototype is set up. Simulation results are shown and experimental results for a single-phase voltage regulator are presented.

# 2 Circuit Description and Principle of Operation

There are several types of the dynamic voltage regulator or restorer. A four switches ac chopper converter and isolated transformer are adopted in this design. The converter topology and commutation strategy are discussed as follows.

#### 2.1 Proposed Topology

The previous ac voltage regulators shown in Fig.1(a) and (b) can only regulate the output voltage lower than input voltage.



Fig.1 the topology of ac voltage regulator (a) phase control (b) PWM control

In this paper, the ac chopper converter shown in Fig.1(b) and the power transformer work together to compensate the voltage sags and swells. The power circuit of the proposed topology is shown in Fig.2.



Fig.2 the power circuit of the proposed dynamic voltage regulator

The buck type PWM ac chopper converter is employed to generate the compensation voltage. The injection transformer is used to isolate the voltage regulator from the load. The ac chopper converter changes the output voltage by regulating the duty ratio of the PWM control signals. Solid State Relay(SSR) can be used to connect the ac chopper and the power transformer. The switches SW1-SW4 are used to change the polarity of the compensation voltage. The compensation voltage of the critical load is realized by adding or subtracting the output voltage of the chopper converter. As a result, the proposed voltage regulator can compensate the load voltage in case of voltage sags and swells.

In normal conditions, the PWM ac chopper converter does not work. Thus, the compensation voltage is zero. When a voltage disturbance occurs, the chopper converter is controlled to generate a proper compensation voltage to keep the load voltage stable. When the source voltage goes back to normal, the voltage regulator stops working.

#### 2.2 PWM AC Chopper

AC chopper converter is one type of direct AC/AC converter. It can regulate the output voltage without DC bulk energy storage capacitor or inductor. This reduces the size and costs of the system. Compared with the matrix converter, this converter uses less switching devices. However, it can not change the frequency of the output voltage. The basic structure of the ac chopper converter is shown in Fig.3.



Fig.3 the power circuit of buck type ac chopper converter

The ac chopper converter model is based on a buck converter configuration, with an injection transformer used at its output. The topology of the converter is shown in Fig.2. This buck type AC chopper is powered by the source voltage  $u_s$ . Inductor  $L_i$  and capacitor  $C_i$  construct the input filter to absorb the harmonic currents. The power

switches S1, S2, S3, S4 are insulated gate bipolar transistors (IGBT). The used IGBT has inner antiparallel 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. These switches are controlled by PWM signals with high frequency. The output filter capacitor  $C_0$  reduces the output voltage ripple.

#### **2.3 Commutation Strategy**

The voltage regulation function of ac chopper converter is realized by applying PWM techniques to the switching devices. The main operation modes are defined as: active mode and freewheeling mode. The PWM control signals are shown in Fig.4.



Fig.4 PWM control signals of the ac chopper converter

S1 and S2 are used periodically to connect and disconnect the inductor L to the power supply, i.e., they regulate the power delivered to the inductor L. S3 and S4 provide a freewheeling path for the inductor current to discharge the stored energy of the inductance L. These switches are controlled by PWM signals. When the power source voltage  $u_s$  is positive(negative), S1 and S3 (S2 and S4) are controlled by PWM signals with S2 and S4 (S1 and S3) in the on state. When  $u_s$  is positive, S1 and S3 work in complementary mode. When S1 is switched on, S3 is switched off. The ac chopper converter works in active mode. During the active mode, the inductor current is forced to flow through the voltage source via the modulated switch S1 during its on-state periods and the inductor storages the energy. The freewheeling mode is defined when S1 is switched 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 S3 and S4 with the help of its body diodes according to the direction of the load current. Fig.5 illustrates the circuit operation when the power source voltage is positive.

The relation between the source voltage  $u_s$  and the output voltage  $u_c$  is expressed by eq. (1)

$$u_c = Du_s \tag{1}$$

where D is the turn-on ratio of S1.



Fig.5 the commutation process of the ac chopper converter

## 2.5 Voltage Compensation Under Voltage Sags and Swells

In order to keep the load voltage stable when voltage sags or swells occur, the polarity of compensation voltage can be changed by controlling the SSR(SW1, SW2, SW3, SW4). According to Fig.2, when SW1, SW3 are in the on states and SW2, SW4 are in the off states, the voltage regulator works in voltage sags compensation mode. The compensation voltage has the same polarity with the source voltage. The load voltage is the sum of the source voltage and the compensation voltage.



Fig .6 the voltage vector diagram in (a) voltage sags compensation mode (b) voltage swells compensation mode

From Fig.6(a), the expression for the load voltage is:

 $u_L = u_s + u_c$  (2) where  $u_s$  is the power source voltage, and  $u_c$  is the compensation voltage provided by the ac chopper.

On the other hand, when SW1,SW3 are in the off states and SW2, SW4 are in the on states, the voltage regulator works in voltage swells compensation mode. The load voltage is the subtraction of the source voltage and the compensation voltage. According to Fig.6(b), the expression for the load voltage is

 $u_L = u_S - u_C$ 

The control signals of the AC chopper and the SSR in different working conditions are shown in table 1.

(3)

Mada	Phase	Series transformer				AC chopper			
wode		SW1	SW2	SW3	SW4	S1	S2	S3	S4
		1	0	1	0	1	1	0	1
Voltage	+	1	0	1	0	0	1	1	1
Sags		1	0	1	0	1	1	1	0
	_	1	0	1	0	1	0	1	1
<b></b>	+	0	1	0	1	1	1	0	1
Voltage		0	1	0	1	0	1	1	1
Swells	_	0	1	0	1	1	1	1	0
		0	1	0	1	1	0	1	1

Table 1 the switching operation in different working conditions.

#### **3** System Analysis and Calculation

When voltage disturbances occur, the ac chopper converter generates the compensation voltage  $u_c$ . According to working principles of the ac chopper converter, the relation between the input voltage and the output voltage is analyzed as follows.

Let the power source voltage  $u_s$  is defined as:

 $u_s = V_{sm} \sin(\omega t) \tag{4}$ 

where  $\omega$  and  $V_{sm}$  are the angular frequency and the amplitude of the input voltage respectively.

Theoretically, the intermediate chopper voltage can be expressed as:

$$u_{cp} = DV_{sm}\sin(\omega t) + \sum_{k=1}^{\infty} \frac{V_{sm}\sin(kD\pi)}{k\pi}\sin(k\omega_s \pm \omega)t$$
(5)

where  $\omega_s$  are the switching frequency of the PWM control signal respectively. The first term of the right-hand side of equation (5) is the fundamental component and the second term is the harmonic components around the switching frequency. The fundamental component of  $u_{cp}$  is proportional to the duty ratio D. Since  $\omega_s$  is much higher than  $\omega$ , the harmonic components can be absorbed by small-size output filter. As a result, the filtered output voltage of converter can be approximately expressed by:

$$u_c = DV_{sm}\sin(wt) \tag{6}$$

According to equation (6), the compensation voltage can be regulated by changing the duty ratio D. The size of the filter components is inversely proportional to the orders of the harmonic voltage. Therefore, the switching frequency  $f_s$  of the PWM signal should be kept high enough to raise the order of harmonics to a high level.

Letting  $u_n$  represents the nominal source voltage, voltage sags are present when  $u_s$  (the true source voltage) is less than  $u_n$ . In order to regulate  $u_L$  to  $u_n$ , SW1, SW3(SW2, SW4) are switched on (off). The voltage regulator works in voltage sags compensation mode. According to eq.(6), the converter output voltage  $u_c$  is determined by the duty ratio *D*. By means of the close loop feedback control, the duty ratio changes with the degree of the source voltage sags. The desired load voltage is  $u_n$ .

In normal condition,  $u_s$  and  $u_L$  are equal to  $u_n$ . When voltage sags occur,  $u_s$  changes to the following value:

$$u_s = p u_n \tag{7}$$

where p is magnitude of the source voltage expressed in per unit. The series compensation voltage  $u_{csec}$ , shown in Fig.2, is a function of the source voltage  $u_s$  and the duty ratio D. It has the same polarity with  $u_c$ , can be expressed as:

$$u_{csec} = \frac{u_c N2}{N1} = \frac{Du_s N2}{N1}$$
(8)

where  $\frac{N2}{N1}$  is the turn ratio of the transformer.

The load voltage can be written as:

$$u_L = u_s + u_{csec} = pu_n + \frac{Dpu_n N2}{N1}$$
(9)

In order to keep  $u_L=u_n$ , the duty ratio *D* should satisfy:

$$D = \frac{(1-p)N1}{pN2} \tag{10}$$

In this approach, the maximum compensation voltage is obtained. The magnitude of compensation voltage is:

$$1 - p = \frac{DN2}{N1 + DN2} \tag{11}$$

In this design, assuming the maximum voltage sag is 30% of  $u_n$ , according to eq.11, the turn ratio of the series transformer should be 1:1.

When voltage swells are presents, the source voltage  $u_s$  is more than  $u_n$ . In order to regulate the  $u_L$  to  $u_n$ , the compensation voltage polarity should be changed. Thus, SW2, SW4(SW1,SW3) are switched on(off). The voltage regulator works in voltage swells compensation mode. According to eq.11, when the turn ratio of the series transformer is 1:1, the maximum compensation voltage up to 30% of  $u_n$  can be obtained.

#### 4 Voltage Control Strategy Design

In order to supress the voltage fluctuations with fast response speed, it is necessary to design the effective controller to keep the load voltage stable.

For fast output voltage control by the voltage regulator, a fast control strategy is required. Generally, the previous research used peak voltage feedback control method.[18] The peak voltage detector with diodes, capacitor, and resistor is used as a voltage sensing circuit. When the input signal is decreased, the capacitor is discharged through the resistor, and when increased, the capacitor is charged. However, the peak voltage value changes slowly compared with the instantaneous voltage value. The RMS voltage feedback control plan has the similar problems in slow dynamic performance.

Based on the analysis of the commutation strategy and working principle, the voltage feedforward and feedback control strategy is designed. The instantaneous values of both the power source voltage and load voltage are adopted as the inputs of the voltage controller. As a result, compared with RMS voltage control or peak voltage control, the dynamic performance is highly improved. The feedback control part can regulate the output voltage with no steady-state error. The feedforward control part can suppress the voltage fluctuations effectively with fast response speed. The control system structure is shown in Fig.7.



Fig.7 the feedforward and feedback control system structure diagram

Let the nominal power source voltage is:

 $u_n = u_{np} \sin(314t) \tag{12}$ 

where  $u_{np}$  are the nominal peak-voltage. When  $u_s=u_n$ , the compensation voltage is zero. When the voltage sags or swells are present, the voltage regulator should work following the designed the working principles. As the compensation voltage is proportional to the duty ratio of the PWM control signal, the feedforward control is designed as:

$$D_f = \frac{u_n - u_s}{u_n} \tag{13}$$

where  $D_f$  is the output of the feedforward control part.

The proposed feedforward control uses the instantaneous value of power source voltage  $u_s$  and the reference compensation voltage  $u_s$ - $u_n$  as the controller input to regulate the duty ratio. At the operation point, the feedforward control can obtain  $D_f$  to compensate the power source voltage fluctuations. This method is simple and effective.

The feedback PI (proportional-integral) controller is designed to make no steady-state error. As shown in Fig.7, the output voltage is subtracted from the reference voltage. The error voltage passes through PI controller block and then is used to regulate the duty ratio. The duty ratio  $D_{fk}$  of feedback control is given by:

$$D_{fk} = k_p (u_n - u_L) + k_i m(t)$$

$$\frac{dm(t)}{dt} = u_n - u_L$$
(14)

where  $k_p$ ,  $k_i$  are proper proportional and integral gains respectively. m(t) represents the integral of the load voltage error  $\Delta u$ . The integral part of the designed controller makes the steady-state output voltage error zero. D is limited within the range from 0 to 1. Thus, D can be expressed as:

$$D = \begin{cases} 1 & D(t) \ge 1 \\ D_f + D_{fk} & 0 < D(t) < 1 \\ 0 & D(t) \le 0 \end{cases}$$
(15)

When the source voltage is normal, the SW1,SW4 are in the off states and the SW2,SW3 are in the on states. Thereby, the converter output voltage  $u_c$  equals zero and the load voltage  $u_L$  is equal to  $u_s$ . The power is directly delivered to the load.

The compensation voltage control strategy and the SSR switching plan can be implemented with micro processor. In experiment, the controller hardware is setup and programmed to implement the control algorithm. The duty ratio D can be calculated according to different working conditions. Then, the PWM control signals  $S_{g1}$ ,  $S_{g2}$ ,  $S_{g3}$ ,  $S_{g4}$  are generated by modifying the corresponding register value directly.

#### **4** Simulation

The fundamental operations are examined by simulation. Table 2 shows circuit parameters used in the simulation. The power source frequency is 50 Hz, the switching frequency for PWM control is 40 kHz.

Item	Symbol	Parameter
nominal voltage	$u_n$	$220\sqrt{2}\sin(314t)$
input filter inductor	$L_i$	0.2 <i>mH</i>
input filter capacitor	$C_i$	$1\mu F$
output filter inductor	L	1mH
output filter capacitor	$C_o$	$1\mu F$
Load	R	40Ω

Table 2 the parameters of the prototype in experiment

When D=0.5, the simulation results are shown in Fig.8. The input current  $i_i$  is shown in Fig.8(b). The input current is nearly sinusoidal waveform. The intermediate chopper voltage  $u_{cp}$  and the compensation voltage  $u_c$  are shown in Fig.8(c) and Fig.8(d) respectively. The intermediate chopper voltage  $u_{cp}$  contains high order harmonic components. The spectrum analysis of the  $u_{cp}$  and  $u_c$ is shown in Fig.9. The THD (total harmonic distortion) of  $u_{cp}$  and  $u_c$  are 122.49% and 0.48% respectively. Because the switching frequency is much high than the line frequency, the size of both input filter and output filter are highly reduced. By using the designed output filter, the harmonic is eliminated and sinusoidal voltage the compensation voltage is obtained.



Fig.8 simulation results of (a)input voltage  $u_s$ , (b)input current  $i_i$ , (c)intermediate chopper voltage  $u_{cp}$ , (e)output compensation voltage  $u_c$ 



Fig.9 the spectrum analysis of (a)  $u_{cp}$  and (b)  $u_c$ 

Fig.10 shows the occurrence of 30% singlephase voltage sags by 5 periods on a utility grid.  $u_s$ and  $u_L$  are the source voltage and load voltage respectively. The simulation results show that the designed approach can keep the load voltage stable without introducing additional voltage transients.



Fig.10 load voltage waveforms when voltage sags occur

Fig.11 shows the simulation results of the output voltage waveforms when input voltage swells occur. At 0.043s, input voltage increases abruptly by 30% during 5 periods. The load voltage can be kept stable under voltage swells faults. The simulation results verified that the proposed control plan can suppress the voltage fluctuations effectively.



Fig.11 load voltage waveforms when voltage swells occur

#### **5** Experiment

In order to validate the proposed approach, experimental results were obtained on a prototype.

In experiment, a proper micro processor must be well chosen to ensure the system performance. The digital signal processor (DSP) can implement with smaller size and lower cost than the general purpose micro processor. Moreover, compared to the micro-controller, DSP has higher processing speed and more powerful ability in executing complex control algorithm. Thus, this prototype adopts DSP as the controller hardware.

In experiment, the overall system consists of six parts. The power circuits (part 1) regulate the output voltage of the ac chopper converter to obtain the desired compensation voltage. The signal detection circuits (part 2) use the voltage sensors and the signal conditioning circuits to measure and filter the signals of the power source voltage and the load voltage. The controller (part 3) includes the DSP running the proposed control algorithms. The feedforward and feedback control algorithm of the proposed voltage regulator is implemented using 30MIPS DSPIC30f4011. This processor is designed for high performance applications and has a variety of peripherals. Switching period and duty ratio calculation are implemented in software. The PWM control signals are generated by the PWM function unit in DSP. Voltage signals obtained from the part 2 are converted by using the analog digital converter (ADC) function unit in DSP. The duty ratio is changed in every sampling period.

The driver circuits (part 4) convert the PWM control signals generated by the controller into the driver signals of the IGBT in the power circuits. The faults protection circuits (part5) can disable all PWM control signals and show the faults types when over-currents, over-voltage or over-heat faults occur. The auxiliary power supply (part 6) provides the +5V dc power to part 3,  $\pm 15V$  dc power to part 2,  $\pm 24V$  dc power to part4.

Fig.12 shows the picture of the prototype. The circuit parameters in experiment are shown in Table.3.



Fig.12 prototype of the proposed dynamic voltage regulator

Item	Symbol	Parameter		
Source voltage	<i>u</i> s	$\sqrt{2}60\sin(314)t$		
input filter inductor	Li	0.2 <i>mH</i>		
input filter capacitor	$C_i$	$1\mu F$		
output filter inductor	L	1mH		
output filter capacitor	$C_o$	$1\mu F$		
IGBT	S1,S2,S3,S4	600V/10A		
SSR	SW1, SW2, SW3, SW4	380V/5A		
switching frequency	f <sub>s</sub>	40kHZ		
sampling frequency	fsam	5kHZ		

Table 3 the parameters of the prototype in the experiment



Fig.13 PWM control signals of the ac chopper converter



Fig.14 the waveforms of (a) power source voltage  $u_s$  (b) the compensation voltage  $u_c$ 



Fig.15 the waveforms of the intermediate chopper voltage  $u_{cp}$ 



Fig.16 when voltage sags occur, the waveforms of (a) the power source voltage and (b) the load voltage

The designed commutation process shown in Fig.4 is also realized. The PWM control signals corresponding to the commutation strategy are shown in Fig.13. Fig.14 illustrates the source

voltage  $u_s$  and the compensation voltage  $u_c$ , when D=0.5. The compensation voltage is nearly sinusodial waveform. Fig.15 shows the waveforms of the intermediate chopper voltage  $u_{cp}$ . The input voltage is chopped into segment. In addition, by using the designed commutation strategy, there are no voltage spikes in  $u_{cp}$ . The snubber circuits are not needed in this design.

Fig.16 shows the performance of the approach for the 30% voltage sags. Fig.17 shows the results of the approach for the 30% voltage swells.



Fig.17 when voltage swells occur, the waveforms of (a) the power source voltage and (b) the load voltage

With the proposed topology and control method, the output voltage is nearly unaffected with the suddenly supply voltage change. The feedforward and feedback controller can regulate the duty ratio and keep output voltage stable. These results verify the validity of the proposed method.

#### **5** Conclusion

A novel topology of dynamic voltage regulator design using transformer and PWM AC chopper converter is proposed. This topology does not use energy storage devices, such as battery, bulk capacitors or inductors. The sinusoidal compensation voltage and input current waveforms can be obtained. In addition, the feedforward feedback instantaneous voltage control strategy is designed to enhance the performance of the converter. When input voltage sags and swells occur, the compensation voltage can be regulated by changing the duty ratio of the PWM signals to keep the load voltage stable. The proposed converter and control strategy present the advantages of fast dynamic response and effective compensation to the voltage fluctuations. Simulations are performed to investigate the performances of the proposed converter. The prototype is designed by using DSP to implement the control algorithms. The simulation and experiment results shows that it has fast transient response, and can keep the load voltage stable effectively.

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