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Voltage Quality Improvement Using AC-Chopper in Distribution Line

Veligeti Divya *1, P.Soumya*2

M.Tech(PE) Student, Dept of EEE, SR Engineering College, Warangal AP, India

Sr. Assistant Professor, Dept of EEE, SR Engineering College. Warangal AP, India

Abstract

Voltage sag is an important power quality problem, which may affect domestic, industrial and commercial customers. Voltage sags may either decrease or increase in the magnitude of system voltage due to faults or change in loads. Momentary and sustained over voltage and under voltage may cause the equipment to trip out, which is highly undesirable in certain application. In order to maintain the load voltage constant in case of any fluctuation of input voltage or variation of load some regulating device is necessary. The focus of this paper is the study of direct alternating-current (ac)–ac converters. The ac/ac power converter takes energy from the grid during voltage sag/swell. By connecting the ac-chopper converter's input terminals on the load side and injecting the compensation voltages on the supply-side, it is possible to hold a constant input voltage, resulting in an efficient solution for compensating deep voltage sags and swells. Thus, this paper proposed to eliminate the sag and swells. It has the ability to compensate balanced and unbalanced voltage fluctuations and to eliminate the energy storage elements. The pulse width modulation (PWM) technique is utilized to fulfil the input and output requirements. Numerical simulation results are presented to validate the approach. Voltage compensator based on an AC buck chopper, which is operated using the strategy of non-complementary control without current detection. It is suitable for compensation long term voltage sags and could adjust pulse widths according to the ratio of required output in real time. Simulations and experiment results proved functionality of this circuit.

Index Terms—Dynamic Voltage Restorer (DVR), Ac-Ac converter (Ac Chopper), voltage control, Sag.

I. INTRODUCTION

Voltage in the system of distribution sags is mainly due to the fault occurring in the transmission and distribution system, loads like welding and operation of building construction equipment, switching of the loaded feeders or equipment's. Both momentary and continuous voltage sags are undesirable in complex process controls and household appliances as they use precision electronic and computerized control. Major problems associated with the unregulated long term voltage sags include equipment failure, overheating and complete shutdown. Tap changing transformers with silicon controlled rectifiers (SCR) are usually used as a solution of continuous voltage sags. They require large transformer with many SCRs to control the voltage at the load which lacks the facility of adjusting to momentary changes. Some solutions have been suggested in the past to encounter the problems of voltage sag.

The DVR requires energy storage device to compensate the voltage sags. Flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors are generally used as energy storage devices. The rated power operation of DVR depends on the size and capacity of energy storage device which limits its use in high power applications. Whereas, switching regulator needs no energy storage devices, therefore, can be used both in low power and high power applications.

The existing methods include tap changers, FACTS devices such as the distribution STATCOM (D-STATCOM), the Unified Power Quality Controller (UPQC), and the Dynamic Voltage Restorer (DVR) [4-7]. The series compensation device DVR was introduced for voltage sag mitigation and has been adopted as a common solution to the problem.

A traditional DVR consists of series and shunt converters that are connected back-to-back with common dc-link capacitor used as an energy storage element as shown in Fig. 1.1 [1,2]. The power converter stage in the Conventional DVR is definitely of an indirect ac-ac power Conversion, which implies the possible drawbacks such as more device counts in power semiconductor devices, more loss, less efficiency compared to a direct ac-ac power conversion. Also, the dc capacitor as an energy storage element may be problematic due to its size and maintenance [2]. Moreover, the DVR in Fig. 1.1 can treat only one side compensation, for example one of voltage sag or swell compensation, because of the limited voltage gain of the series and shunt converters. To overcome such drawbacks, a matrix converter can be considered as a direct power conversion stage [3]. However, the matrix converter not only requires too many active switches but also has limited voltage gain of 0.866, i.e., buck operation only. In [4], another approach to reduce energy storage element is reported but it is limited to sag correction. In [5], the ac-chopper converter is used for the DVR applications. However, the inter phase topology requires 8 bi directional switches for three-phase application. In this paper, ac-chopper converter based DVRs are presented for single-phase and three-phase systems. The ac-chopper converter can change the magnitude of its

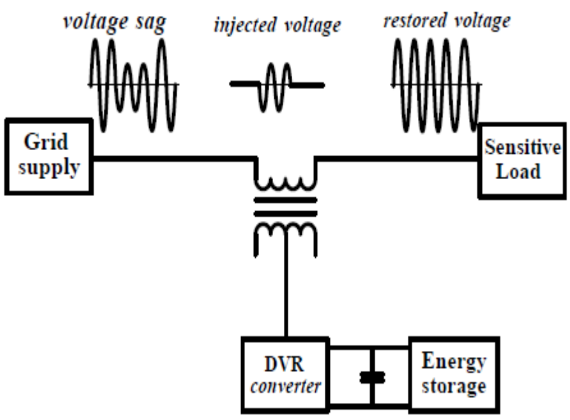


Fig 1.1 Principle of operation of the dynamic Voltage Restorer

Output voltage through direct ac-ac conversion [6,7]. The proposed DVR has fewer counts of semiconductor devices and no bulky dc-link capacitor. Also, depending on the adopted types of ac-chopper converter, the DVR can compensate both input voltage sag and/or swell. This paper will present the circuit configuration and operating principle of the proposed DVR with various types of ac-chopper converters such as buck, boost and buck boost converters.

II. THE PROPOSED CONFIGURATION

The PWM control circuit is commonly available as integrated form. The designer can select the switching frequency by choosing the value of RC to set oscillator frequency. As a rule of thumb to maximize the efficiency, the oscillation period should be about 100 times longer than the switching time of the switching device such as Transistor, Metal oxide semiconductor field-effect transistor (MOSFET), Insulated gate bipolar transistor (IGBT). For example, if a switch has a switching time of 0.5 us, the oscillator period would be 50 us, which gives the maximum oscillation frequency of 20 KHz. This limitation is due to the switching loss in the switching devices. The switching loss of switching devices increases with the switching frequency. In addition, the core loss of inductor limits the high frequency operation.

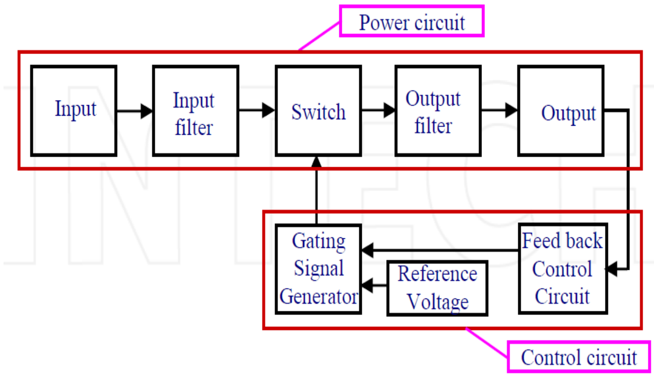


Fig. 2.1 shows the system configuration of the proposed Ac-chopper converters.

In Fig. 2.2, k means the voltage gain of the Ac-chopper converter, which can be expressed by

$$k = \begin{cases} D & \text{(Buck)} \\ 1/(1-D) & \text{(Boost)} \\ D/(1-D) & \text{(Buck-Boost)} \end{cases} \qquad (1)$$

depending on the converter types. Fig. 2.3 shows the various single-phase circuit configurations of the Ac-chopper converter that can be utilized in Fig. 2.3 the Ac-chopper converters in Fig. 2.3 are referred to as ac chopper and can change only voltage magnitude.

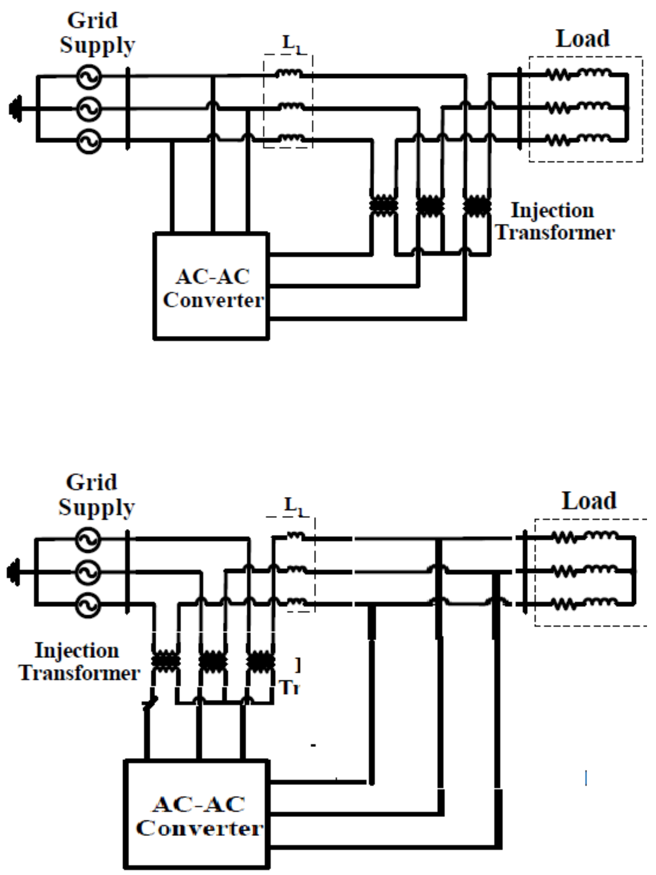


Fig.2.2 The proposed Ac-chopper converter; (a) shunt series, (b) series-shunt configurations.

It should be noted that the Ac Chopper converter has only one control variable, i.e., the duty-ratio, *D*. In Fig. 2.3, the switch set (*S*1, *S*2) is simultaneously turned on/off with duty ratio, *D*. Similarly, the switch set (*S*3, *S*4) is operated together with duty ratio, 1-*D*. Fig. 2.4 illustrates the control block diagram for the DVR. The load voltage *vo* is sensed and fed into the magnitude detector which produces the signal *Vo* that means the magnitude of the load voltage. The control is a regulation problem, in which the magnitude of the load voltage must be regulated to the reference magnitude *Vf* The DVR controller has two operating mode, i.e., bypass mode and normal mode. Such operating mode is determined by the amount of the error voltage *Ve*.

Normal mode: If the absolute value of *Ve*, |*Ve*| is greater than the predetermined value, for example, 5% of *Vf*, then the DVR is actively and actually controlled through PI controller and PWM operation. Error-driven PI controller produces the duty ratio *D* which is compared with a triangular carrier in PWM block.

Bypass mode: In bypass mode, there is no need to actively control the switches because the magnitude of the load voltage is almost equal to that of the reference voltage with allowable difference.

In bypass mode, the injected voltage must be zero. Such condition is made by turning on the switch set (*S*3,*S*4) and turning off the switch set (*S*1, *S*2) in both buck converter and buck-boost converter. In the case of the boost converter, however, a separate back-to-back SCR thyrister may be needed to make the injected voltage zero because any switching state cannot make the transformer terminals short-circuited. In bypass mode, all the gating signals are locked and the power is directly delivered from the voltage source to the load without action of the PWM ac-ac converter. If the source voltage has no voltage sag or swell, the DVR will be under such bypass mode, resulting in higher efficiency.

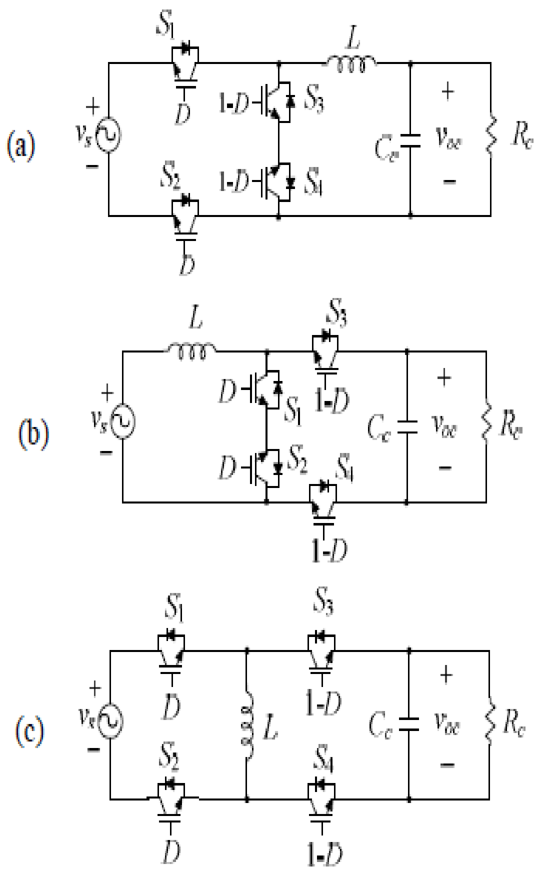


Fig.2.3. The single-phase Ac-chopper converters; (a) buck, (b) boost, (c) buck-boost types.

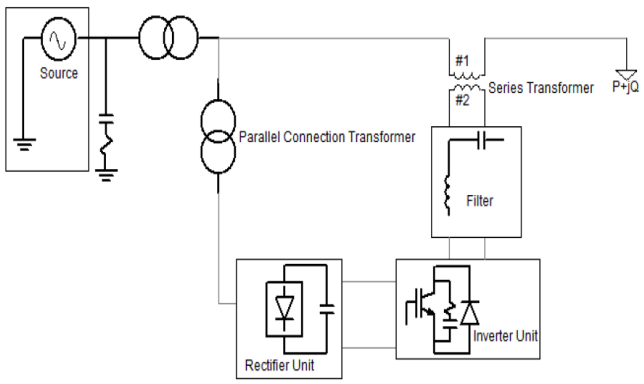


Fig. 2.4 Series ans Parallel Connection Block DVR

Due to the excellent dynamic performance of the Dynamic Voltage Regulator it is the most efficiency solution dealing with the dynamic voltage problem. Additionally, the large capacity of the DVR makes it as an economic method also.
The analysis of DVR will be performance in several divisions during the following work:

1) Construction, operation principle of DVR An overall presentation of the whole system and some detailed description of each component will be given in the second chapter.
2) Corresponding circuit design of DVR To use PSCAD to organize an AC buck chopper circuit that is corresponding to the DVR.
3) Simulation

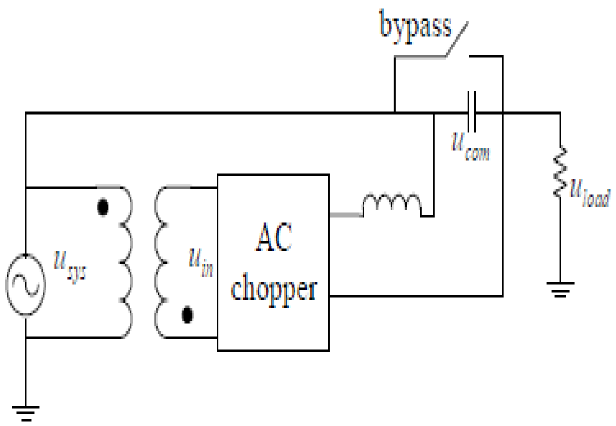


Fig. 2.5 Principle Block Diagram of AC-Chopper

Let u_{in} be the transformer output u_{com} is the circuit output, u_{load} is the load voltage, n is the turns ratio of transformer, and D is the duty cycle. So the value of u_{load} could be derived by the equations 1-1 to 1-3.

$$u_{in} = \frac{u_{sys}}{n} \quad \text{1-1}$$

$$u_{com} = Du_{in} \quad \text{1-2}$$

$$u_{load} = u_{sys} + u_{com} \quad \text{1-3}$$

$$u_{load} = u_{sys}(1 + \frac{D}{n}) \quad \text{1-4}$$

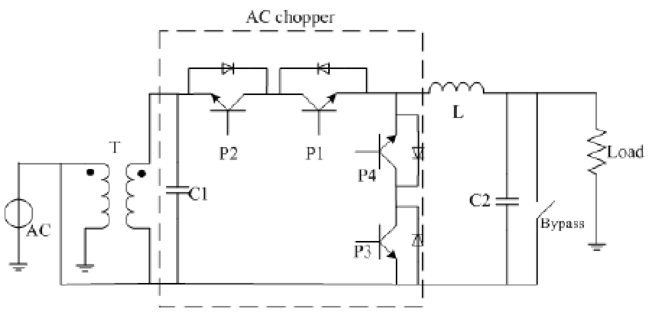


Fig. 2.6 AC-Chopper Circuit Structure

III. THE BASIC CHARACTERISTICS

Voltage regulators using servo systems are quite common. Both single and three-phase types are available. The rating of this type of regulator is quite high and is more economical for high power rating. This regulator normally consist a variac driven by a servomotor, a sensing unit and a voltage and power amplifier to drive the motor in a reversible way. Various types of driving motor may be used for regulating the unit, such as direct current, induction and synchronous motors. However, in all cases, the motor must come to rest rapidly to avoid overrun and hunting. The amount of overrun may be reduced by dynamic braking in the case of a DC motor or by disconnecting the motor from the variac by a clutch as soon as the signal from the measuring unit ceases.

In shunt-series configuration, the load voltage is given by

$$v_s + kv_s = v_o \tag{2}$$

Thus, the overall voltage gain of the shunt-series DVR is expressed by

$$G_{FF\_p} \equiv \frac{v_o}{v_s} = 1 + k \tag{3}$$

On the other hand, there exists another possibility to the polarity in inserting the compensation voltage, *voc*, by the reverse connection. In such case, the overall voltage gain of the shunt-series DVR will be

$$G_{FF\_n} \equiv \frac{v_o}{v_s} = 1 - k \tag{4}$$

Similarly, one can obtain the overall voltage gains of
the series-shunt DVR as follows,

$$G_{FB\_p} \equiv \frac{v_o}{v_s} = \frac{1}{1-k} \tag{5}$$

$$G_{FB\_n} \equiv \frac{v_o}{v_s} = \frac{1}{1+k} \tag{6}$$

Where GFB_*p* and *GFB_n* mean the overall voltage gain of the series-shunt DVR with positive injection and negative injection, respectively.

The voltage is corrected by tap-charging switches in steps. Where stepless control is required, variable autotransformers or variacs are used. The normal variac consists of a toroidal coil wound on a laminated iron ring. The insulation of the wire is removed from one of the end faces and the wire is grounded to ensure a smooth path f or the carbon brush. Carbon brush is used to limit the circulating current, which flows between the short-circuited turns. A Buck-Boost transformer is sometimes used for AC voltage regulation when the output voltage is approximately the same as the mean input voltage as shown in Fig. 3.5(b). In this case if the output voltage is less than or greater than the desired value, it can be increased or decreased to the desired value by adding a suitable forward or reverse voltage with the input through the Buck-Boost transformer.

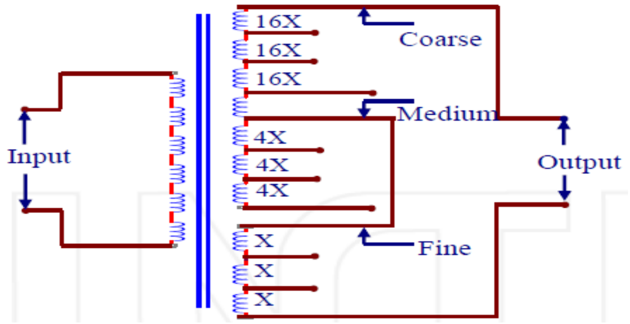


Fig. 3.1 Changing Switch Arrangement in offload

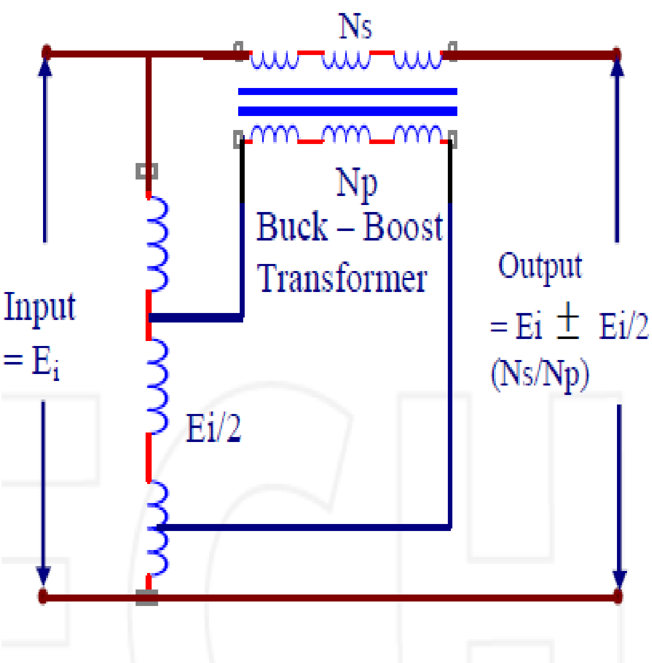


Fig. 3.2 Voltage control by combination of a Buck–Boost transformer and a variac

Based on table I, the basic operation of the DVR with Ac-chopper converter can be plotted as seen in Fig. 3.4. For compensating voltage sag, the DVR must be operated in boost region whereas, for compensating voltage swell, in buck region. From the table I and the gain graphs in 3.4, one can notice that some configurations are adequate for voltage sag or swell compensation but some configurations are not proper. It can be summarized as follows;

- Regardless of series-shunt and shunt-series configurations, the DVR including the buck converter which is positively connected can be used only for compensating voltage sag
- When the boost converter is negatively connected, the DVR with the boost converter can compensate both voltage sag and swell.
- In configurations using the buck-boost converter, there is the polarity change of the gain as *D* varies.

IV. STEADY STATE ANALYSIS

In this section, the steady state analysis is carried out to investigate the characteristics of the DVR system with a Ac-chopper converter. As an analysis example, the DVR that is composed of the buck converter which is positively connected is selected. Fig. 4.2 shows the circuit diagram under analysis.

To facilitate the analysis procedure, the switching frequency is much greater than the line frequency so that during a switching period all the voltages and currents can be considered constant.

Fig. 4.3 illustrates the equivalent circuits during each duty cycle. As seen in Fig. 4.3, the inductor voltage is given by

$$v_L = \begin{cases} 2v_s - v_o & (\text{during } DT_s) \\ v_s - v_o & (\text{during } (1-D)T_s) \end{cases} \qquad (7)$$

where *Ts* is the switching period. Thus, the average inductor voltage during one switching period is expressed by

$$v_L = (D+1)v_s - v_o \qquad (8)$$

Regardless of the switching state change, the following circuit equations are obtained;

TABLE I

THE IDEAL OVERALL VOLTAGE GAIN

DVR configuration \ converter topology	Buck converter	Boost converter	Buck-boost converter
Series-shunt & positive injection (G_{FF_p})	$1+D$ (Boost)	$\frac{2-D}{1-D}$ (Boost, G>2)	$\frac{1}{1-D}$ (Boost)
Series-shunt & negative injection (G_{FF_n})	$1-D$ (Buck)	$-\frac{D}{1-D}$ (Buck-boost)	$\frac{1-2D}{1-D}$ (Buck-boost)
Shunt-Series & positive injection (G_{FB_p})	$\frac{1}{1-D}$ (Boost)	$-\frac{1-D}{D}$ (Buck-boost)	$\frac{1-D}{1-2D}$ (Buck-boost)
Shunt-Series & negative injection (G_{FB_n})	$\frac{1}{1+D}$ (Buck,0.5<G<1)	$\frac{1-D}{2-D}$ (Buck,0<G<0.5)	$1-D$ (Buck)

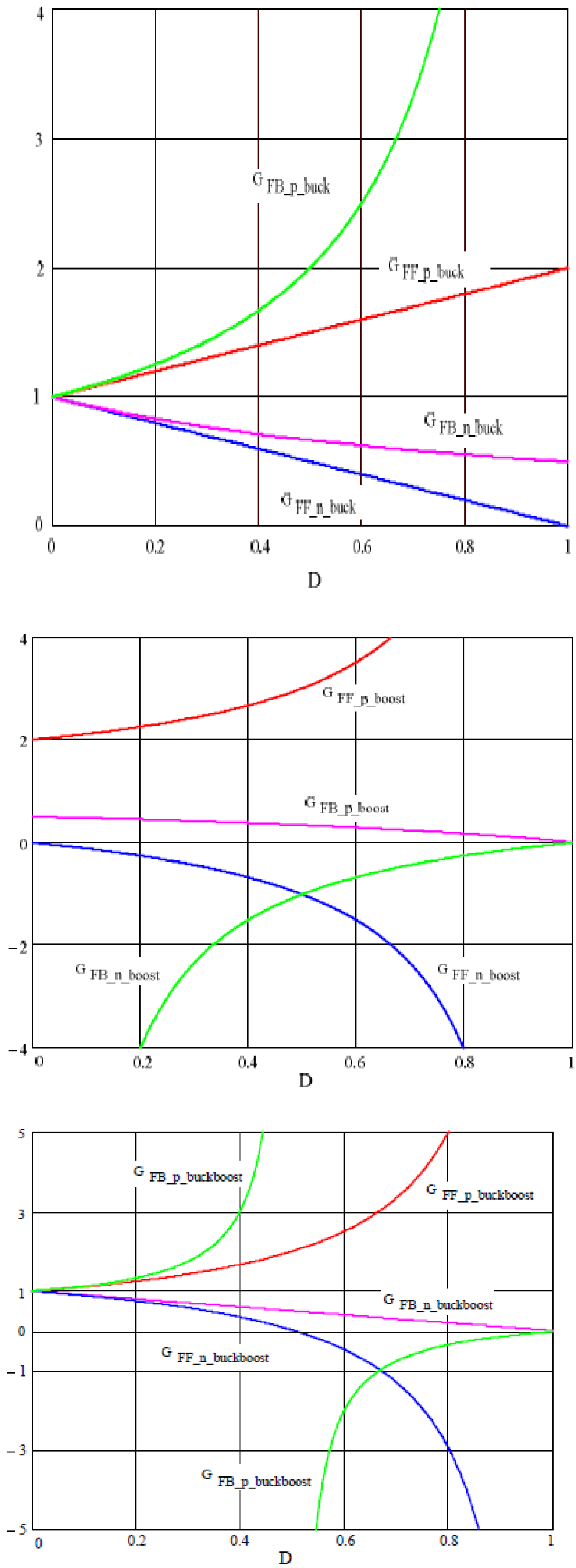


Fig. 4. 1 The overall voltage gains when employing (upper) buck, (Middle) boost , (lower) buck-boost converters.

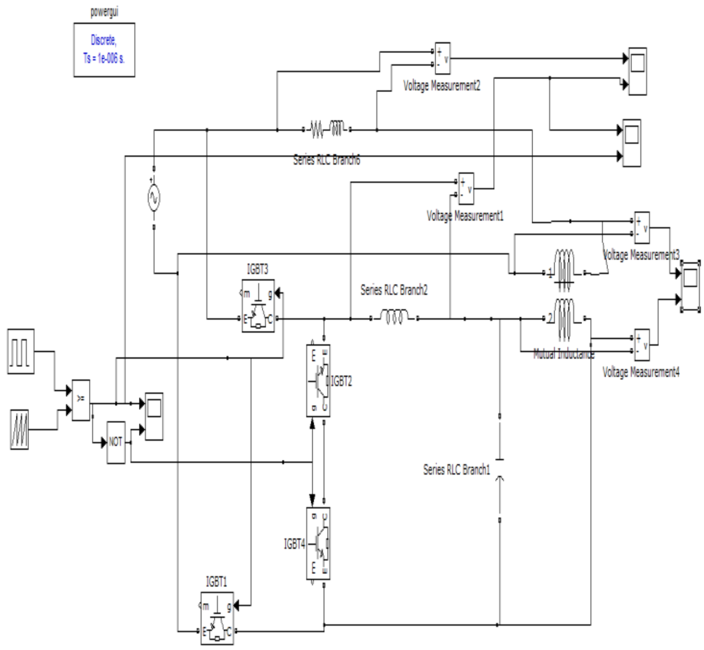
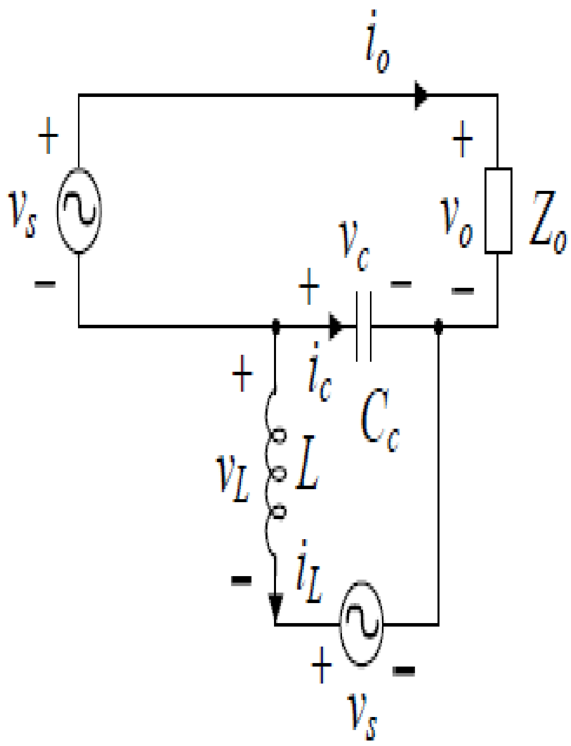


Fig.4.2 . The DVR system with a buck ac-ac converter.



(a)

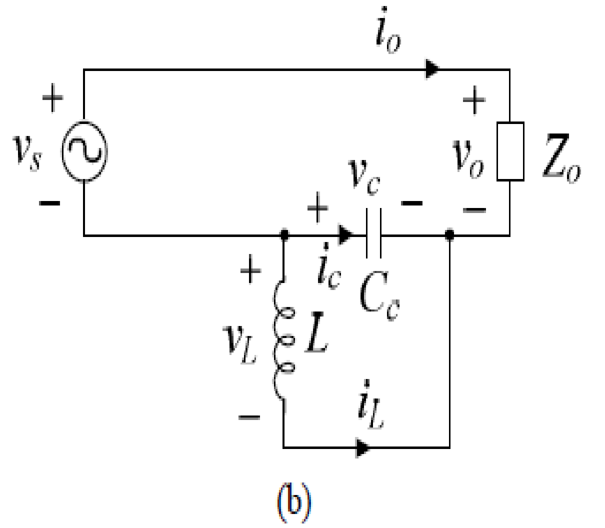


Fig. 4.3 The equivalent circuits (a) during *DTs*, (b) during (1-*D*) *Ts*

$$v_c = v_o - v_s \tag{9}$$

$$i_c = i_L - i_o \tag{10}$$

$$L\frac{d}{dt}i_L = v_L \tag{11}$$

$$C_c\frac{d}{dt}v_c = i_c \tag{12}$$

From (8), (10) and (11), the following relation is Obtained.

$$L\frac{d}{dt}(i_c + i_o) = (D+1)v_s - v_o \tag{13}$$

Also, from (9) and (12), one can obtain

$$i_c = C_c\frac{d}{dt}(v_o - v_s) \tag{14}$$

Furthermore, substituting (14) into (13), the following differential equation is obtained.

$$LC_c\frac{d^2v_o}{dt^2} + v_o + L\frac{di_o}{dt} = LC_c\frac{d^2v_s}{dt^2} + (D+1)v_s \tag{15}$$

In Fig. 5, *Zo* means the load impedance, the equation of which can be expressed in frequency domain by

$$V_o(s) = Z_o I_o(s) \tag{16}$$

where *s* is the Laplace variable. Therefore, using (15) and (16), the transfer function can be expressed by

$$\frac{V_o(s)}{V_s(s)} = \frac{s^2LC_c + D + 1}{s^2LC_c + sL/Z_o + 1} \tag{17}$$

Under the condition of $\omega L \ll Z_o$, (17) becomes

$$\frac{V_o(s)}{V_s(s)} \cong \frac{s^2LC_c + D + 1}{s^2LC_c + 1} = 1 + \frac{D}{s^2LC_c + 1} \tag{18}$$

From (18), one can obtain the voltage gain as follows

$$\frac{V_o}{V_s} \cong 1 + \frac{D}{1 - \omega^2LC_c} \tag{19}$$

From (19), the design guideline for choosing *L* and *Cc* values can be expressed by

$$\omega^2LC_c \ll 1 \tag{20}$$

If the condition of (20) is satisfied, the voltage gain of (19) becomes 1+*D* which is an ideal case as seen in Table I.

By the same analysis methodology used in this section, one can analyze the other DVR circuit configuration to obtain the more practical voltage gain equations, which can lead to design guideline. Finally, one can expand the DVR concept shown in Fig. 4.2 from single-phase to three-phase cases in similar fashion; Fig. 7 shows an example of the series-shunt configuration of the proposed DVR with three-phase Ac Chopper converter in the balanced three-phase system. Fig. 8 shows the three-phase buck, boost and buck boost Ac Chopper converters that can be used in Fig. 7. The overall voltage gain and the basic operation principle in the three-phase DVR will be the same as that of the single-phase one.

V. SIMULATION RESULTS

To confirm the operation of the proposed DVR, simulation for the single-phase shunt-series DVR employing the buck ac-ac converter (Fig. 4.2) was carried out by using PSIM software. The circuit parameters are as follows;

Vs (peak voltage) : 100 V
f (line frequency) : 60 Hz
RL-LL (*RL*-load) : 5 , 10 mH
L = 1 mH, *Cc* = 5 uF
fs (switching frequency): 10 kHz.

Supposing the system voltage is fluctuated from 150V to 200V, run the simulation model for AC chopper compensator with PSCAD simulation software. The simulation results indicate that when line the voltage drops down from 200V to 150V and then rises to 200V, the load voltage RMS value keeps around 220V stable. Voltage waveforms of u_{sys}, u_{com}, u_{load} are presented

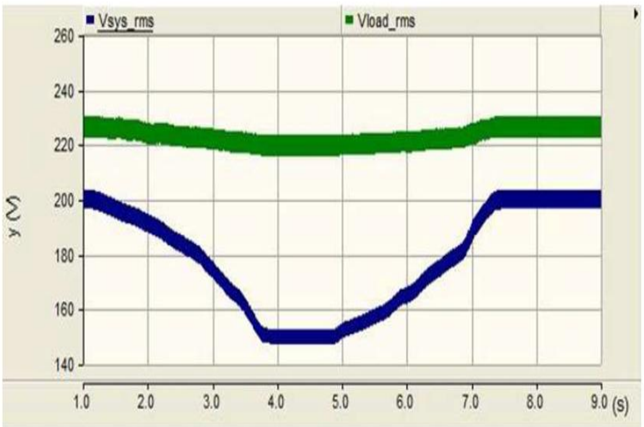


Fig. 5.1 Green line: Voltage on load side/Blue line: System voltage wave form

Fig. 5.3 shows the waveforms when the voltage sag of 30% occurs for 55 msec. As seen in Fig. 5.3, the load voltages are well regulated to the reference voltages except for short transient times after abrupt jumps in input voltages.

Fig. 5.4 shows the waveforms of the voltage error and duty ratio. Duty ratio *D* is automatically changed by the error-driven PI controller.

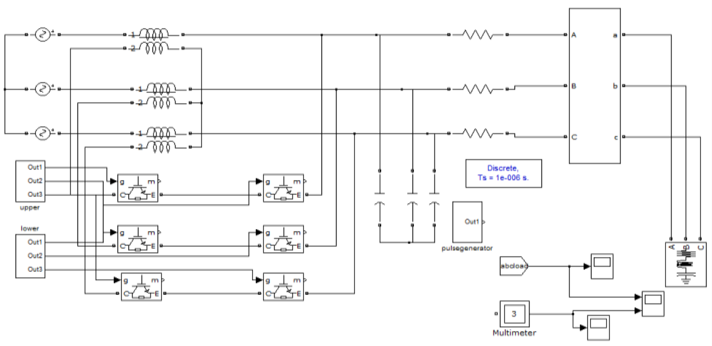
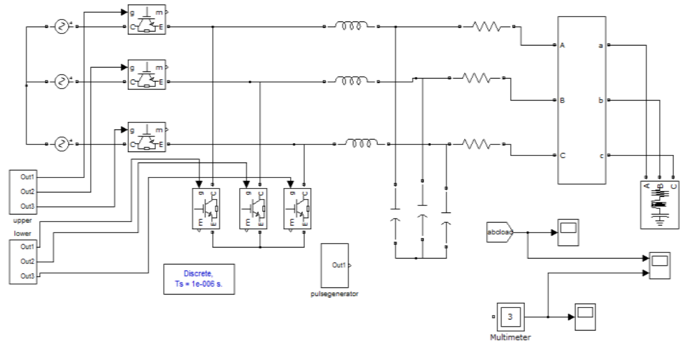
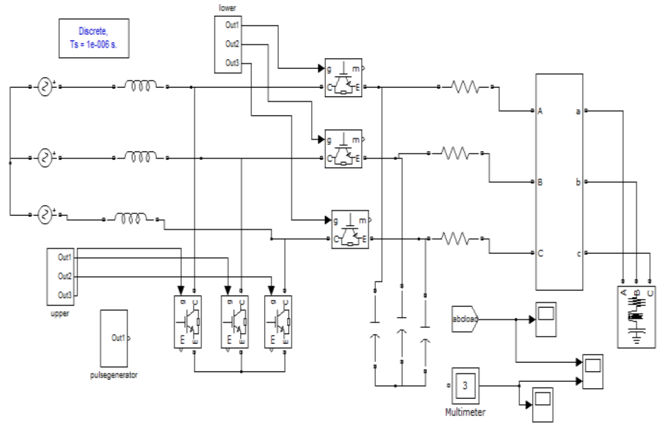


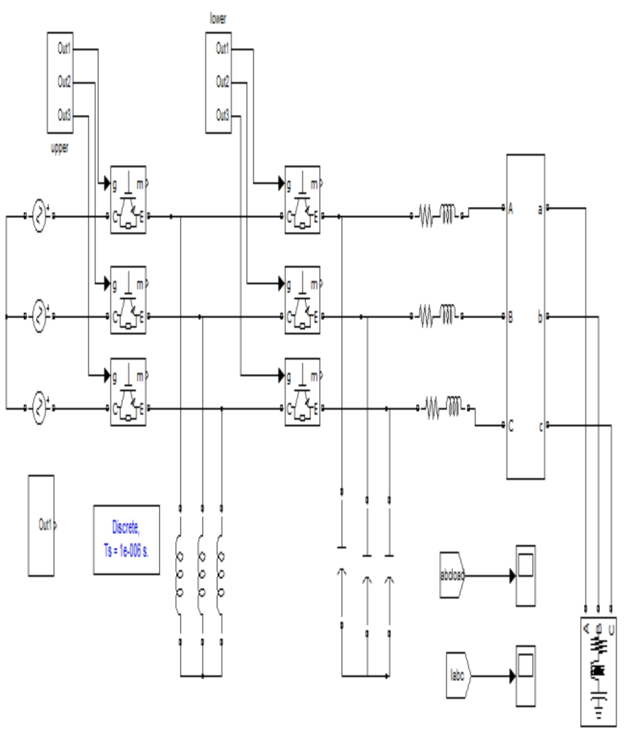
Fig. 5.2 . The proposed series-shunt three-phase DVR using three-phase PWM ac-ac converter.



(a) buck



(b) boost



(c) buck-boost

Fig. 5.1. The three-phase PWM ac-ac converters; (a) buck, (b) boost, (c) buck-boost types.

To verify the operation of the three-phase DVR, simulation for the shunt-series DVR employing the buck boost ac-ac converter (Fig. 5.4) was carried out. The circuit parameters are as follows;

Vs (rms line-to-line of ac mains) : 220 V
f (frequency of ac mains) : 60 Hz
RL-LL (*RL*-load) : 10 , 5 mH
Lf = 0.5 mH, *Cf* = 47 uF

Also, the switching frequency is 10 kHz. Fig. 5.6 shows the waveforms when the voltage swell of 30% occurs for 50 msec. As seen in Fig. 5.6, the load voltages are well regulated to the reference voltages. Fig. 13 shows the waveforms when the voltage sag of 20% occurs for 50 msec. As seen in Fig. 13, the load voltage is also well controlled to follow the fixed reference voltages.

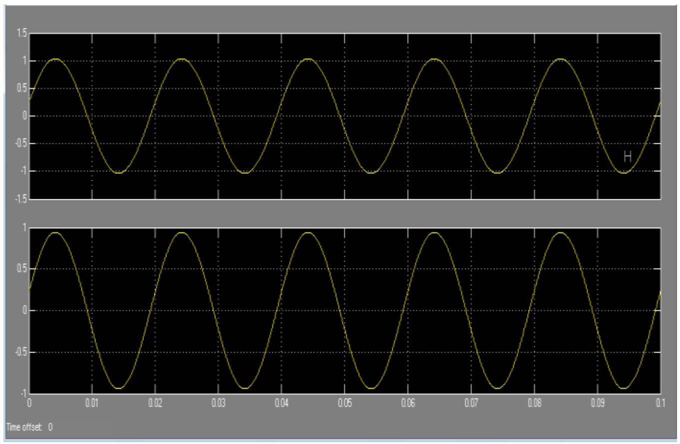


Fig. 5.3. The simulated waveforms when voltage sag occurs, (upper) input voltage, *vs* with 30% sag, (bottom) load voltage, *vo*.

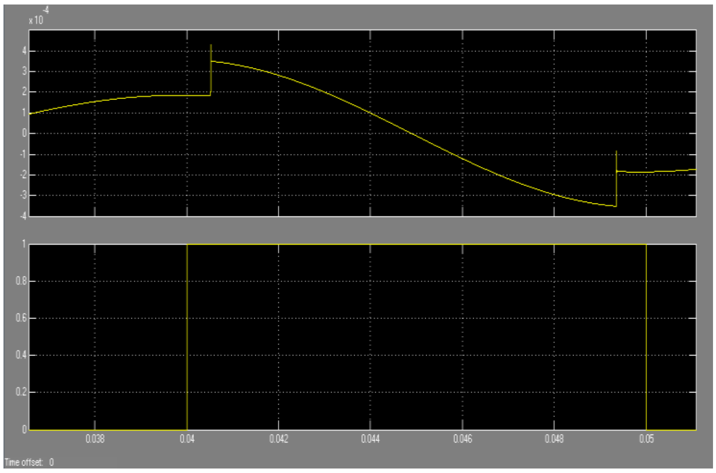


Fig. 5.4. The simulated waveforms when voltage sag occurs, (upper) error voltage, *ve*, (bottom) u_{ty} ratio, *D*.

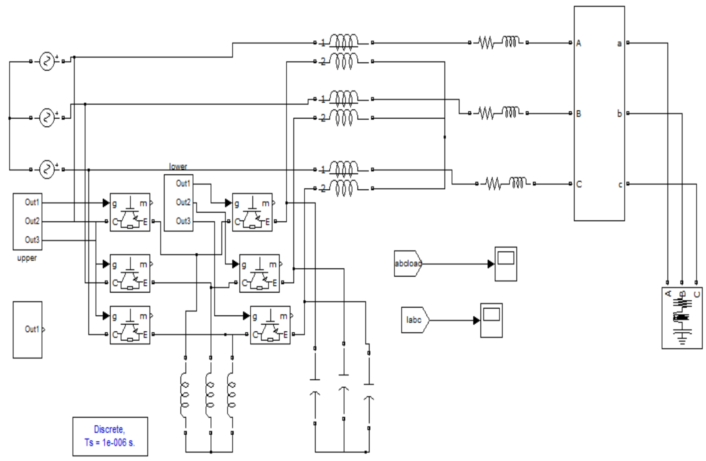


Fig. 5.5. The shunt-series three-phase DVR using three-phase PWM buck-boost ac-ac converter.

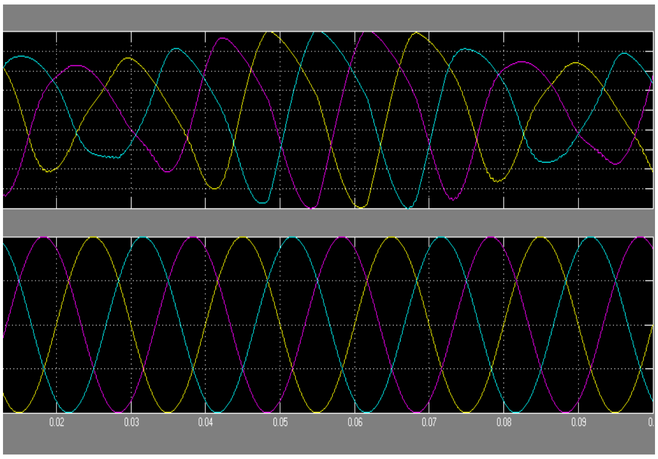


Fig. 5.6 . The simulated waveforms when voltage swell occurs, (top) three-phase input voltages, *vsa*, *vsb*, *vsc* with 30% swell, (bottom) threephase .load voltages, *voa*, *vob*, *voc*.

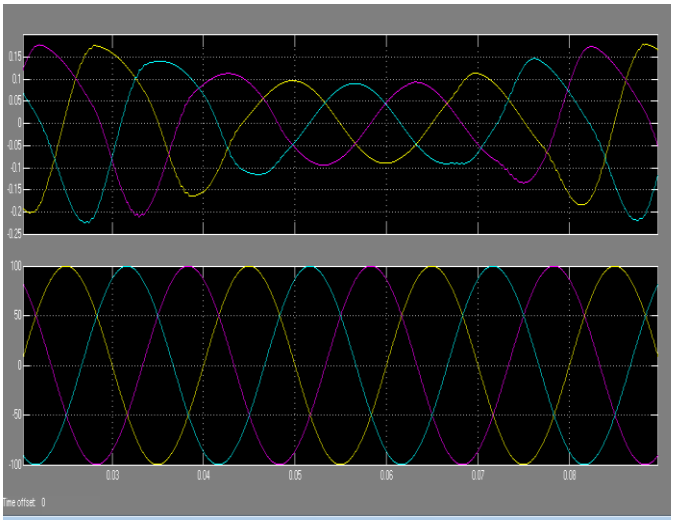


Fig. 5.7. The simulated waveforms when voltage sag occurs, (top) three p hase input voltages, *vsa*, *vsb*, *vsc* with 20% sag, (bottom) three phase. load voltages, *voa*, *vob*, *voc*.

From the experiment results, it can be seen that when system voltage drops down to 140V gradually, the load voltage is 220V and it doesn't change. When system voltage rises above 200V, the circuit stops and the bypass switch closes, load voltage changes according to system voltage. After system voltage drops to 200V again, the circuit runs again. The experimental results agree with the simulation results.

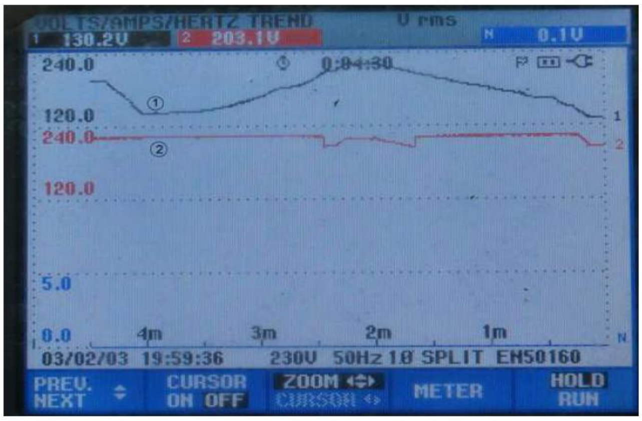


Fig. 5.8 RMS value Voltage wave form.

VI. CONCLUSION

This paper presents the Ac-chopper utilizing various types of Ac Chopper converters for single-phase and three-phase systems. By using the Ac Chopper converter which can change directly ac voltages to other ac voltages, the dc link capacitor can be removed and the device count of power semiconductor devices is reduced. Voltage compensator based on an AC buck chopper, which is operated using the strategy of non-complementary control without current detection. It is suitable for compensation long-term voltage sags and could adjust pulse widths according to the ratio of required output in real time. Simulations and experiment results proved functionality of this circuit.Moreover, the Ac chopper that can compensate both voltage sag and swell can be constructed by properly selecting the appropriate circuit configuration and the Ac-chopper converter type. The simulation results with a single phase and three-phase DVRs show the feasibility of the proposed Ac-chopper system.

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