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A Novel Dynamic Voltage Regulator with a Multi-level AC/AC Converter

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Abstract

This article proposed a novel topology of dynamic voltage regulator using transformer and PWM multi-level AC/AC converter. In this paper for finding the best value of duty ratio for switches to minimize the THD, the GA algorithm has been used and THD output voltage is assumed to be fitness function. The proposed voltage regulator employs multi-level AC/AC converter to generate compensation voltage and uses the transformer to isolate the power converter from the load. The proposed converter provides a highly sinusoidal and regulated output voltage with a simple topology. When input voltage under-voltage and overvoltage 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, PI 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.

Keywords: multi-level AC/AC chopper, Voltage Regulator, Pulse Width Modulation.
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1. Introduction

The voltage sags (under-voltage) and swells (overvoltage) are common problems in power systems. In modern industries, the dynamic voltage regulators (DVR) have the most significant impact on the proper operation of equipment and the industry processes. Voltage sag range varies between 0.1 and 0.9 of the nominal voltage in root mean square (RMS) voltage at grid. Voltage sags are usually caused by starting large loads, fault or short circuit in loads, or faults in power systems and have great impacts on normal working conditions of the equipment. If the voltage sags duration exceeds more than two to three cycles, sensitive protection equipment diagnoses that fault, especially in semiconductor industries. On the other hand, the voltage swell happens when the voltage amplitude increases to 1.1 and 1.8 time of the nominal RMS voltage. 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 disruption and important data loss [1,2] These problems also lead to great financial losses and the waste of resources. The increasing market competition and costs have increased the importance of power quality improvement for industries. 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 thyristors need to be used to change the transformer ratio of the tap-changing. The complex operation limits 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 [7-8], soft-starter and speed regulator of the inductor motor, light dimmer and so on. Three switches [9-10] and four switches AC chopper are investigated in literatures. In these researches, the switching patterns are critical. DC regenerative snubber capacitor [11-12] 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 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 [13-14]. As a result, compared with the previous voltage sag compensators, this topology can compensate voltage sags and swells both. The proposed DVR does not use bulk capacitors or inductors for energy storage and as a result provides fast dynamic response while reduce cost. In previous researches [15-16], 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 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 to stable voltage at terminals for critical loads. This paper discusses a design example of the proposed system. Simulation results are provided and verified with experimental results.

2. Proposed Topology

The power circuit of the proposed DVR is shown in fig. 1. The compensation voltage Vco is generated by a single phase buck AC/AC converter. S1, S2 and S3 are switches of the DVR. T is a transformer to compensate the input voltage Vi and to stabilize the output voltage Vo. NP1 and NP2 are the number of primary windings turns and NS is the number of secondary winding turns which NP1 = NP2 = NS. The AC link capacitor voltage Vc1 and Vc2 are transformed into Vco that is the chopper modulated voltage and VL is the inductor voltage. The DVR system uses PWM controller to generate and modulate the PWM signals, and control the output of the ac chopper.

The Proposed AC/AC converter consists of five switches, an inductor and AC link capacitors. The output voltage can be controlled by the duty ratio of the chopping pulses. The low-pass filter is used to filter the harmonic components of the output of the ac chopper. *L* is the filter inductor, *C* is the filter capacitor. The AC chopper provides direct AC–AC conversion without conversion energy such as rectifier systems. Thus, the size and cost of the DVR reduce. The AC chopper compensates for only the deviations from the required voltage, thus the rating and stress of the switches decrease compared to DVRs that handle 100% of the system power capability. In fig. 2, S_1 , S_2 and S_3 are used as level switches, which are bidirectional IGBTs and allow a bidirectional current flow. When the under voltage (sag) is detected, the DVR operates under the voltage sag condition (S_{B1} on). Under the voltage sag condition, S_1 and S_2 turn on. At this time, the compensation voltage V_{co} is in phase with the input voltage. Then, V_{co} is added to the input voltage, so the DVR can compensate the voltage sag. On the other hand, when the swell is detected (S_{B2} on), the DVR operates under the voltage-swell condition. Under the voltage-swell condition, S_1 is and S_{b2} turn on. At this time, the compensated voltage V_{co} becomes a reversed phase of the input voltage. Then, V_{co} is subtracted from the input voltage, so the DVR can compensate the voltage swell.

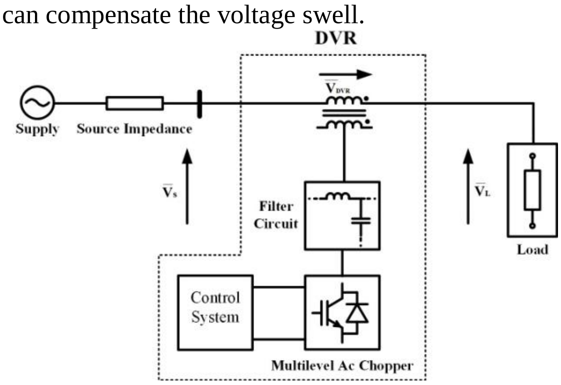


Fig. 1. Block diagram of DVR

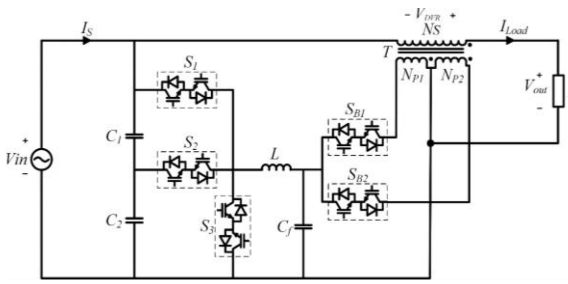


Fig. 2. Proposed DVR based on the multi-level AC/AC chopper

3. Operation Modes of Proposed Dynamic Voltage Regulator

The output voltage is controlled by changing the duty ratio of the drive signals. The switching patterns are decided by the value of the PCC voltage. The drive signals of the switches are shown in fig. 5. T_s is the switching period, and D_1 and D_2 are the duty ratio of S_1 and S_2 respectively. During the under voltage mode (sag), switch S_{B1} is set to conduct, and switches S_1, S_2 and S_3 are driven by PWM and also during the over voltage mode (swell), S_1, S_2 and S_3 are driven by PWM.

Fig. 6 shows the control block diagram that uses fast RMS calculator for calculating the root mean square voltage in half switching period. The block diagram of fast RMS calculator is shown in fig.7.

PCC voltage compares with reference voltage, if the voltage of PCC is less than the reference voltage, the switch S_{B1} turns on and proposed AC/AC converter operation in sag mode. If voltage of PCC is higher than reference voltage, the switch S_{B2} turns on and proposed AC/AC converter operation in swell mode. For both operation modes (sag and swell) AC/AC converter has just three operation modes that is discussed as below.

Fig.3 and fig.4 represent the under and over voltage respectively.

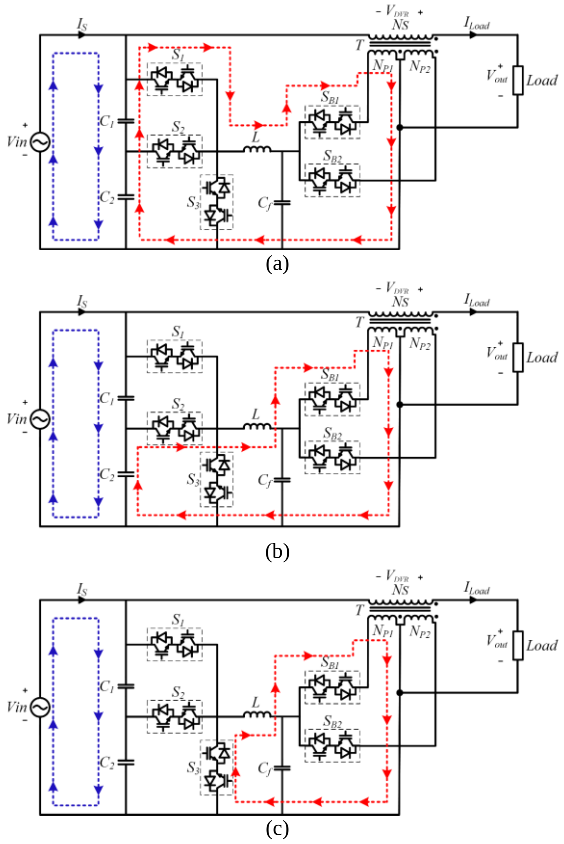


Fig. 3. Operation modes of proposed DVR during under voltage; (a) state I. (b) stateII. (c) state III

In under voltage operation, injection voltage has similar phase with PCC voltage that leads to voltage drop compensation. In over voltage operation, injection voltage has 180-degree phase shift with PCC voltage that lead to compensate excess voltage.

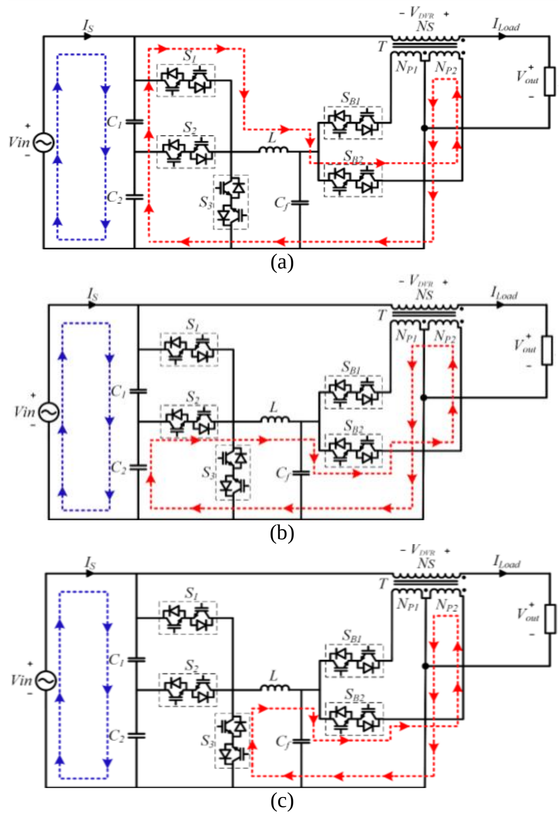


Fig. 4. Operation modes of proposed DVR during over voltage; (a) state I. (b) stateII. (c) state III

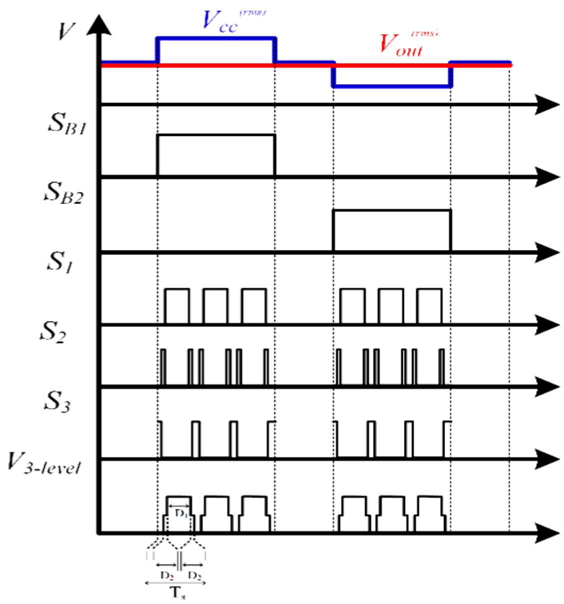


Fig. 5. Switching signals

Table 1 shows the switching patterns of proposed DVR in sag and swell modes.

A) *Operation in mode I*

In this mode inductor is charged with nominal voltage. According to fig.3(a), current of the inductor is given by (1).

Table.1.
Switching Pattern

switch	modes	
	Over voltage (swell)	*Under voltage (sag)*
S_1	PWM	PWM
S_2	PWM	PWM
S_3	PWM	PWM
S_{B1}	OFF	ON
S_{B2}	ON	OFF

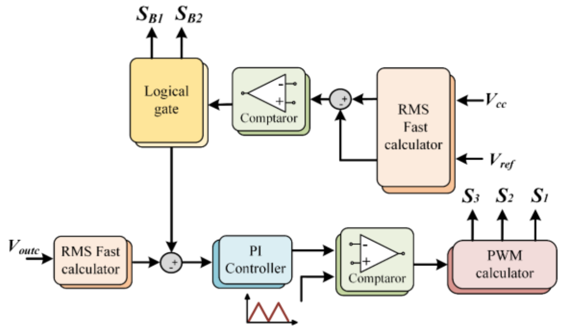


Fig. 6. Control algorithm

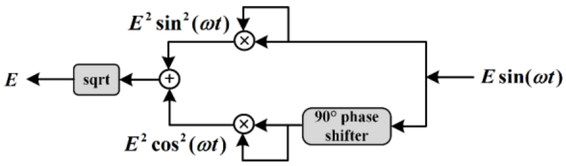


Fig. 7. Fast peak detector

B) *Operation in mode II*

Inductor in this mode is charged with half of the voltage and current:

$$\Delta I_L = \left(\frac{V_i - V_c}{L}\right) D_1 T \quad (1)$$

Operation in mode t of the inductor is given by (2) and fig. 6(b) shows this mode:

$$\Delta I_L = \left(\frac{V_i / 2 - V_c}{L}\right) D_1 T \quad (2)$$

C) *Operation in mode III*

Fig 6(c) shows the freewheeling mode of AC chopper and inductor current can be calculated as:

$$\Delta I_L = \left(\frac{-V_c}{L}\right)(1 - D_1 - 2D_2)T \quad (3)$$

In the steady-state condition the average inductor voltage over one switching period is zero. With respect to this point and also $D = D_1 + D_2$, one can derive voltage gain as.

$$V_c = DV_i \quad (4)$$

Equation (4) is similar to the steady-state voltage gain of the conventional buck chopper, with the extra flexibility that the voltage gain can be adjusted with two parameters D_1 and D_2, and provides continuous inductor current.

The fundamental relations for the proposed converter are:

$$D_1 + D_2 = Gain \quad (5)$$

$$D_1 + 2D_2 < 1 \quad (6)$$

An exact evaluation of (24) and (25) reveals the possible variations range of duty ratios as summarized in Table 2.

Table.2.
Simulation parameters

GAIN<0.5	GAIN>0.5
$0<D_2<0.5$	$0<D_2<0.5$
$0<D_1<0.5$	$D_{1min}<D_1<D_{1max}$ $D_{1min}=Gain-D_{2max}$ $D_{1max}=Gain-D_{2min}$

4. Control Algorithm and Optimization

Fig. 6 shows the control block diagram for the proposed converter. The output voltage is sensed and fed into peak voltage detector to detect the peak voltage. It is compared with the reference voltage to generate the error signal. The proportional-integral (PI) controller compensates and the value of D1 and D2 are adjusted accordingly as expressed below:

$$D(t) = K_p(V_{o.ref} - V_{o.rms}) + K_i x(t) \quad (7)$$

$$\frac{dx(t)}{dt} = V_{o.ref} - V_{o.rms} \quad (8)$$

where K_p and K_i are the proportional and integral gain of the PI controller.

According to the section III and fig.6 that shows the control block diagram of proposed DVR, switches S_{1B} and S_{2B} operate in two different modes (sag and swell). When V_{PCC} greater than V_{out}, switch S_{B1} is turned on and for V_{PCC} is lower than V_{out}, S_{B2} is turned on.

Proposed AC/AC converter is same buck converter so output voltage of converter has been compared with reference voltage to make error signal for PI controller. The output of controller compares with carrier signals to make duty ratios (D_1, D_2) and D_3) for S_1, S_2 and S_3.Genetic algorithm is the searching algorithm which can be used for optimization problems. In this paper for finding the best value of duty ratio for switches to minimize the THD, the GA algorithm has been used and THD output voltage is assumed to be fitness function. Fig. 8 represents GA algorithm flowchart and equations (9-11) are the equality, inequality constrains and fitness function respectively. In this paper to find the best values for the duty ratios in order to minimize the THD value of the output voltage a Genetics Algorithms (GA) optimization is employed, where the THD equation of (11) is chosen as the fitness function, which is minimized subject to (9) and (10) constraints.

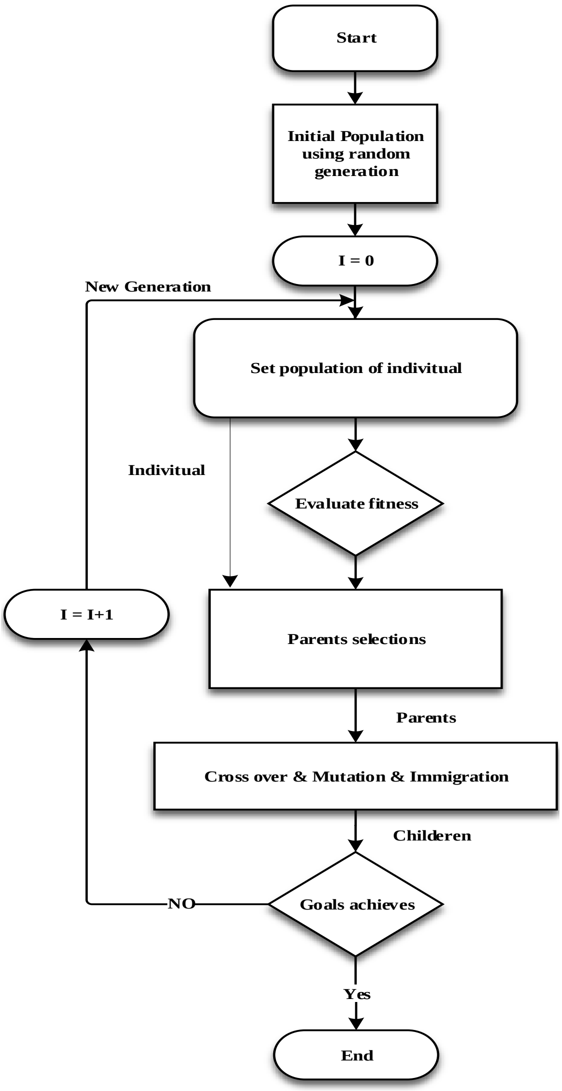


Fig. 8. Flowchart of genetic algorithm

$$\begin{cases} 0 < D_1 < 1 \\ 0 < D_2 < 0.5 \\ D_1 + 2D_2 < 1 \end{cases} \qquad (9)$$

$$D_1 + D_2 = Gain \qquad (10)$$

The gain in (10) is defined as the output to the input voltage ratio. Fig. 9 shows that the proper selection of the duty cycles leads to a very small THD.

According to optimization the best value of duty ratio has been obtained. The best fitness function and individual parameters in GA algorithm are shown in fig.10.

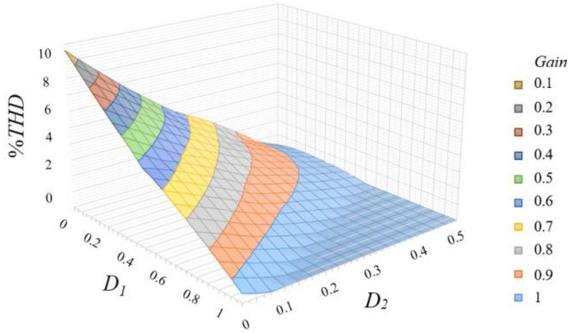


Fig. 9. THD variations as a function of duty ratios

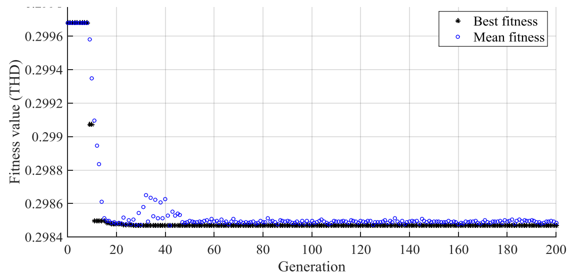


Fig. 10. Result of fitness function

5. Simulation Results

The proposed dynamic voltage regulator is simulated under the MATLAB/Simulink environment. Table 3 shows the simulation parameters. Fig.11 and 12 show the swell and sag operations of proposed DVR respectively.

Table.3.
System parameters

Parameter	*Value*
Switching frequency	10 kHz
C_1 ,C_2	50 µF
Converter inductor	1 mH
Output filter capacitance	5 µF
Transformer (n=1)	Lm=100µH

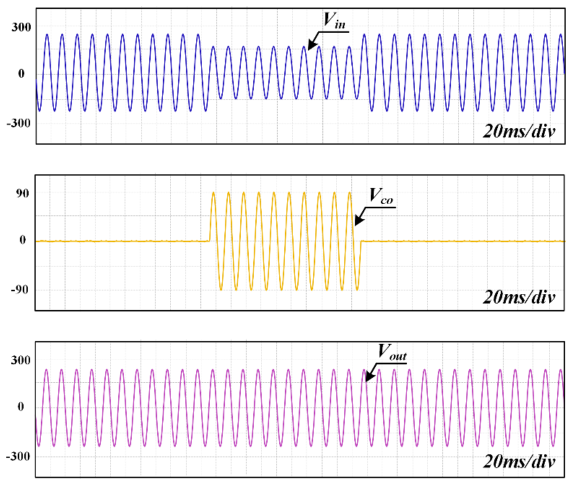


Fig. 11. Simulation results during a sag

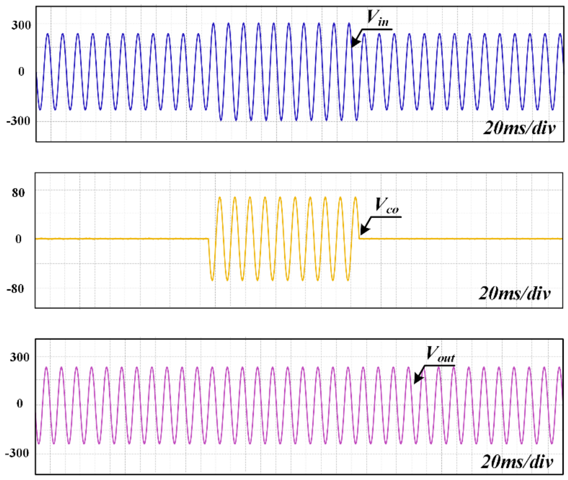
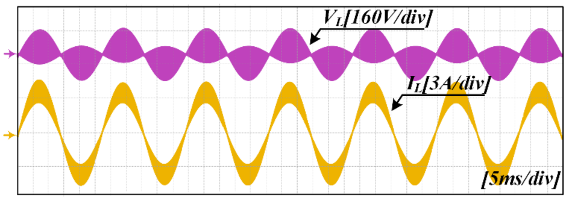
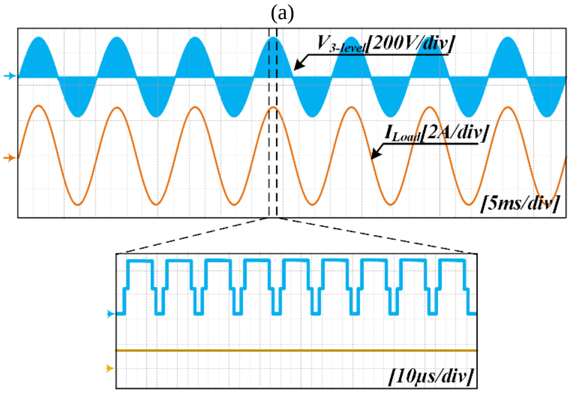


Fig. 12. Simulation results during a swell



(a)



(b)

Fig. 13. Simulation results of proposed AC/AC chopper: (a) voltage and current of inductor. (b) Tthree level voltage and load

Fig.13 shows the injected voltage with 180° phase shift in comparison with PCC voltage. Fig.13 (a) shows the inductor current and voltage that according to inductor current, proposed AC/AC converter work in CCM mode. Output voltage of proposed AC/AC converter has three levels voltage that is represented in fig.13(b) which provides low THD in the output. THD of output voltage is the best factor for comparison between two levels and three levels AC/AC converter which are shown in fig.13. According to fig.13 value of each harmonic has been reduced in three levels mode and also by increasing the number of levels total harmonic distortion will become less.

6. Conclusion

In this paper, a new DVR based on a novel three level direct PWM AC/AC converter is proposed to compensate both voltage sags and swells. The proposed AC/AC converter generates a three level voltage and in each state just one semiconductor conducts. Therefore, this topology has a high efficiency. Proposed AC/AC converter can be readily extended to any levels in order to decrease the THD of the output voltage as low as desired.

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