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Application of Three-level Diode-clamped Converter on 10 kW Distribution Voltage Restorer

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Abstract

This paper presents the application of three-level diode-clamped converter on 10kW distribution voltage restorer (DVR) for creating compensation voltage. The three-level converter is designed by using IGBT as switching devices and is controlled by using MATLAB/Simulink through dSPACE board. The simulation results show the performance of DVR including the proposed converter and controller. The injection voltage waveform of three-level diode-clamped converter can be able to compensate the grid voltage in proposed time. Moreover, three-level diode-clamped converter can also get a higher voltage range. The experimental results show 10 kW DVR hardware implementation that can compensate the grid voltage with 0.1 second. Therefore, this study can be the prototype of DVR using three-level diode-clamped converter for future work.

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Keywords: Distribution Voltage Restorer; Three-level Diode-clamped Converter; Voltage Sag

1. Introduction

Power delivery is very important and essential for economic development, especially the development of industries that require large amounts of electrical energy. The electrical energy that is supplied from the electric source to the load must have the high stability and reliability. If the disturbance occurred on power system, the power quality problems will be generated, for example voltage sag, voltage swell,

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interruption or disturbances. There are many type of power quality problem that are cause of voltage variation [1]. The voltage variation is directly affected the electrical consumers, especially the sensitive loads. Most of the electrical load currently is sensitive to the failure of the voltage which causes damage to the equipment and information systems.

Nomenclature

DVR	distribution voltage restorer
p.u.	per unit
PCC	point of common coupling
VSC	voltage source converter
PWM	pulse width modulation
APOD	alternative phase opposition disposition
POD	phase opposition disposition
PD	phase disposition
V_{sag}	peak value of voltage at PCC point when fault occurred
V_s	voltage source
Z_f	impedance between PCC point and Fault point
Z_s	impedance between source and PCC point
ϕ	voltage angle at PCC point when fault occurred
C_{bus}	capacitor size
$V_{com(\max)}$	maximum voltage can be compensated
$I_{com(\max)}$	maximum current can be compensated
$t_{com(\max)}$	maximum duration can be compensated
$V_{bus(\max)}$	maximum DC bus voltage
$V_{bus(\min)}$	minimum DC bus voltage

The power quality problems that may affect the electrical devices which are damage or cannot operate in complete function. Power quality problems have many type, depending on the source and configuration of power system [2]. Short duration variation is one of power quality problem caused by fault in power system that can change the amplitude of voltage or current in short time. The phenomenon of power quality in this group are voltage sag, voltage swell and voltage interruption [3].

Distribution Voltage Restorer (DVR) is the equipment that used to solve these problems. DVR is series-connected in the grid for generating the compensation voltage. Control of DVR is required the high performance of detection method to detect the voltage magnitude and frequency [4]. The power system requirements are rapid operation for protecting the sensitive loads. In the recent past, there are many researches on the DVR, such as design using a single loop control which can control the peak of voltage but the sensitivity of DVR control slow. Two-level converter had been proposed in many literatures which low power rating. Therefore, this paper proposes development of 10 kW DVR by using the proposed topology of diode-clamped three-level converter [5].

The rest of this paper organized as follows, section 2 presents the definition of voltage sag. The distribution voltage restorer including topology and control algorithm is explained in section 3. Section 4 expresses the simulation and experimental results of DVR. Finally, the conclusion and discussion are given in section 5.

2. Voltage Sag

Voltage sag is the magnitude of the voltage lower than normally voltage during a short period and return to normal, mainly, cause by fault in power system or the start-up of a large load. Fig. 1 shows the voltage sag caused by single line to ground fault from 0.1s to 0.25s. The amplitude of three phase voltage change during fault occurred. The definition of voltage sags in power system under IEEE 1159-1995 standard is the reduction of the magnitude of voltage supply in a short time, since 0.5 cycles until a minute and return to normal conditions as shown in Fig. 2 [6]. The rms value of voltage between 0.1 p.u. and 0.9 p.u. compared with the voltage of the system is 1.0 p.u..

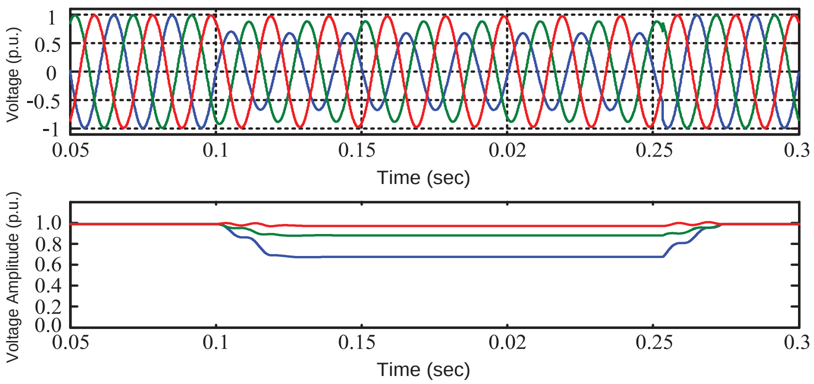

Fig. 1. voltage sag caused by the single-phase to ground fault

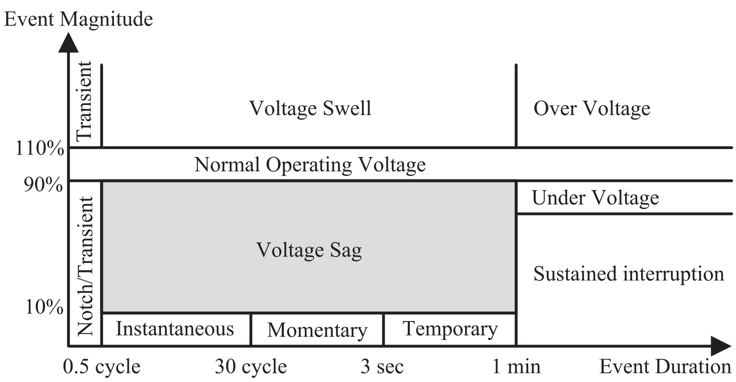

Fig. 2. IEEE 1159-1995 standard

Fig. 3 shows the example of the configuation of power system that faults occurred as remote area. The system volatge at PCC point must be kept at 1.0 p.u. Therefer the compensation device has to intall at PCC to protect the sensitive load. The detalied analysis can be computed as follows.

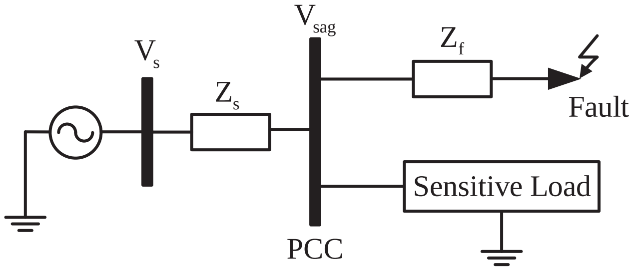

Fig. 3. Example of fault in power system

Voltage sag drop across load line can be obtained from equation (1).

$$V_{sag} = V_s \frac{Z_f}{Z_s + Z_f} \quad (1)$$

When V_{sag} is peak value of voltage at PCC point when fault occurred
V_s is voltage source
Z_f is impedance between PCC point and Fault point
Z_s is impedance between source and PCC point

Fault in the power system are not only voltage levels reduced but also the main reason that causes the phase angle of the electrical equipment as well [7]. This can be obtained from equation (2).

$$\phi = \tan^{-1}\left(\frac{X_F}{R_F}\right) - \tan^{-1}\left(\frac{X_S + X_F}{R_S + R_F}\right) \quad (2)$$

When $Z_F = R_F + jX_F$ is impedance between PCC point and Fault point
$Z_S = R_S + jX_S$ is impedance between source point and PCC point
ϕ is voltage angle at PCC point when fault occurred

3. Distribution Voltage Restorer (DVR)

DVR is the series-connected device that uses to compensate the grid voltage at PCC up to 1.0 p.u. Fig. 4 shows components of DVR and their typical connection. The DVR consists of multi-level voltage source converter, detection and controller unit, output filter, injection transformer, DC link and energy storage device. The measured voltage and currents are input signals to detection and controller unit. It gives signals to the control unit when the measured quantities differ from the settings of the controller. The detection and controller unit triggers start of compensation when the supply voltage comes outside of normal range.

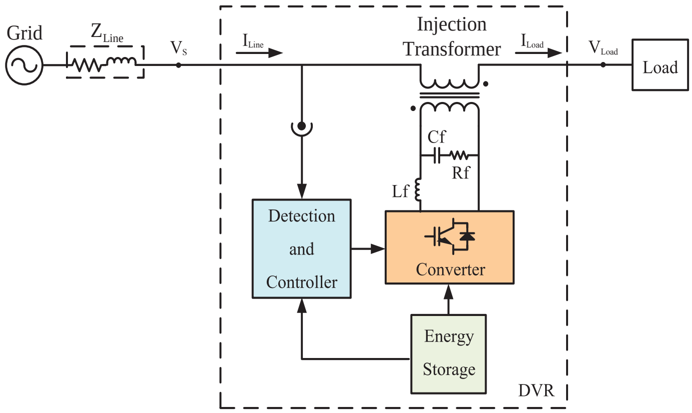

Fig. 4. Schematic diagram of DVR

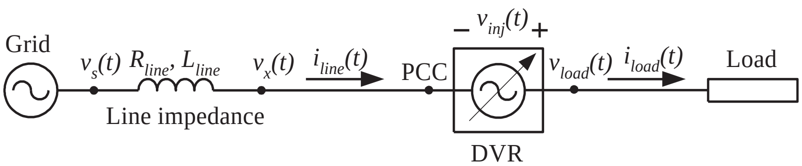

Fig. 5. Equivalent circuit of DVR

Fig. 5 shows the equivalent circuit of DVR, which is as a series voltage source that can control the peak, frequency and phase of voltage. Injected voltage source is connected in series with the power system line. The voltage injection of the DVR is controlled and converted from reference signal to converter operation. The difference of the reference signal depends on the suitability of various control methods which there is 3 control methods, namely pre-sag compensation, in-phase compensation and energy optimization technique [8]. It is obvious that the magnitude of the voltage injected into the system of pre-fault compensation and minimum energy optimization is larger than the in-phase compensation methods. But the minimum energy optimization method, DVR will use active power in very small quantities. The pre-fault compensation method is used active power larger than other method. However, it is the most accurate to compensate. To simplify, we split the components into four parts as follows:

3.1. Converter

The main function of converter part is to generate the injection voltage in order to compensate the grid voltage. The reference signal of injection voltage is computed by controller unit. The main component of converter part consists of voltage source converter, voltage filter, and series transformer. Some application, especially high and medium voltage application need series transformer, but this paper is implemented in lower voltage level. Therefore, there is no series transformer.

Fig. 6 shows equivalent circuit of three-phase DVR for high and medium voltage level that proposed in this paper. As mentioned before, this paper will be implemented in low voltage level. That means, it is not appreciated used transformer connect to between converter circuit and power system. It is a direct converter to power system. Moreover, the disadvantages of the series transformer connection are the cause of phase shift and voltage drop [9]. In addition the important problem is the saturation of the transformer and Inrush current. This makes requires transformer size is 2 times of size of the DVR [10]. As a result, transformer has large size and expensive.

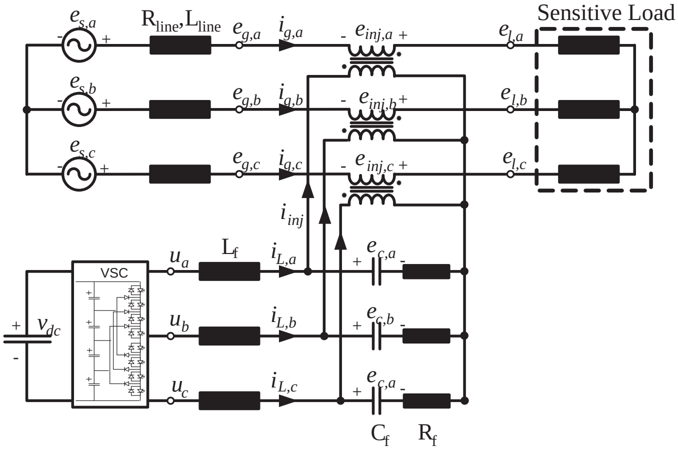

Fig. 6. Equivalent circuit of the 3-phase DVR

3.2. Diode-Clamped Topology

Diode-clamped three-level converter as shown in Fig. 7 generates a three-level of DC voltage using the switching function algorithm. The advantages of three-level converter compared to two-level converter are the voltage levels increases, making the output current with low distortion and reduced inrush current for the switching device at same DC link voltage level. The pulse width modulation (PWM) method for multi-level converter can divide to 3 types [11] is as follows:

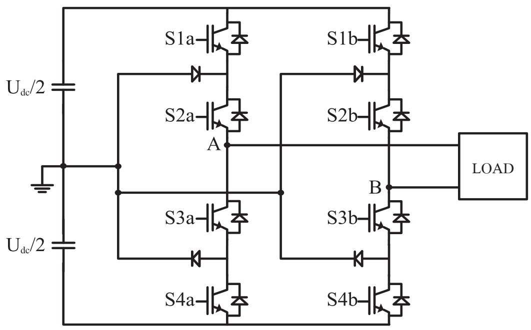

Fig. 7. Diode-clamped three-level converter (1-leg)

1. APOD: Alternative Phase Opposition Disposition

Triangle waveform is adjacent to the phase difference 180°. Triangle waveform for three-level converter is similar to generate PWM method POD type as shown in Fig. 8.

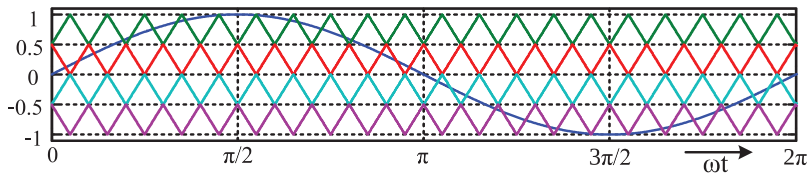

Fig. 8. Alternative Phase Opposition Disposition

2. POD: Phase Opposition Disposition

Triangle waveform is above with below when compared to the reference zero point will have the phase difference 180 ° as shown in Fig. 9.

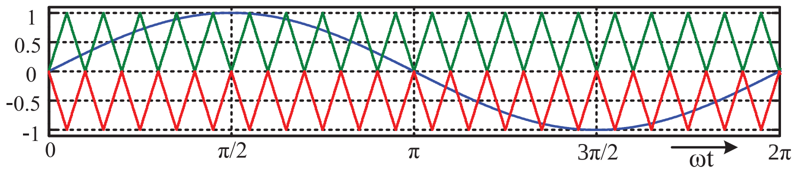

Fig. 9. Phase Opposition Disposition

3. PD: Phase Disposition

All triangle waveform must have the same phase as shown in Fig. 10.

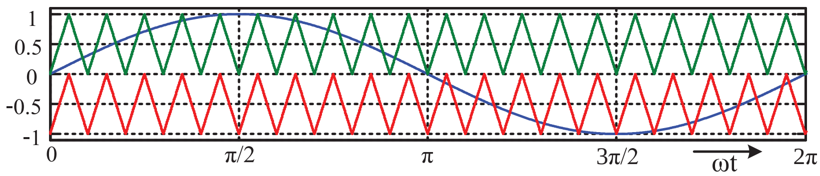

Fig. 10. Phase Disposition

From the above PWM techniques above, PD type will generate waveform with the least harmonics. So this paper selects of PD technique to generate the PWM signal. Fig. 11 shows the PD-PWM signal and output voltage waveform of three-level converter. The advantages of this technique is low frequency of the harmonics frequency was born the two times of the switching frequency. In addition the two times of harmonics frequency of the switching frequency will zero just remaining sideband as shown in Fig. 12. Therefore the low pass filter is easy to implemente in the real system.

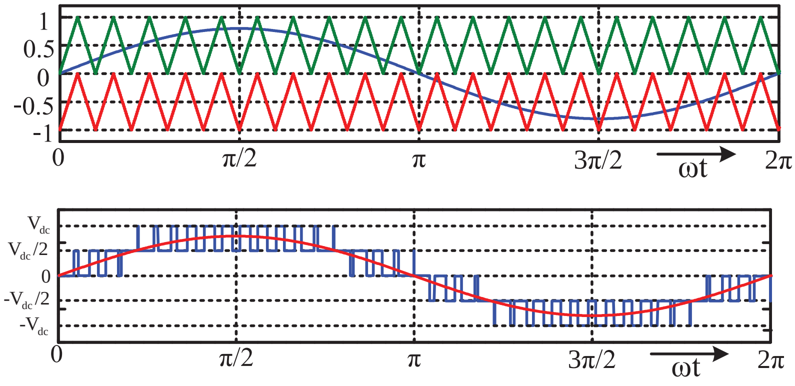

Fig. 11. Output of three-level converter using PWM signal-PD type

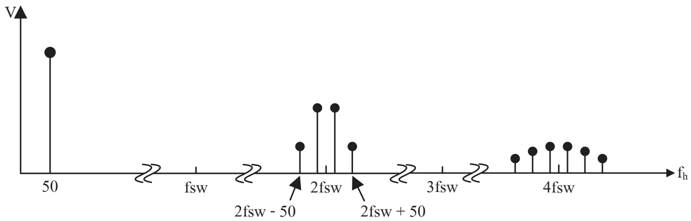

Fig.12. Spectrum of voltage using PWM-PD type

3.3. Energy Storage

This part is very important for power capability to compensate the voltage sag in term of load that can be received and compensation duration. Energy storage is generally use capacitor because it is easily and cheaply purchased. The capacitor size can be obtained from equation (3).

$$C_{bus} = \frac{2V_{com(\max)} I_{com(\max)} t_{com(\max)}}{(V_{bus(\max)}^2 - V_{bus(\min)}^2)} \tag{3}$$

When C_{bus} is capacitor size

$V_{com(\max)}$ is maximum voltage can be compensated

$I_{com(\max)}$ is maximum current can be compensated

$t_{com(\max)}$ is maximum duration can be compensated

$V_{bus(\max)}$ is maximum DC bus voltage

$V_{bus(\min)}$ is minimum DC bus voltage

3.4. Controller Unit

This part is the most important in the compensation voltage sag that is responsible for controlling the start or stop the system and calculate the voltage compensation at PCC then send signal to the power converter unit to generate the injection voltage. Fig. 13 shows the block diagram of DVR control unit. The unit has detected the voltage signal at PCC, then send the signal to reference voltage generator to generate the output comamd siognal for power converter. The power converter will be starts to generate the injection voltage whenever it receives the command from sag detector. It will be standby mode when there are no power quality problem.

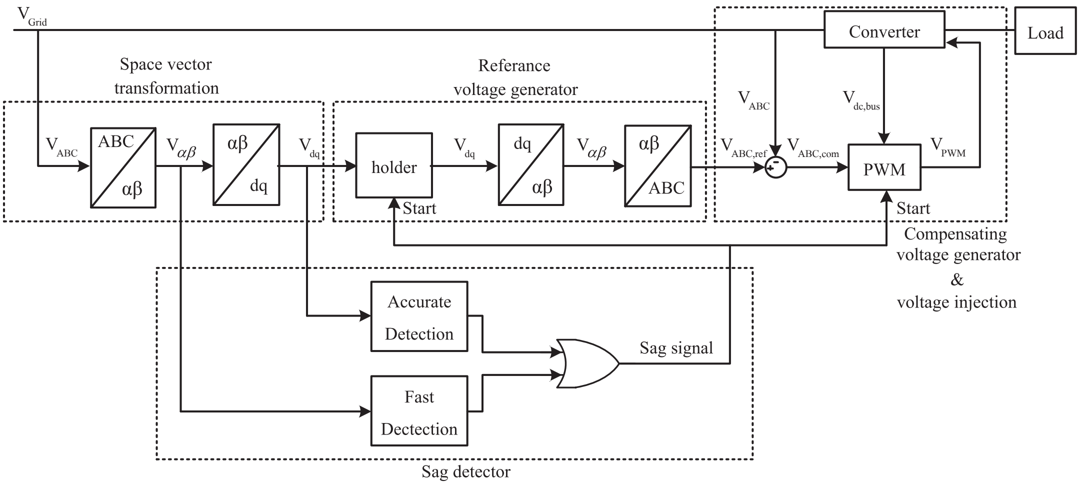

Fig.13. Block diagram of the control of the DVR

4. Simulation and Experimental Results

4.1. Simulation result

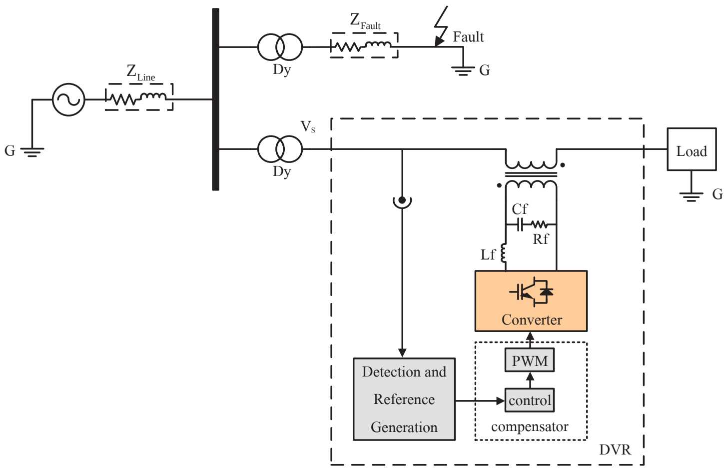

Fig. 14. configuration of DVR that used to simulation program

This paper displays the propopsed methods using power system tool block in MATLAB/simulink program. The DVR is connected to the secondary side of transformers in the distribution system as shown in Fig. 14. The defined as fault in the power system at a time 0.1 seconds until 0.04 seconds, three-phase voltage 380 V 50 Hz, Switching frequency 20 kHz, $C_f = 8\mu F$, $L_f = 2mH$, $R_f = 32\Omega$, $C_{bus} = 6{,}600\ \mu F$, Criteria of the voltage sag $|V| \leq 198$ V , $\Delta\theta > 1.85°$ or $\Delta\theta < 1.75°$ and load is series RL , it has value $13\ \Omega$ and 19 mH respectively.

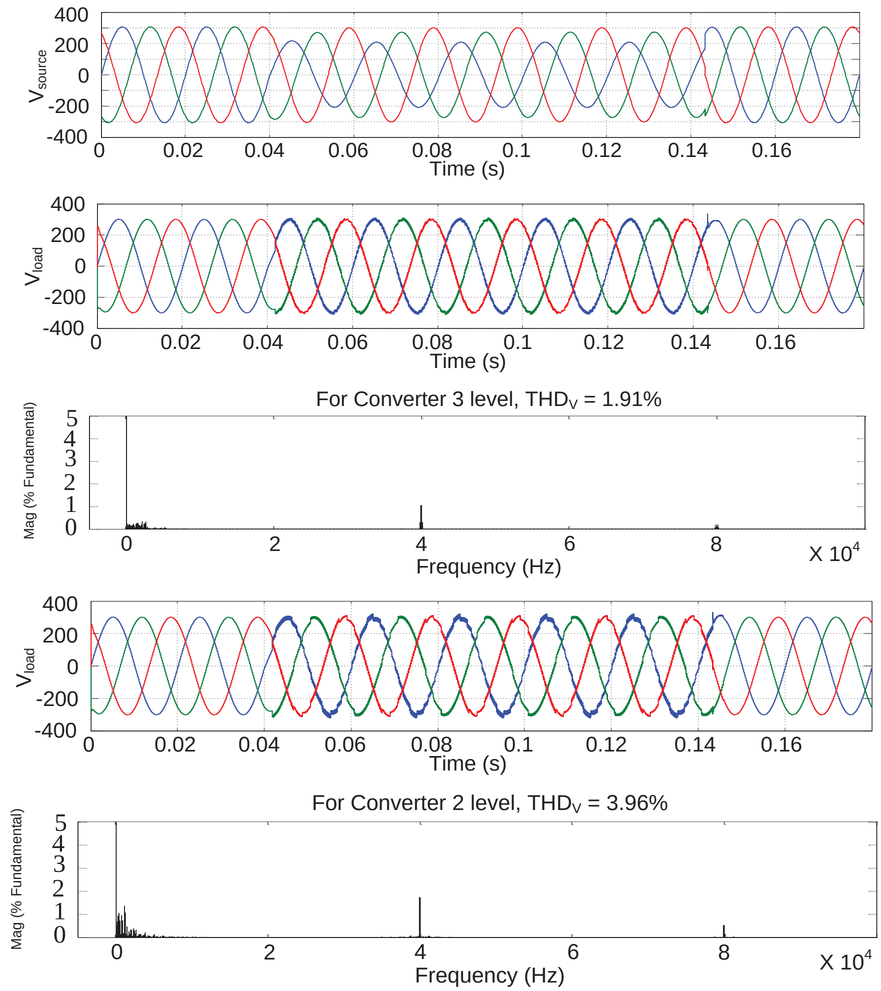

Fig. 15. Voltage compensation with three-levels and two-levels converter, respectively. In case of single line to ground fault at phase A to ground

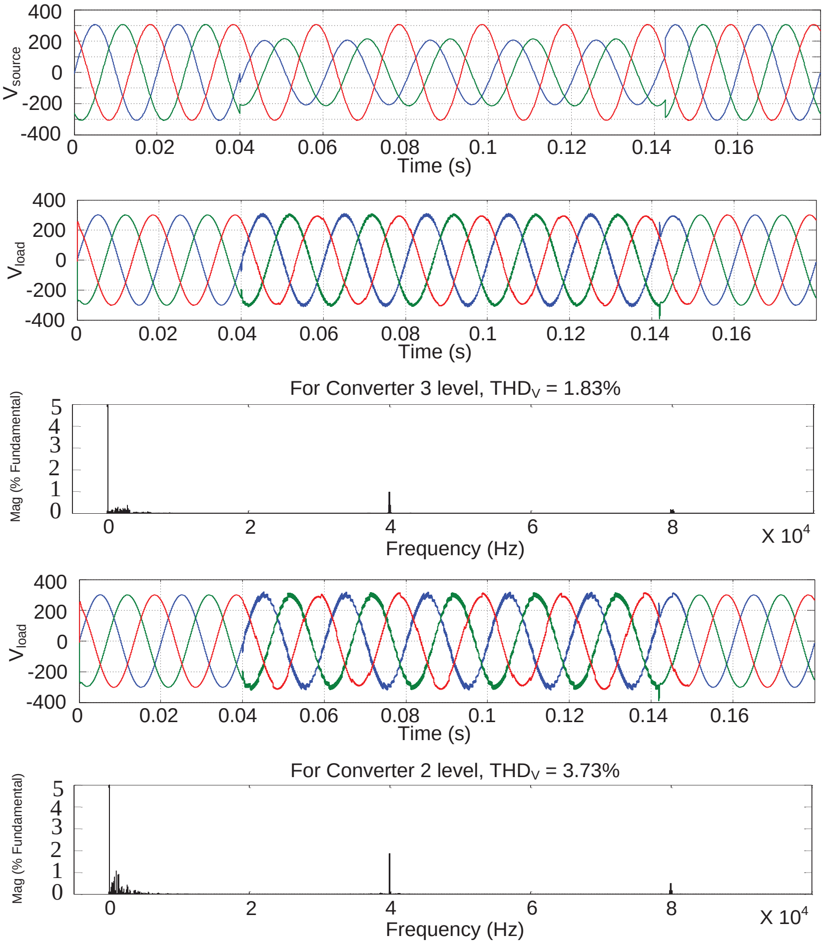

Fig. 16. voltage compensation with three-levels and two-levels converter, respectively. In case of double line fault between phase A and B

From simulation compensation voltage sag the results in case of single line to ground fault at phase A to ground and double line fault between phase A and B as shown in Fig. 15 and 16 respectively. That compensation by three-level and two-level converters can compensate for voltage sag as well. However, in the circuit used three-level converter, it is obvious that the harmonics frequency (f_h) 40 kHz and 80 kHz is less than used two- level converter. The total harmonics distortion of voltage (THD_V) is equal to 1.91%. For the effect of a single line to ground fault, three-level converter is less than two-level converter to 2.05%. In the three-level converter circuit the THD_V equal to 1.83%. This is less than a two-level converter to 1.90% for the effect from double line fault.

4.2. Experimental result

The experiment, DVR is installed series-connection into the power system which is no series transformer. The controller unit of DVR uses MATLAB/Simulink operation through dSPACE board as shown in Fig. 17. Fig. 18 shows input and load voltage when do not have voltage sag.

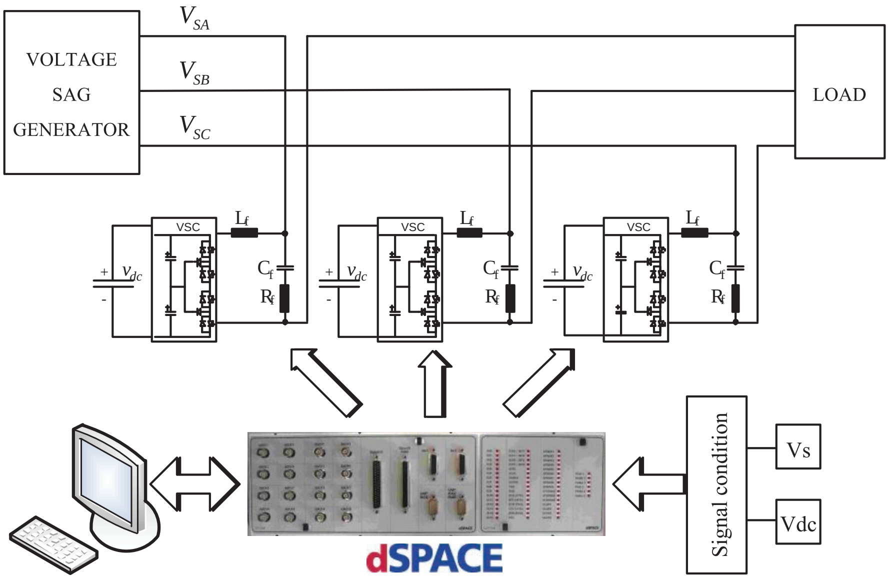

Fig. 17. Circuit Experiment of DVR

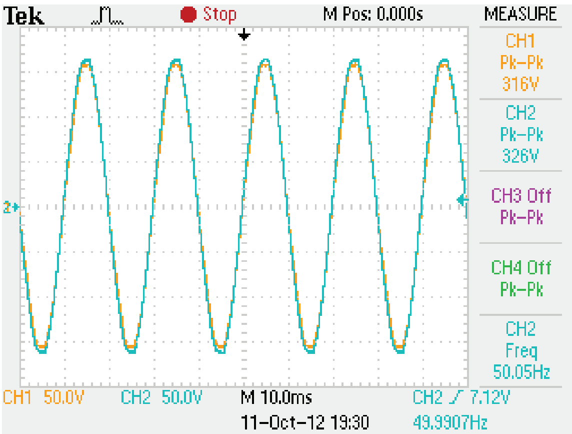

Fig. 18. Input and load voltage when no voltage sag

From Fig. 19, the output voltage magnitude is decreased less than 0.9 p.u.. the DVR will create voltage compensate in order to maintain voltage up to normal 1.0 p.u. and the beginning and ending of voltage sag are shown in Fig. 20 and 21 respectively.

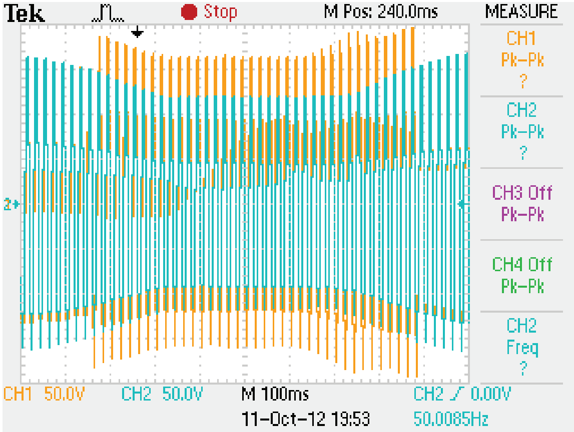

Fig. 19. Input and load voltage during havevoltage sag.

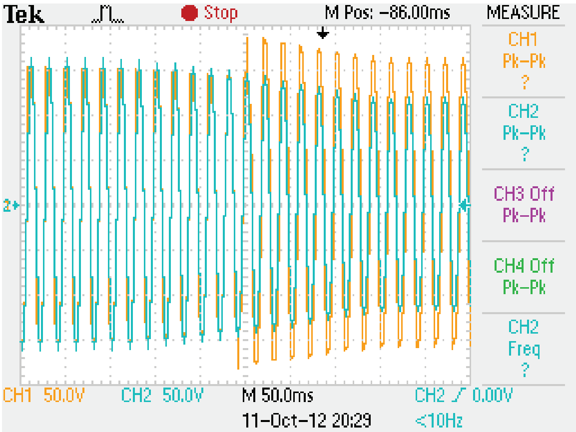

Fig. 20. Input and load voltage duration begin to voltage sag.

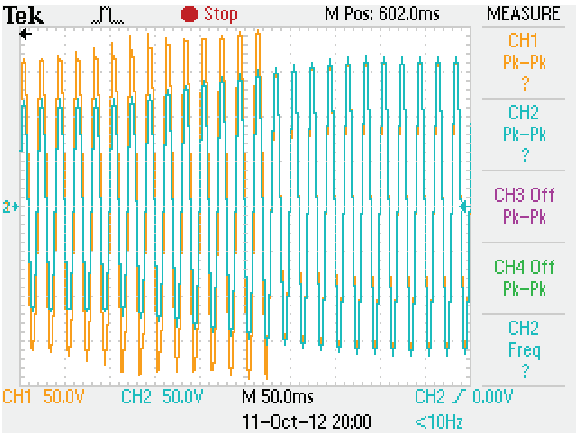

Fig. 21. Input and load voltage duration before the end of voltage sag.

5. Conclusion

The application of three-level diode-clamped converter on 10kW distribution voltage restorer (DVR) for creating compensation voltage is proposed in this paper. The three-level converter is designed by using IGBT as switching devices and is controlled by using MATLAB/Simulink through dSPACE board. The simulation and experiment results show the performance of DVR including the proposed converter and controller. The injection voltage waveform of three-level diode-clamped converter can be able to compensate the grid voltage in proposed time. Moreover, three-level diode-clamped converter can also get a higher voltage range. This study is able to be the prototype of DVR using three-level diode-clamped power converter for the future.

Acknowledgment

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