A New ISPWM Switching Technique for THD Reduction in Custom Power Devices

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Abstract. This paper addresses the application of a new Pulse-Wide Modulation (PWM) technique called inverted-sine PWM (ISPWM). This technique can be used to control Voltage Source Converters (VSC) of custom power devices. The proposed switching technique uses a sinusoidal reference signal and an inverted-sine as a carrier signal. The ISPWM technique generates lower voltage Total Harmonic Distortion (THD) in comparison with conventional Sinusoidal PWM (SPWM) technique. The proposed switching technique has been studied on a simple VSC, Distribution Static Compensator (D-STATCOM) and Dynamic Voltage Restorer (DVR). Simulation results with PSCAD/EMTDC show the effectiveness of the proposed switching technique.

Key words

PWM, Power Quality, Harmonics, VSC, Custom power devices, D-STATCOM, DVR

1. Introduction

Inverters based on Voltage Source Converters (VSC) are widely used as a basic component in custom power devices. These devices should improve power quality problems such as voltage sag and swell, flicker and harmonics [1]. These controllers produce voltage harmonics due to switching operation of power electronic converters [2].
The harmonics in the output voltage of power electronic converters can be reduced using Pulse-Width Modulation (PWM) switching techniques [3].
PWM methods reduce the harmonics by shifting frequency spectrum to the vicinity of high frequency band of carrier signal. In the case of sinusoidal PWM (SPWM) scheme, the control signal is generated by comparing a sinusoidal reference signal and a triangular carrier. The SPWM technique, how ever, inhibits poorperformance with regard to maximum attainable voltage and power [4].

A novel PWM technique, called Inverted-Sine PWM (ISPWM), for harmonic reduction of the output voltage of ac-dc converters is presented in [5]. In addition, the control scheme based on ISPWM can maximize the output voltage for each modulation index [5].
In this paper, ISPWM switching technique has been developed for controlling of VSC based inverters which has lower Total Harmonic Distortion (THD) than conventional techniques.

2. Proposed ISPWM Technique

The proposed ISPWM has new forms of carriers, carrier1 and carrier2, as shown in Fig. 1. These waveforms have been generated by inversion of ISPWM carrier of [5] in half-cycle of power frequency and half-cycle of carrier frequency, respectively. In each case, equivalent triangular carriers have been shown by dashed lines in Fig. 1.

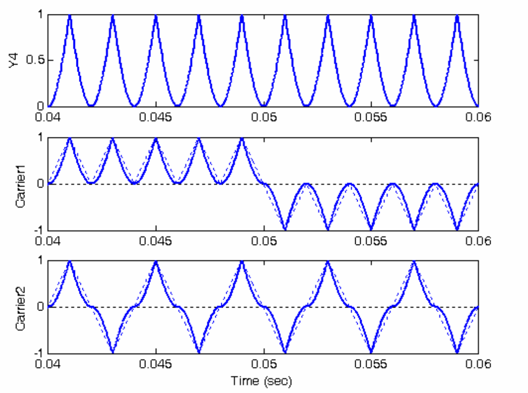


Fig.1. Proposed ISPWM carriers

The firing control signals have been generated by comparing sinusoidal reference signal (with the frequency f and magnitude m_a) with the inverted-sine carrier signal (with the frequency m_f and magnitude 1 p.u.), as shown in Fig.2.

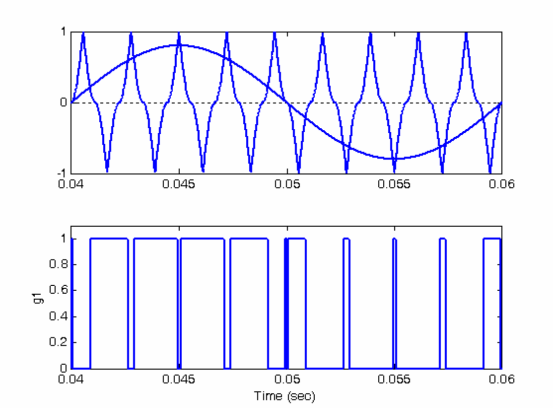


Fig.2. Firing pulse generation in proposed ISPWM

Fig. 3 shows the phase and line output voltages for m_f=9.

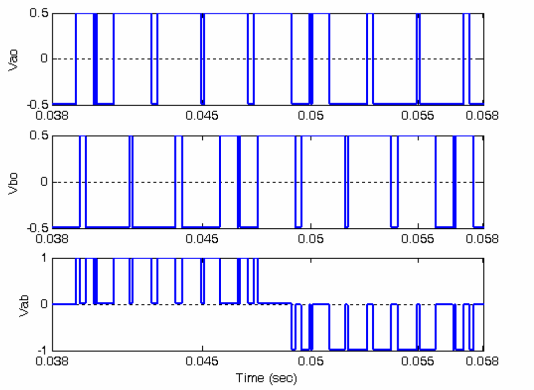


Fig.3. Phase and line output voltages for m_f=9

Considering angle θ_p as an intersection angle of carrier and reference signals, the following equations can be calculated:

$$1 - Sin[m_f\theta_p - \frac{\pi}{2}(p-1)] = m_a Sin\theta_p\,, \quad for\ p = 1,3,5,... \qquad (1)$$
$$1 + Sin[m_f\theta_p - \frac{\pi}{2}(p-2)] = m_a Sin\theta_p\,, \quad for\ p = 2,4,6,...$$

Based on Fourier analyais, all harmonics of output voltage waveform can be calculated.
When m_f is an odd number, the half cycles of the phase voltage V_{ao} are the same but with opposite sign and each half cycle is symmetrical with respect to half cycle midpoint. Therefore, $\frac{m_f - 1}{2}$ angles should be determined using following equations.

$$\frac{\pi}{2} - \theta_{(m_f-1)/2} = \theta_{(m_f+1)/2} - \frac{\pi}{2} = \frac{3\pi}{2} - \theta_{(3m_f-1)/2} = \theta_{(3m_f+1)/2} - \frac{3\pi}{2} \qquad (2)$$
$$\frac{\pi}{2} - \theta_{(m_f-3)/2} = \theta_{(m_f+3)/2} - \frac{\pi}{2} = \frac{3\pi}{2} - \theta_{(3m_f-3)/2} = \theta_{(3m_f+3)/2} - \frac{3\pi}{2},...$$
$$\theta_{m_f} = \pi, \theta_{2m_f} = 2\pi$$

Fourier expantion of the output waveform when m is also an odd number, consists of only odd harmonic orders.

$$V_{ao} = A_1 Sin\omega t + A_3 Sin3\omega t + A_5 Sin5\omega t + ... + A_n Sinn\omega t \qquad (3)$$

Where

$$A_n = \frac{4}{\pi}\int_0^{\pi/2} v_{AO} Sinn\omega t d\omega t$$
$$= \frac{4}{\pi}\frac{V_{DC}}{2}[\int_0^{\theta_1} Sin\omega t d\omega t - \int_{\theta_1}^{\theta_2} Sin\omega t d\omega t + ... \pm \int_{\theta_{m-1/2}}^{\pi/2} Sin\omega t d\omega t]$$
$$A_n = \frac{1}{n}.\frac{4}{\pi}.\frac{V_{DC}}{2}(1 - 2Cosn\theta_1 + 2Cosn\theta_2 - .... \pm 2Cosn\theta_{m-1/2})$$

Using the same method, Fourier series for V_{bo} can be expressed as follows:

$$V_{bo} = A_1 Sin(\omega t - \frac{2\pi}{3}) + A_3 Sin3(\omega t - \frac{2\pi}{3}) + \qquad (4)$$
$$A_5 Sin5(\omega t - \frac{2\pi}{3}) + ... + A_n Sinn(\omega t - \frac{2\pi}{3})$$

It is obvious that the line voltage V_{ab} has no triple harmonics. In addition, if m_f is equal to 3k for k=1, 2… then the line lowest harmonic orders are m_f-2, m_f+2, $2m_f$-2 and $2m_f$+2 (e.g., for m_f=9 the order of these harmonics are 7, 11, 17 and 19).

3. VSC-Based Custom Power Devices

This section presents an overview of the VSC-based custom power controllers studied in this paper.

A. D-STATCOM

Usually, the D-STATCOM configuration consists of a two-level VSC, a dc energy storage device; a coupling transformer connected in shunt with the ac system, and control circuits [6].
Fig. 7 shows the schematic representation of the D-STATCOM.

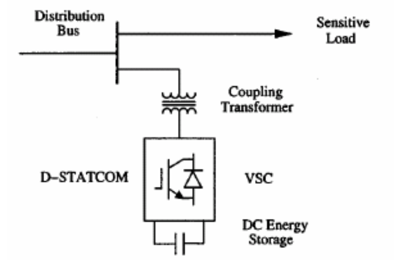


Fig. 4. Schematic representation of D-STATCOM

The VSC converts the DC voltage across the storage device into a set of three-phase AC output voltages. These AC voltages are in phase and coupled with the AC system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the AC system.
The VSC connected in shunt with the AC system can be used with following control strategies:

a) Voltage regulation and compensation of reactive power;
b) Correction of power factor and
c) Elimination of current harmonics.

In this paper, the D-STATCOM is used to regulate voltage at the connecting bus.

B. Dynamic Voltage Restorer (DVR)

The DVR is a powerful controller commonly used for voltage sags mitigation [7]. The DVR employs the same blocks as the D-STATCOM, but in this application the coupling transformer is connected in series with the AC system, as illustrated in Fig. 5.

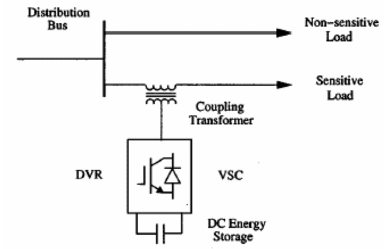


Fig. 5. Schematic representation of DVR

The VSC generates a three-phase AC output voltage which can be controlled in phase and magnitude. These voltages are injected into the AC distribution system in order to maintain the load voltage at the desired voltage level.

4. Simulation Results

This section is divided into three parts. Simulation results of conventional VSC based inverter are presented first. This is followed by simulations carried out for the D-STATCOM and DVR.

A. VSC Based Inverter Simulation

Fig. 6 shows the VSC based inverter test system simulated by PSCAD/EMTDC.
The test system uses a constant 5 kV DC source as a DC link. Fig. 7-a and 7-b show the rms voltage and its frequency spectrum at the load connecting bus using SPWM and ISPWM techniques, respectively (for m_a=0.8, m_f=9).

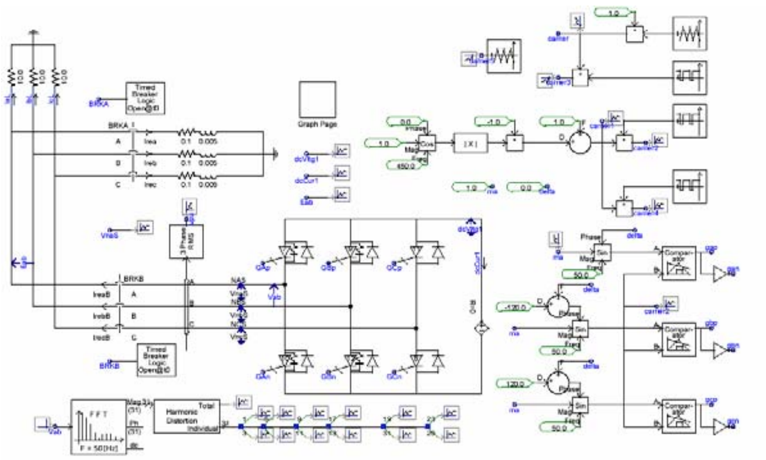
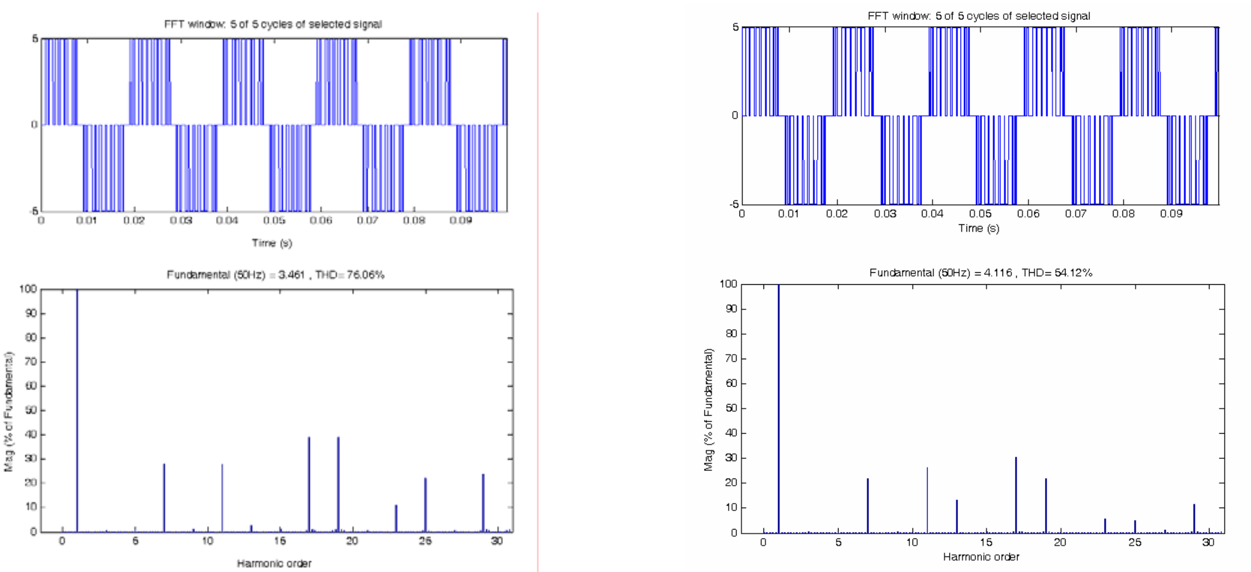


Fig. 6. Control scheme and VSC based inverter test system



(a) (b)

Fig. 7. Output voltage and frequency spectrum for VSC based inverter using (a) SPWM technique (b) ISPWM techniques

The capability of ISPWM scheme for improving frequency spectrum and hence, reduction of output THD, can be seen in this figure.
Fig.8 shows the results of the same simulation but in the full range of amplitude modulation index. As it can be seen, the proposed ISPWM technique has always lower THD than the conventional SPWM.

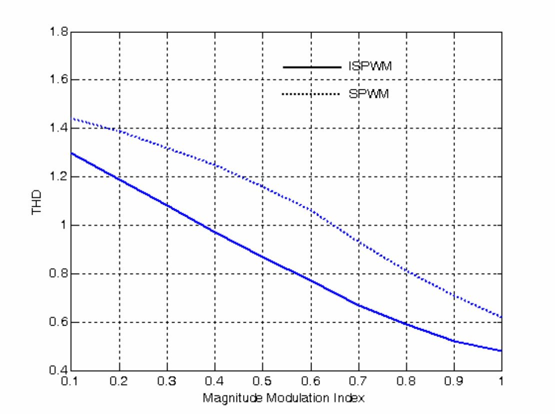


Fig. 8. THD versus m_a for VSC based inverter

B. D-STATCOM Simulation

Fig. 9 shows the D-STATCOM test system. The test system comprises a 230 kV transmission system, represented by a Thevenin equivalent, feeding into the primary side of a 3-phase 3-winding transformer. The load is connected to the 11 kV bus, i.e., secondary side of the transformer. A two-level D-STATCOM is connected to the 11 kV tertiary winding to provide instantaneous voltage support at the load bus. A 19 kV DC source is used as an energy source link.
The set of switches shown in Fig. 9 have been used to simulate different loading scenarios.
In control system an error signal is obtained by comparing the reference voltage with the rms voltage measured at the load bus. The PI controller process the error signal and generates the required angle to drive the error to zero, i.e., the load rms voltage is brought back to the reference voltage, under system disturbances. The VSC switching strategy is based on SPWM and ISPWM techniques as shown in Fig. 9.
To show the effectiveness of this controller in providing continuous voltage regulation, this system has been also simulated without D-STATCOM.

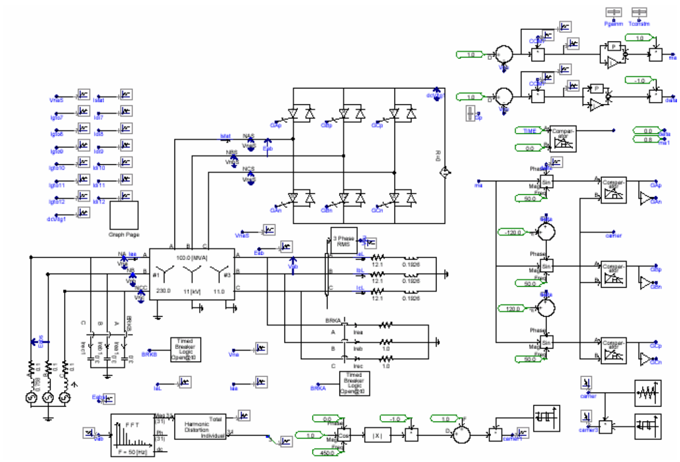
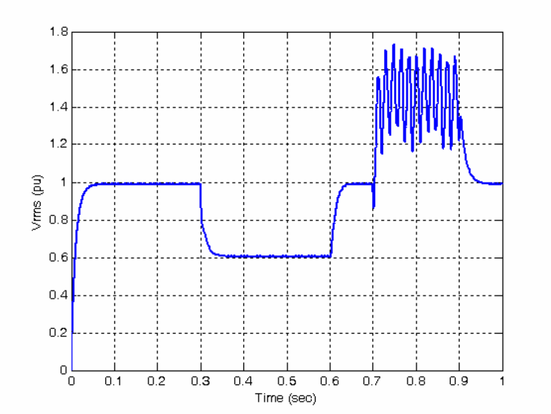
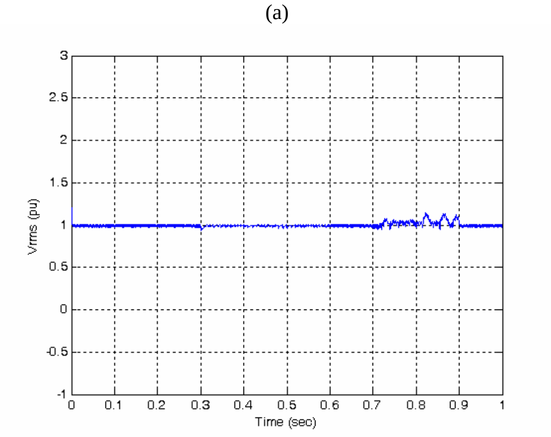


Fig. 9. Control scheme and D-STATCOM test system

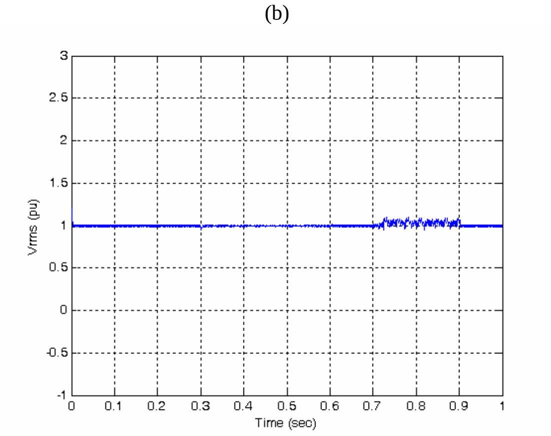
The simulation has three steps:
Step 1) in the period 300–600 ms, the load is increased by closing Switch *A*. In this case, the voltage drop is about 40% as shown in Fig. 10-a.
Step 2) at t=600 ms, the switch *A* is opened. The load voltage is very close to the reference value, i.e., 1 pu.
Step 3) in the period 700–900 ms, Switch *B* is closed, connecting a capacitor bank to the high voltage side of the network. The load voltage shows 40% increase as it can be seen in Fig. 10-a.
The same system has been simulated with D-STATCOM. This D-STATCOM uses SPWM or ISPWM techniques.
The simulation results are shown in Fig. 10-b and 10-c for SPWM and ISPWM, respectively. It is obvious that the voltage regulation is provided by the D-STATCOM in both cases.



(a)



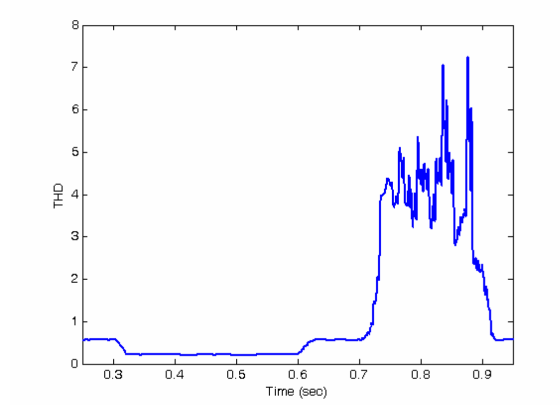
(b)



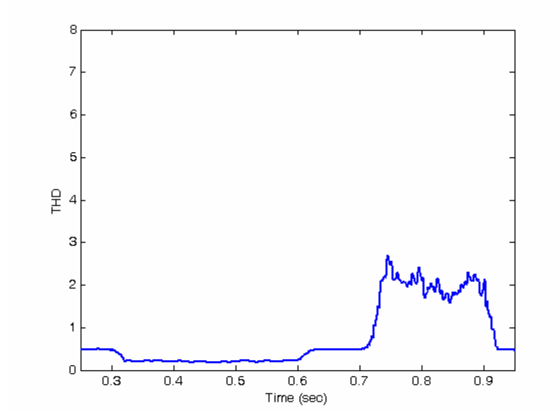
(c)

Fig. 10. Load Voltage (a) voltage sag and swell
(b) Compensated by D-STATCOM with SPWM technique
(c) Compensated by D-STATCOM with ISPWM technique

Fig. 11 shows the load voltage THD for SPWM and ISPWM switching techniques.



(a)



(b)

Fig. 11. Voltage THD at the load bus: (a) SPWM technique (b) ISPWM technique

C. DVR Simulations and Results

Fig. 12 shows the DVR test system. The DVR coupling transformer is connected in delta in the DVR side, with a leakage reactance of 10% and unity turns ratio. The voltage of the dc storage device is 5 kV.

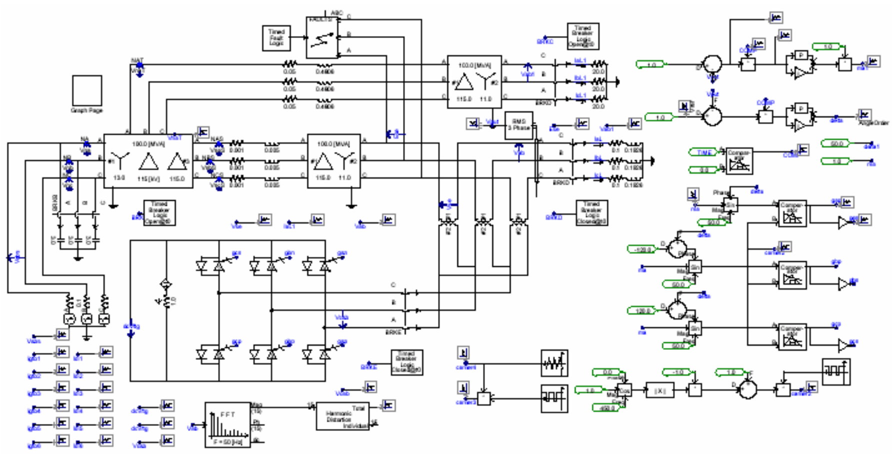
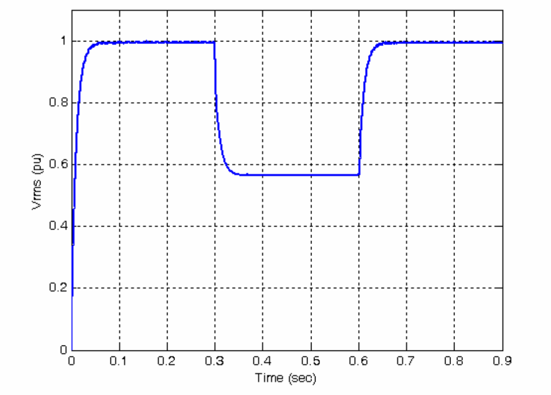


Fig. 12. Control scheme and DVR test system

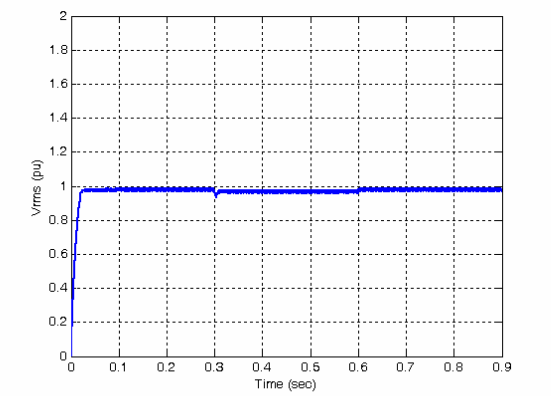
In this case, simulation has one step. A three-phase short-circuit fault is applied to point A, during the period 300–600 ms. If there is no DVR in the system, the voltage sag at the load bus is 50% with respect to the reference voltage as shown in Fig. 13-a.

If the DVR with SPWM and ISPWM techniques is in operation, then the voltage sag is mitigated almost completely as shown in Fig. 13-b and 13-c, respectively.

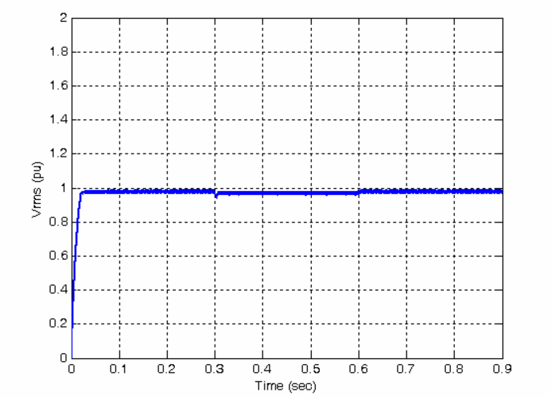
The SPWM and ISPWM control scheme controls the phase of the injected voltages, restoring the rms voltage very effectively. The THD of output voltages of both control schemes has been presented in Fig. 14.



(a)



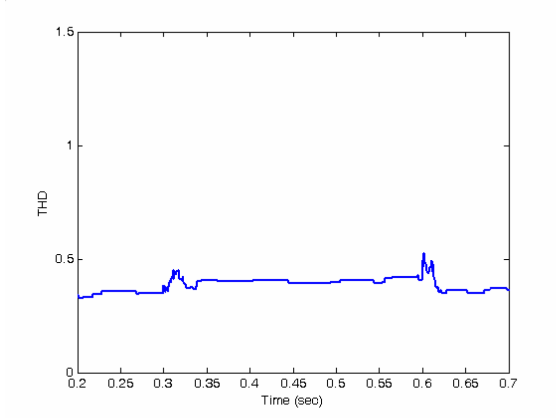
(b)



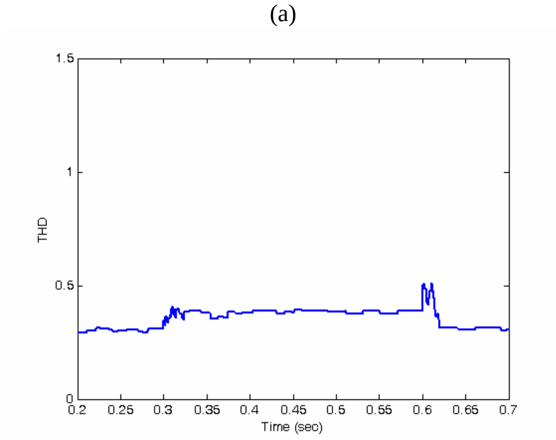
(c)

Fig. 13. Load Voltage (a) voltage sag (b) compensated by DVR with SPWM technique (c) compensated by DVR with ISPWM technique

The THD of output voltages of both control schemes has been presented in Fig. 14.



(a)



(b)

Fig. 14. Voltage THD at the load bus: (a) SPWM technique (b) ISPWM technique

In this case, the both techniques have almost the same behavior.

5. Conclusion

This paper presents a novel PWM technique for VSC based inverters.

Using this technique, paper also presents the method for controlling shunt and series custom power devices such as D-STATCOM and DVR. It is shown that custom power devices based on proposed switching technique has a lower THD than the conventional SPWM. The simulations results show very good voltage regulation with lower harmonic contents in output voltage of these devices, too.

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