Evaluation of Interharmonics in Variable Speed Drives and Matrix Converter fed Drives

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Abstract

The major consequence of the paper is about the interharmonics appearing in the variable frequency drive. It specifies the causes for the interharmonics in the drive, continued by the interharmonics frequency derivations. The paper illustrates the various interharmonics elimination methods of SVPWM inverter fed drive and the associated drawbacks. The drawbacks are eliminated by using matrix converter fed adjustable speed drive. The advantages and modulation technique of the matrix converter are also discussed in detail. The simulated waveforms and interharmonics values obtained from conventional adjustable speed drive are compared with the simulated results of elimination methods and matrix converter fed drive.

Keywords: Conventional AC/DC/AC converter; interharmonics; matrix converter; space vector modulation; unbalanced load; variable speed drives.

1. Introduction

Variable speed drives (VSD) have wide applications in both industrial and home appliances. Home appliances like fans, pumping systems and industrial appliances like conveyors, compressors and chillers widely use the variable speed drives. This variable speed drive has many advantages like reliable control of speed for wide range of frequencies, reduced power consumptions, high efficiency etc., The variable speed drives are also known as variable frequency drive (VFD) or adjustable speed drives (ASD) is usually of a double stage conversion type AC/DC/AC converter type. The general block diagram of VSD is shown in Figure 1.

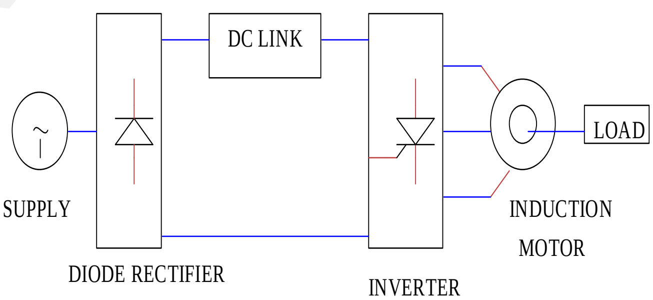

Figure 1. Variable Speed Drive

The three phase supply is rectified using diode rectifier and smoothened using DC link and fed to an inverter which feeds the stator terminals of the induction motor (IM) driving a load. The variable speed is obtained by means of varying the frequency of the inverter. Such drives are badly affected by interharmonics, when there is an unbalanced load or over modulation of the inverter[. They also occur in the drive, when two AC systems are not properly decoupled by DC link [1-7]. Interharmonics are the harmonic components which are not the integer multiple of the fundamental frequency (f_s or ω_{in}). This paper deals with the interharmonics occurred in ASD due to unbalanced load. The adverse effects of interharmonics are voltage fluctuations, light flicker, high distortion of the current waveforms, overheating of the motor and useful life reduction of the motor.

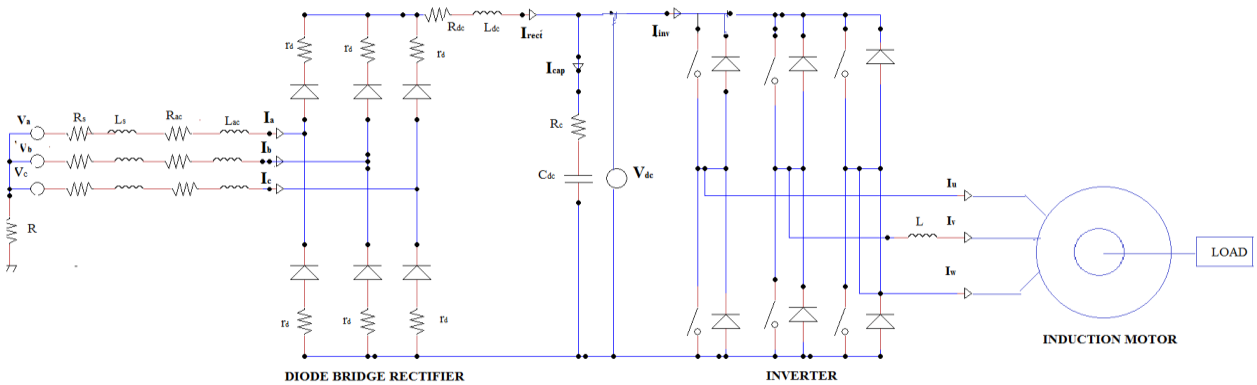

Figure 2. Equivalent circuit of Variable Speed Drives

Section II deals with the derivation of interharmonics frequency. Section III comprises of the conventional VSD, the elimination methods employed in conventional VSD and their drawbacks. Section IV depicts matrix converter (MC) fed VSD and its modulation technique. Besides the comparison of simulation results of AC/DC/AC along with the harmonic elimination methods and MC fed VSD are presented. Section V deals with the conclusion of the paper based on the comparison.

2. Interharmonics Frequency Derivation

The VSD with balanced load is subjected to fundamental harmonics components only. But when VSD is fed with an unbalanced load, it has both the fundamental harmonic and the interharmonics components appearing in the voltage and current of the drive [1]-[2]. The interharmonics originates from the load side of the drive ie inverter AC side. Then, on propagation through the DC link, the interharmonics get magnified by the DC link resonance. Finally, this current appears at the AC side of the rectifier as a combination of both the supply and inverter frequencies.

2.1. Induction Motor Stator Current Expression

An easy way to obtain the interharmonics frequency is done by deriving the equation of current in each section. Because, the unbalance load leads to unbalanced current in the circuit. The equivalent circuit of the VSD is depicted in Figure 2. From the expressions of unbalanced current in the drive, the frequency at which the interharmonics occur can easily be found. Initially, the unbalance starts from the AC side of the inverter therefore interharmonics current expression at the stator terminals of the induction motor is derived [1]. The unbalanced current at the stator terminals is given as,

$$I_u = \sqrt{2} I \cos(\omega t)$$

where, I_u is the current flowing through the phase u.

The disturbed current leads to the formation of positive, negative and zero sequence components in the current expression. The zero sequence components do not occur in the drive because IM is a three wire device. The IM has three stator terminals namely phase *u*, *v* and *w*. The inverter current expression is obtained by multiplying the inverter switching functions along with the respective phase current expression and summing all the phase current expression. The unbalanced inverter current expression is obtained only in terms of positive and negative sequence components as given as,

$$I_{inv} = [I_+ + I_-]$$

$$I_+ = AI_+ \cos\phi_+$$

$$I_- = AI_- \cos(2\omega_{out} t + \phi_-)$$

$$A = 1.03m$$

where, I_+, I_- and m represent the positive sequence, negative sequence components and modulation index respectively. I_+ contributes for the active power transfer in the drive. I_- does not contribute for any power transfer. The negative sequence current expression shows the frequency ($2\omega_{out}t$) at which interharmonics occurring at the stator terminals of the motor.

2.2. DC link Current Expression

The I_{inv} on further propagation increases the magnitude of the interharmonics by the resonance caused by the DC link of the drive. The DC link current expression of the

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drive is given in (3). The magnification factor of the DC link is represented by MF_{dc}, whose value depends on the resonant components present in the DC link side. Here, only the magnitude gets increased and there is no change in the interharmonics frequency.

$$I_a = A\left[I_+ + I_-\right]$$

$$I_+ = I_+ \cos\left(\omega_{in} t + \phi_+\right)$$

$$I_- = \left(MF_{dc}\left(I_- \cos\left(2\omega_{out} \pm \omega_{in}\right)t\right) + \rho\right)$$

$$A = 3.7m$$

As inferred from the supply side current expression, the positive sequence component is appearing at the system fundamental frequency $\omega_{in}t$, where the negative sequence component is appearing at the frequency $(2\omega_{out} \pm \omega_{in})t$. These interharmonics are found as side bands around the fundamental frequency components. This current is also represented as I_{rect}. Thus, the interharmonics frequency is derived for each part of the drive starting from the inverter AC side to the supply side of the system.

3. Analysis of Interharmonics in Conventional VSD and Elimination Methods

3.1. Analysis of Conventional VSD

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The inverter frequency decides the frequency of IM. The main aim of the inverter is to provide a pure sinusoidal wave and supply to the motor. And so, inverter is operated using space vector pulse width modulation (SVPWM). This technique provides an easy access to the modulation and frequency change in the output waveform. The theoretical analysis done in section 2 is now validated by the simulation results. The parameters employed in Matlab simulation are listed in Table 1.

The input frequency is 50Hz and the output frequency is 40Hz. Therefore interharmonics appear at the frequency of 80Hz at the inverter AC and at DC link side. The DC link current along with the interharmonics will have the ripple harmonics appearing at the frequency of $2\omega_{in}$ in the drive [2]. The interharmonics will appear at the frequency of 130 Hz ($2\omega_{out} + \omega_{in}$) and 30Hz ($2\omega_{out} - \omega_{in}$) at the supply side of the drive as side bands for the fundamental frequency 50Hz. The current spectrum explaining this concept is shown in Figure 3. The unbalanced current waveforms at each section of the drive operating with SVPWM inverter is shown in Figure 4. The values of interharmonics appearing in the drive are also tabulated in the Table 2.

Table 1. Simulation Parameters

Parameters	Values
Input Voltage, V_s	400V
Input frequency, f_{in}	50Hz
Modulation index, m	0.92
Power rating of the IM, P	75KW
Motor load, T_l	470Nm
Motor speed, N	1200 rpm
Output frequency, f_{out}	40Hz
Inductance value which cause interharmonics	0.125mH

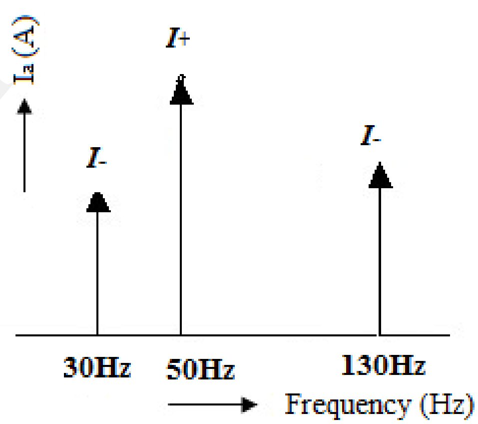

Figure 3. Current Spectrum of Supply side

3.2 Elimination of Interharmonics in Conventional VSD

The interharmonics appearing in the system causes many adverse effects like, high current distortion, voltage flicker, subsynchronous oscillations and reduced life time of the motor due to overheating. The existing methods of eliminating the interharmonics are by increasing the DC link resistance or varying the AC side inductance. The former method is employed because if the DC link value is high, it could prevent the interharmonics propagation through the drive and avoid its presence at the rectifier AC side.

Table 2. Interharmonics values at each section of the drive

Unbalanced current	Interharmonics frequency	Magnitude (%)
I_{inv}	$2f_{out}$ (80Hz)	77.57
I_{dc}	$2f_{out}$ (80Hz)	40.74
	$2f_{in}$ (100Hz)	69.54
I_{rect}	$2f_{out}-f_{in}$ (30Hz)	0.46
	$2f_{out} + f_{in}$(130Hz)	5.47

The later method is also helpful for damping the interharmonics and lowers their magnification. The range of inductance employed for interharmonics elimination is from 0.5 – 3mH [1-4]. Increasing the DC link resistance causes voltage drop in the system and so not widely used in the elimination process. The AC side inductance was varied in the drive and the waveforms obtained from the Matlab simulation is depicted in Figure 5. The magnitude of interharmonics at various stages is given in the Table 3.

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4. Matrix Converter fed Variable Frequency Drive

The variable frequency drive with direct AC/AC conversion and with SVPWM technique is implemented using matrix converter (MC) in the drive [5]. The general block diagram of MC fed VFD is illustrated in Figure 6. The MC has nine switches arranged in 3 $\times$3 matrix form. The matrix converter has many advantages when compared to the conventional one. They are absence of DC link capacitor, sinusoidal waveform both at input and output side, compact size, bidirectional power flow, four quadrant operations etc when compared to conventional VSD.

The space vector modulation is achieved in the MC by two methods. They are direct space vector modulation (DSVM) and indirect space vector modulation (ISVM). DSVM is further classified as, symmetric SVM (SSVM) and asymmetric SVM (ASVM) [6-13]. This paper deals with MC fed VFD with SSVM technique.

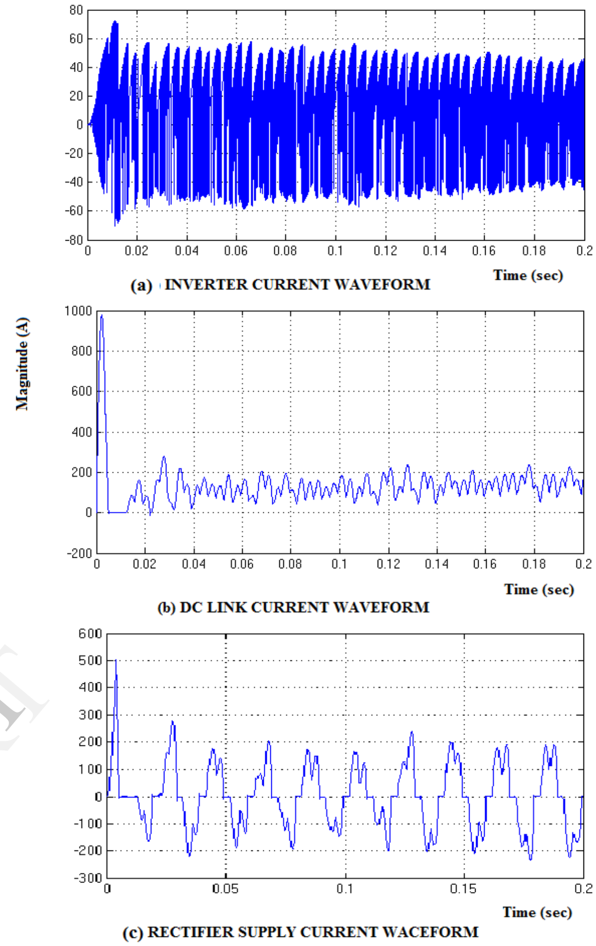

Figure 4. Unbalanced Current waveforms of SVPWM fed ASD

Table 3. Interharmonics value at each section of VSD with Inductance varied

Unbalanced current	Interharmonics frequency	Magnitude (%)
I_{inv}	$2f_{out}$ (80Hz)	57.10
I_{dc}	$2f_{out}$ (80Hz)	56.15
	$2f_{in}$ (100Hz)	42.81
I_{rect}	$2f_{out}-f_{in}$ (30Hz)	4.11
	$2f_{out} + f_{in}$ (130Hz)	0.88

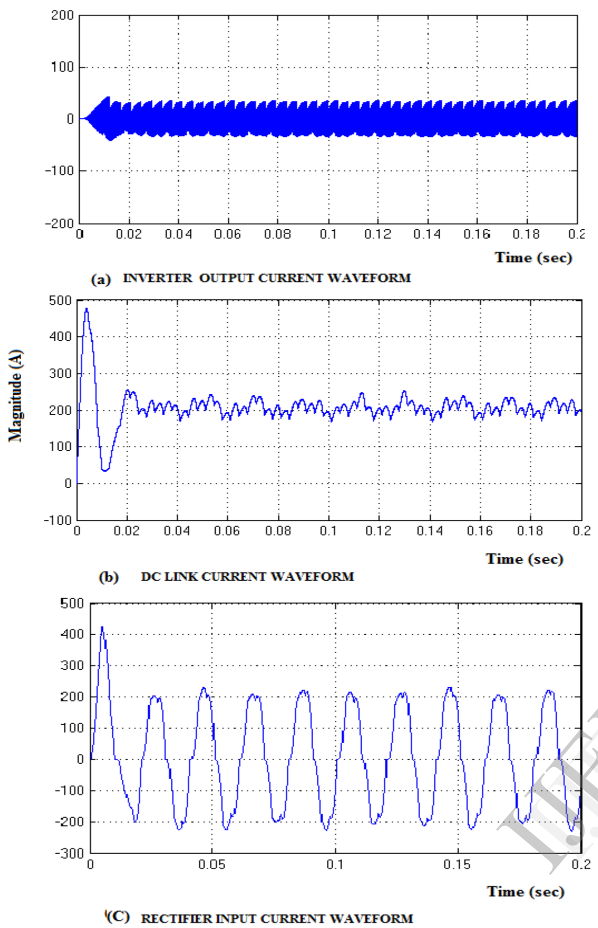

Figure 5. Unbalance Current Waveforms of VSD with AC side Inductance varied

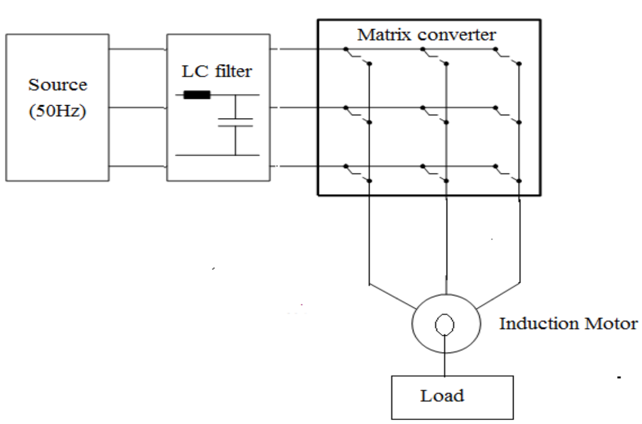

Figure 6. MC fed VSD

The general procedure followed for producing the gate pulse for nine switches of the matrix converter is:

- Initially the sector and angle for the reference vector are calculated.
- Duty ratios are directly evaluated.
- Conduction time for each switch is obtained by duty ratio × switching period (Ts).
- Applying the duty ratios to switching states.
- Depending upon the switching states, the corresponding switches are turned ON.
- For that particular switching combination, the output voltage is obtained at the load side.

The MC can have $2^9 = 512$ switching states. But, applying two constraints, the states are reduced to 27.

(i) Only one switch should be closed at the output terminal, if two switches are closed then short circuit will appear at the input phase.
(ii) If all the switches in the output phase are open, then the load current gets interrupted and overvoltage problem occurs.

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The MC uses only 21 states out of 27. The duty ratio used in SSVM [11-14] is given as,

$$d_I = (-1)^{K_v+K_i} \frac{2}{\sqrt{3}} q \frac{\cos\left(\alpha - \frac{\pi}{3}\right)\cos\left(\beta - \frac{\pi}{3}\right)}{\cos\phi_i}$$

$$d_{II} = (-1)^{K_v+K_i} \frac{2}{\sqrt{3}} q \frac{\cos\left(\alpha - \frac{\pi}{3}\right)\cos\left(\beta + \frac{\pi}{3}\right)}{\cos\phi_i}$$

$$d_{III} = (-1)^{K_v+K_i} \frac{2}{\sqrt{3}} q \frac{\cos\left(\alpha + \frac{\pi}{3}\right)\cos\left(\beta - \frac{\pi}{3}\right)}{\cos\phi_i}$$

$$d_{IV} = (-1)^{K_v+K_i} \frac{2}{\sqrt{3}} q \frac{\cos\left(\alpha + \frac{\pi}{3}\right)\cos\left(\beta + \frac{\pi}{3}\right)}{\cos\phi_i}$$

where K_v and K_i are the sectors in which reference vectors are located, q is the voltage ratio, α and β are the phase angle within the sectors and ϕ_i is the displacement angle between input voltage and current space vectors [12]. The input current and output voltage space vector hexagons of DSVM [14] are shown in Figure 7. The simulation parameters of MC fed VFD are given in Table 4. The values of interharmonics at each section of the drive are tabulated in Table 5. The values of interharmonics are greatly reduced by the direct AC/AC conversion process

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because of the elimination of the DC link. Since the magnification of the interharmonics are avoided, the values of interharmonics appearing at the supply side of the drive are also reduced. The comparison of interharmonics values obtained from simulation of conventional, MC fed VFD along with the elimination method is listed in Table 6. The put and output current waveforms of Matrix Converter fed ASD are given in Figure 8.

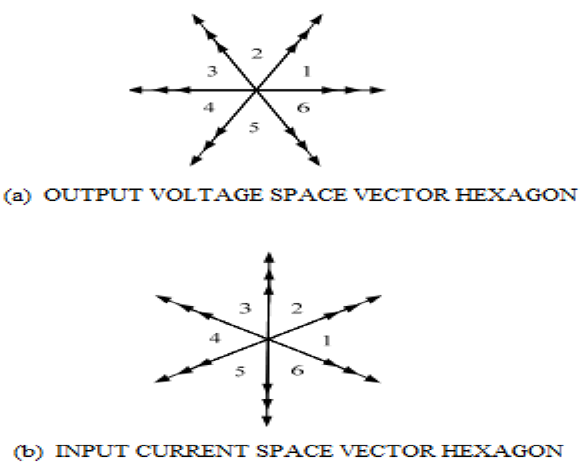

Figure 7. Output Voltage and Input Current Space Vector Hexagon

The THD analysis of conventional and MC fed VFD is shown in Fig. 9. The input current which was badly affected by interharmonics is compared. The rectifier input current THD of conventional VSD shown in Figure 9 (a) is 25.34% whereas the THD of MC fed VSD shown in Figure 9 (b) is 3.44%. Even the dominant harmonics are significantly reduced.

Table 4. Simulation Parameters of MC fed VSD

Parameter	Values
Input Voltage, V_s	400V
Input frequency, f_{in}	50Hz
Input Filter Inductance	30mH
Input Filter Capacitance	25µF
Filter Resistance	0.2Ω
Output frequency, f_{out}	40Hz
Modulation Index, q	0.9

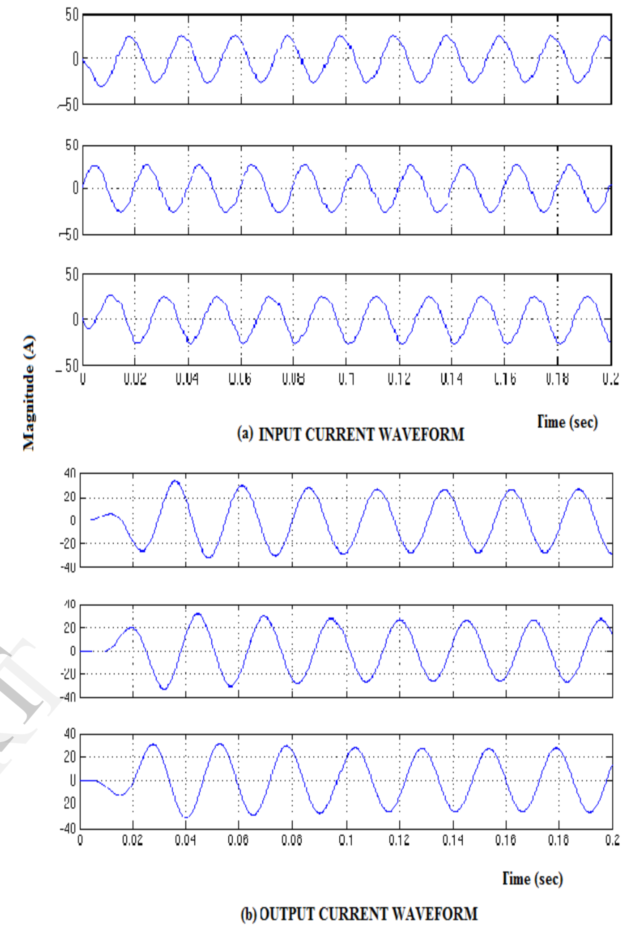

Figure 8. Current waveforms of MC fed VSD

Table 5. Interharmonics value at each section of MC fed VSD

Unbalanced current	Interharmonics frequency	Magnitude (%)
I_O	$2f_{out}$ (80Hz)	23.22
I_S	$2f_{out}-f_{in}$ (30Hz)	0.66
	$2f_{out}+f_{in}$ (130Hz)	0.67

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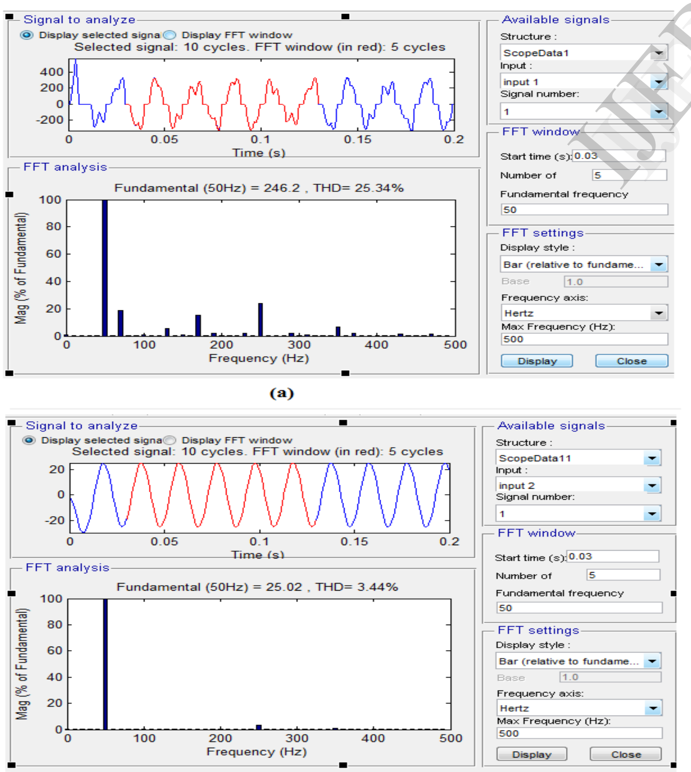
Table 6. Comparison of Interharmonics values

Unbalanced current	Conventional VSD (%)	Elimination method by R or L (%)	MC fed VSD (%)
I_{inv} $2f_{out}$ 80Hz	77.57	57.10	23.22
I_{dc} $2f_{out}$ 80Hz $2f_{in}$ 100Hz	40.74 69.54	56.15 69.54	No DC link current
I_{rect} $2f_{out}-f_{in}$ 30Hz $2f_{out}+f_{in}$ 130Hz	0.46 5.47	4.11 0.88	0.66 0.67



(a)

(b)

Figure 9. THD analysis rectifier input current of Conventional and Supply current of MC fed VSD

5. Conclusion

The conventional variable frequency drives (AC/DC/AC conversion) are likely to be affected by interharmonics when there is an unbalance load. The drive could not restrict the interharmonics to a safer limit by the conventional elimination methods like varying the AC side inductance and DC link resistance due to the presence of DC link. So, adjustable speed drive with matrix converter (AC/AC conversion) is proposed and the values obtained from the Matlab simulation are evaluated. Among them, the MC fed variable speed drives shows better results in damping the interharmonics to the safer limits. And so, it is concluded that the ASD operating with MC can provide better performance along with reduced harmonics and interharmonics levels in the system.

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