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Performance of Modified Indirect Matrix Converter Supplying Power to Static Load

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Abstract: In this paper the performance of modified Indirect Matrix Converter (IMC) and a conventional IMC supplying power to static load is compared. The Rectifier stage in modified IMC uses an improved switching technique to obtain a maximum dc link voltage compared to the conventional IMC and at the same time keeping the fundamental input current at unity power factor for both directions of power flow. The inverter switching technique is based on the output space vectors where the switching losses and output distortions are minimised. By using modified switching techniques for both Rectifier and inverter, the distortions in output side are less as compared with that of the conventional IMC. The performance of the modified IMC and conventional IMC supplying static load is also analysed for both directions of power flow and the THD's of the load current and input current are compared. The performance of both the IMCs for the proposed switching techniques are shown through simulation results.

Keywords: Matrix converters, Asynchronous systems, Static load, Modified switching sequence, Performance analysis.

1. INTRODUCTION

Matrix converters (MCs) [1-4] have received considerable attention since they are highly reliable, compact in design, permit bidirectional power flow and the absence of energy storage elements in the *dc*-link. These MCs are of two types: The direct matrix converter (DMC) and Indirect Matrix converter(IMC) [5-6]. The virtual *dc* link enables the bidirectional power flow between the two stages. The control of IMC is more simpler that of DMC, since the output devices switching is made independent to that of input side switching. But in DMC switching of output devices is dependent on the switching of input. Hence, DMC is not suitable for supplying multiple loads. But IMC is suitable to supply power to multiple loads at different voltages and frequencies[7-8].

The IMC is mainly divided into two stages, the input or Rectifying stage which consists of 6 bi-directional switches and the output or inverter stage consists of 6 unidirectional switches [9-11] as shown in Figure 1. The modified IMC uses an improved switching technique to obtain a maximum positive *dc* voltage compared to that of conventional IMC and the fundamental input current is kept at unity power factor [12]. Also a new switching configuration is used at the inverter in order to reduce the switching losses and distortions in the output. The modified IMC gives very less distortions in the output voltage and current as compared with the conventional IMC [13-14]. The distortions in the output side are improved by using an LC filter as shown in Figure 1. The LC values of the filter are chosen such that negligible phase shift and attenuation are introduced at the fundamental frequency of the inverter output [15].

This paper is organized as follows. Section-2 describes control of the Rectifier stage for both modified IMC and conventional IMC. An improved switching technique is used at the Rectifier for modified IMC to obtain a maximum positive *dc* voltage as compared to that of conventional IMC. The fundamental input current is at unity power factor at the Rectifier end for both directions of power flow. In Section-3 a new switching technique for the inverter is used for the modified IMC to reduce the switching losses and output distortions. The Section-4 deals with the performance of modified IMC supplying power to static

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load at different frequencies for both directions of power flow and the distortions in the load voltage and current are compared with the conventional IMC for the same operating conditions. Section-5 gives the conclusions of this paper.

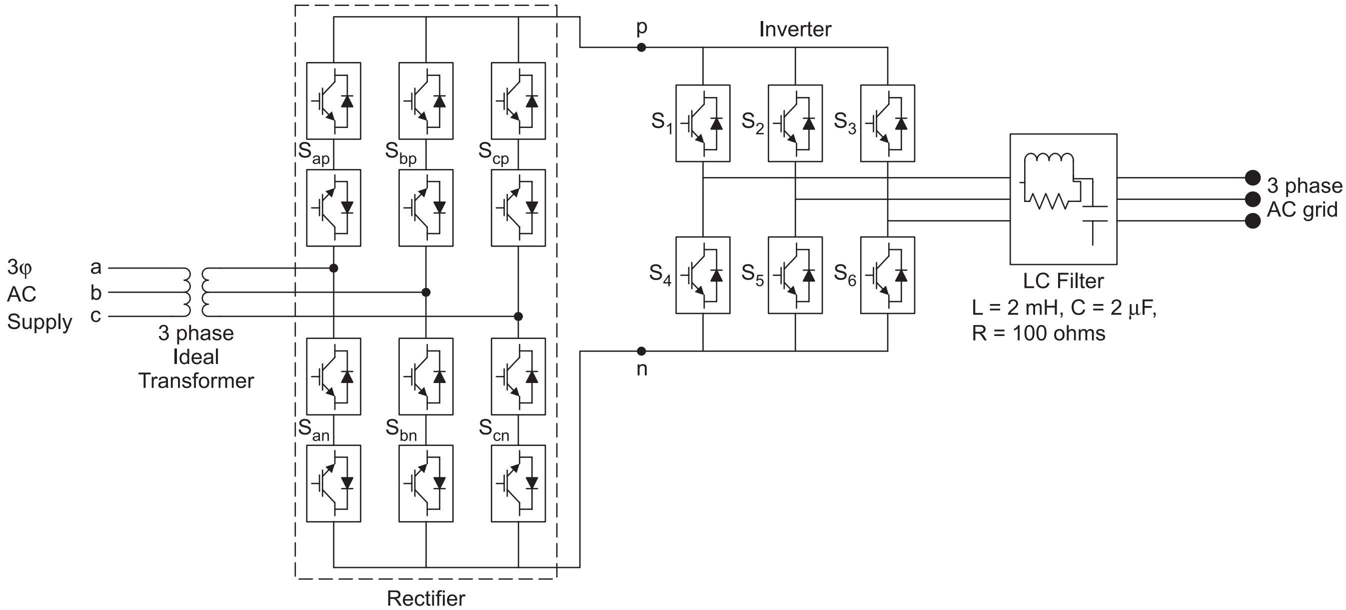

Figure 1: IMC Topology

2. RECTIFIER CONTROL

The following switching technique is used to control the Rectifier stage of the IMC. The three phase supply voltages are given by

$$v_a = V_m \sin \omega t$$

$$v_b = V_m \sin\left(\omega t - \frac{2\pi}{3}\right)$$

$$v_c = V_m \sin\left(\omega t + \frac{2\pi}{3}\right) \tag{1}$$

where V_m and ω are the maximum voltage and angular frequency of the supply phase voltage.

The input stage of the IMC consists of 6 bi-directional switches i.e. ($S_{ap} - S_{cn}$). The upper switches S_{ap}, S_{bp}, S_{cp} are connected to the positive pole and the lower S_{an}, S_{bn}, S_{cn} are to negative pole of the *dc* link (*pn*) of the input stage. The angle θ_{in} (= ωt ranges from (0 to 2π)) is divided into six sectors, each of $\pi/3$ duration as shown in Table 1. The *dc*-link voltages of the Rectifier in each of the sectors is also shown in Table 1.

Table 1
Sector Identification

θ_{in}	*Sector*	*Instantaneous dc-link voltages (V_{dc})*	
$0 - \pi/3$	1	V_{cb}	V_{ab}
$\pi/3 - 2\pi/3$	2	V_{ab}	V_{ac}
$2\pi/3 - \pi$	3	V_{ac}	V_{bc}
$\pi - 4\pi/3$	4	V_{bc}	V_{ba}
$4\pi/3 - 5\pi/3$	5	V_{ba}	V_{ca}
$5\pi/3 - 2\pi$	6	V_{ca}	V_{cb}

In case of the conventional IMC, the active voltage vectors V_{cb} and V_{ab} are switched to the Rectifier output with the following switching times as shown in Eq. 2 and Eq. 3. This results in high ripples on *dc* voltage. The switching times are given by

$$T_p^R = T_s \frac{\sin\left(\frac{\pi}{3} - \theta\,\text{in}\right)}{\left(\sin\left(\frac{\pi}{3} - \theta\,\text{in}\right) + \sin\theta\,\text{in}\right)} \tag{2}$$

$$T_n^R = T_s \frac{\sin\theta\,\text{in}}{\left(\sin\left(\frac{\pi}{3} - \theta\,\text{in}\right) + \sin\theta\,\text{in}\right)} \tag{3}$$

where T_s is the sampling time.

As the reference vector moves into sector-2 to sector-6, the switching times are given by Eq. 4 and Eq. 5.

$$T_p^R = T_s \frac{\sin\left(\frac{n\pi}{3} - \theta\,\text{in}\right)}{\sin\left(\frac{n\pi}{3} - \theta\,\text{in}\right) + \sin\left(\theta\,\text{in} - \frac{(n-1)\,\pi}{3}\right)} \tag{4}$$

$$T_n^R = T_s \frac{\sin\left(\theta\,\text{in} - \frac{(n-1)\,\pi}{3}\right)}{\sin\left(\frac{n\pi}{3} - \theta\,\text{in}\right) + \sin\left(\theta\,\text{in} - \frac{(n-1)\,\pi}{3}\right)} \tag{5}$$

where n is the sector number.

Table 1 gives the sector-wise voltages generated at the output of the Rectifier. The switching time T_p^R is applied to the voltages in column-3 and T_n^R is applied to the voltages in column-4 in the case of conventional IMC.

In case of modified IMC, through proper switching of the devices output *dc* terminals of the Rectifier are connected to particular *ac* terminals of the inverter. Table-2 shows *dc* link voltage in each of the sectors. For example in sector-1 the switches S_{cp} and S_{bn} are turned ON applying voltage V_{cb} across *dc* terminals. Similarly, *dc* link voltage during duration of other sectors is also shown in Table-2. This method of control also ensures UPF for the fundamental of the *ac* input current for both directions of power flow.

Table 2
DC link voltages for Modified IMC

Phase (θ_{in})	*Dc link voltage* (V_{pn})	*Sector*
$-\frac{\pi}{6}$ to $\frac{\pi}{6}$	$V_{cb}(=(V_c - V_b))$	1
$\frac{\pi}{6}$ to $\frac{\pi}{2}$	V_{ab}	2
$\frac{\pi}{2}$ to $\frac{5\pi}{6}$	V_{ac}	3

Phase (θ_{in})	*Dc link voltage* (V_{pn})	*Sector*
$\frac{5\pi}{6}$ to $\frac{7\pi}{6}$	V_{bc}	4
$\frac{7\pi}{6}$ to $\frac{3\pi}{2}$	V_{ba}	5
$\frac{3\pi}{2}$ to $\frac{-\pi}{6}$	V_{ca}	6

The input supply voltage $v_a = 325 \sin 314\, t$ then the average *dc* output voltage obtained for the Rectifier of modified IMC is 537.5 volts and for the conventional IMC with the same input supply voltage the output dc voltage of the rectifier is 511.5 volts. Figure 2 and Figure 3 show the corresponding *dc* voltages of the two converters.

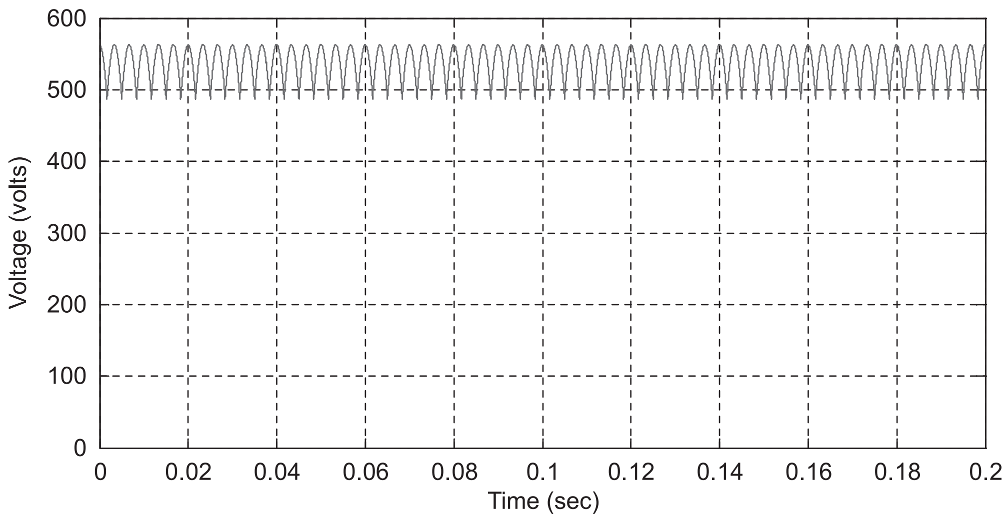

Figure 2: DC voltage for Modified IMC

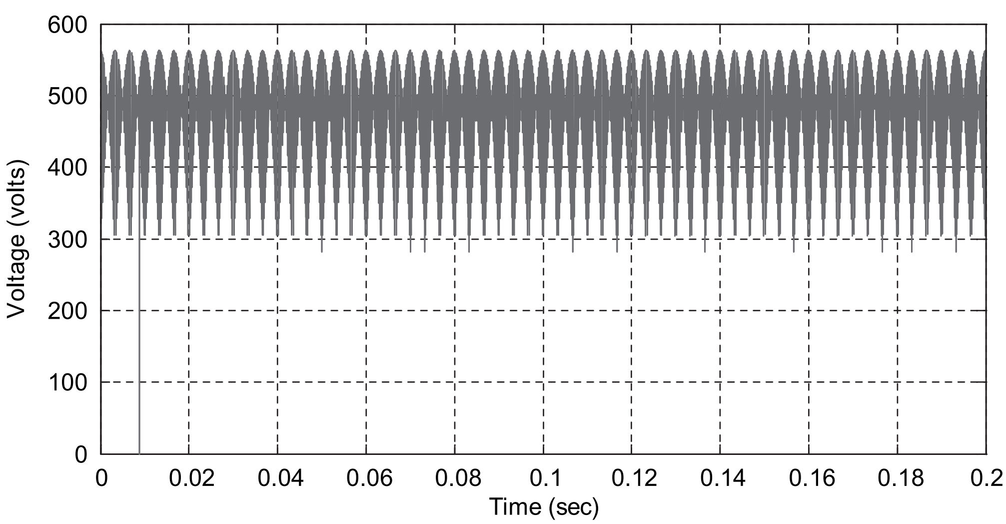

Figure 3: DC voltage for Conventional IMC

3. CONTROL OF INVERTER STAGE

Space vector modulation technique is used to control the inverter. Figure 4 shows the space vector diagram of the inverter. It consists of 6 active voltage vectors ($V_1 - V_6$) and 2 zero vectors V_0, V_7. The angle $\theta_r = (\omega_0 t$, ω_0 is output frequency) ranges from (0 to 2π) is divided into six sectors as shown in Figure 4.

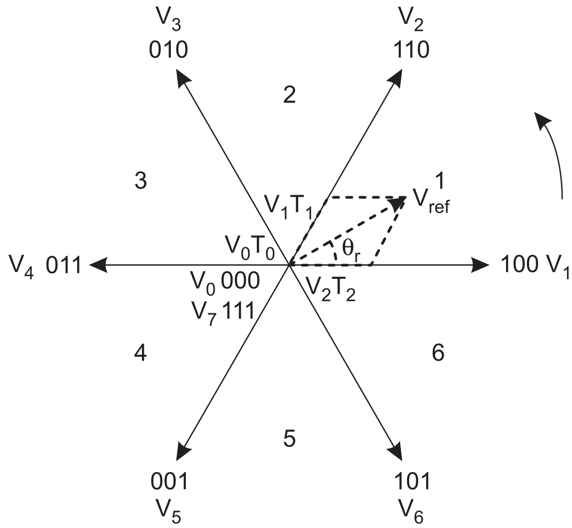

Figure 4: Space vector diagram of the inverter

T_1, T_2 are the switching times for the active voltage vectors (V_1, V_2) and T_0 is the switching time for zero voltage vector (V_0 or V_7) in sector-1. These switching times depends on the magnitude of the reference voltage vector V_r. Where V_r is given by the Eq. 6 below.

$$V_r = V_m \tag{6}$$

where V_m is the maximum value of the output phase voltage of the inverter.

Figure 4 also shows the switching states of the inverter which are used for the active voltage vectors ($V_1 - V_6$). In sector-1, the duty cycle for the switches S_1, S_5, S_6 (V_1) and S_1, S_2, S_6 (V_2) is given by reference vector V_r as shown in Eq. 7.

$$V_r = V_1 \frac{T_1}{T_s} + V_2 \frac{T_2}{T_s} + V_0 \frac{T_0}{T_s} \tag{7}$$

where T_s is the sampling time

Where V_0 or V_7 are the zero voltage vectors with switching states (000) or (111) respectively. The switching times T_1, T_2 and T_0 are given by Eq. 8, Eq. 9 and Eq. 10 as shown.

$$T_1 = \frac{\sqrt{3}}{V_{dc}} V_r \times T_s \times \sin\left(\frac{\pi}{3} - \theta_r\right) \tag{8}$$

$$T_2 = \frac{\sqrt{3}}{V_{dc}} V_r \times T_s \times (\sin \theta_r) \tag{9}$$

and

$$T_0 = T_s - T_1 - T_2 \tag{10}$$

where V_{dc} is the *dc* output voltage of the Rectifier.

By properly defining the angle θ_r, similar equations are obtained for other sectors (2 to 6).

Since the input *dc* voltage to the inverter is not constant as shown in Figure 2, the new switching sequence to the inverter is given by Eq. 11. and Eq. 12 for conventional IMC and modified IMC as shown below.

For conventional IMC , the switching sequence is

$$T_1' = T_1 \frac{T_p^R}{T_s},\ T_2' = T_2 \frac{T_p^R}{T_s},\ T_1'' = T_1 \frac{T_n^R}{T_s},\ T_2'' = T_2 \frac{T_n^R}{T_s} \text{ and } T_0 = T_s - (T_1 + T_2) \tag{11}$$

similarly, the new switching sequence for the modified IMC is given by

$$T_1' = \frac{T_1}{2}, T_2' = \frac{T_2}{2}, T_1'' = \frac{T_1}{2}, T_2'' = \frac{T_2}{2}, \text{ and } T_0 = T_s - (T1 + T_2) \quad (12)$$

By using this switching sequence for the inverter of the modified IMC, the output voltage distortion and the switching losses are minimised, because the number of switching devices required to turn ON and OFF for a given sampling period is also reduced.

By using Eq. 12 the modified switching sequence for the inverter of the modified IMC to obtain the specified V_r is given by Eq. 13.

$$V_r = V_1 \frac{T_1'}{T_s} + V_2 \frac{T_2'}{T_s} + V_0 \frac{T_0}{T_s} + V_1 \frac{T_1''}{T_s} + V_2 \frac{T_2''}{T_s} \quad (13)$$

Similar technique applied for the remaining sectors by properly choosing the voltage vectors and switching times.

4. PERFORMANCE OF IMC SUPPLYING POWER TO THE STATIC LOAD

The performance of the conventional IMC and modified IMC supplying power to the static load are compared. It is observed that the modified IMC has better performance compared to that of Conventional IMC at the load side. This can be analysed by taking the THDs of the load voltage and current for both the IMCs.

Figure 9 to Figure 12 shows the performance of modified IMC supplying power to static load (R = 10 Ω, L = 30 mH). Figure 9 and Figure 10 shows the power flow from Rectifier (50 Hz) to the Inverter (60 Hz). And Figure 11 and Figure 12 shows the power flow from Inverter (60 Hz) to Rectifier (50 Hz). The controls for both Rectifier and inverter for modified IMC are explained in Section-2 and Section-3. Here, Inverter is used to supply power to the static load at 60 Hz frequency.

The THDs for the load voltage and current are shown in the respective Figures.

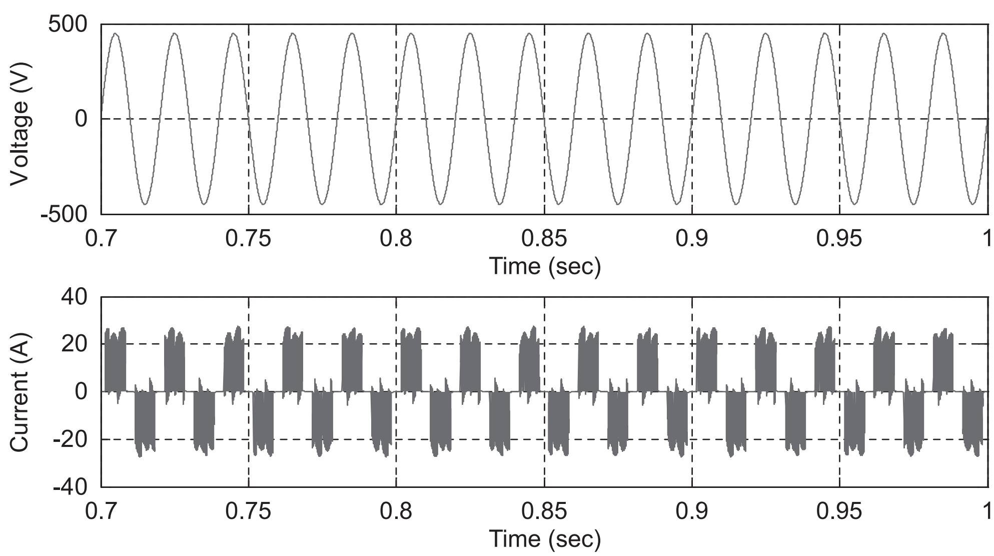

Figure 9: Rectifier input voltage and current (THD = 84.23%)

Similarly, Figure 13 to Figure 16 shows the performance of conventional IMC supplying power to static load (R = 10 Ω, L = 30 mH). The power flows in both directions. The THDs for the load voltage and current are shown in the respective Figures.

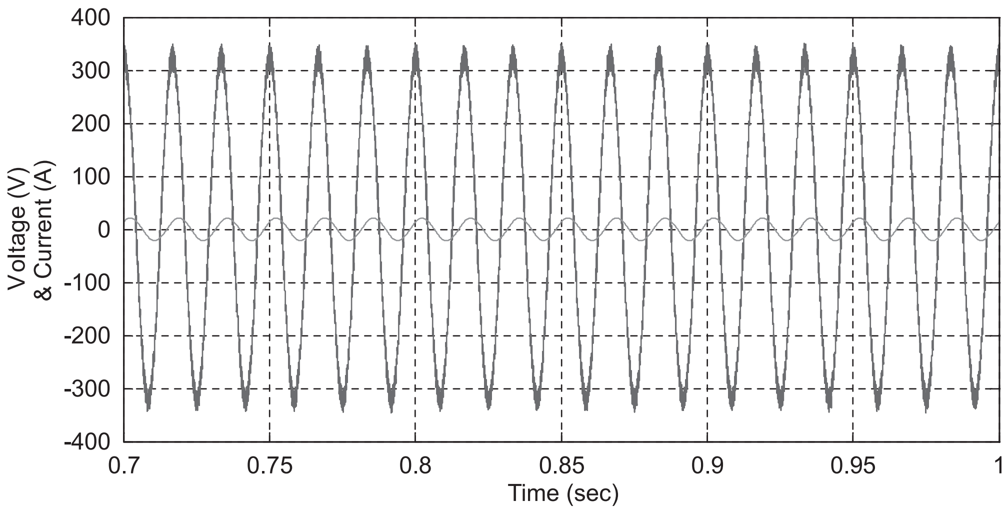

Figure 10: Inverter output voltage (THD = 5.07%) and current (THD = 0.16%)

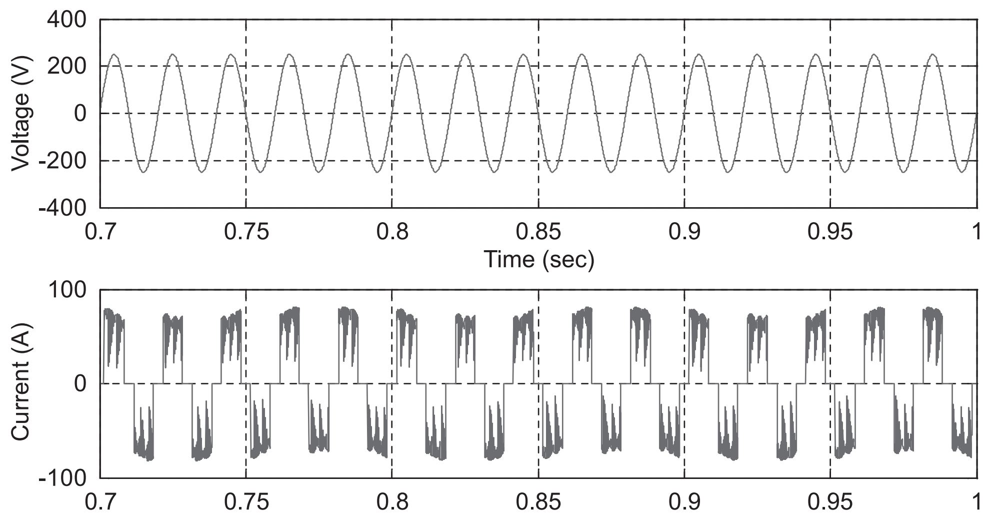

Figure 11: Rectifier output voltage and current (THD = 35.11%)

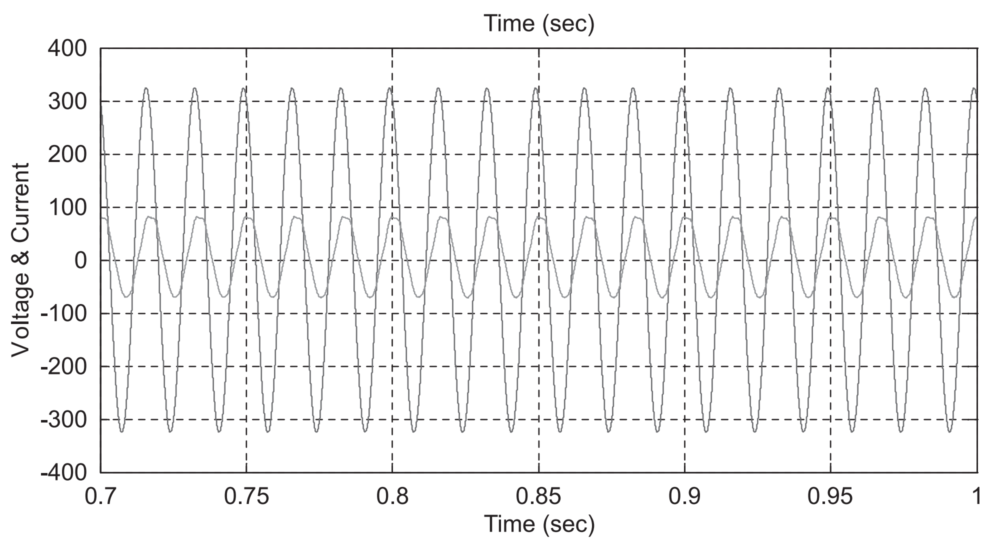

Figure 12: Inverter input voltage and current (THD = 3.89%)

Figure 10 and Figure 14 shows the Inverter side load voltage and current for both modified IMC and conventional IMC. From these it is observed that the distortions for load voltage (THD = 5.07%) and current (THD = 0.16%) for modified IMC are less compared to that of conventional IMC Load voltage

(THD = 8.14%) and current (THD = 0.84%). Here, the power flow is from Rectifier (50Hz) to inverter (60Hz) feeding power to the static load.

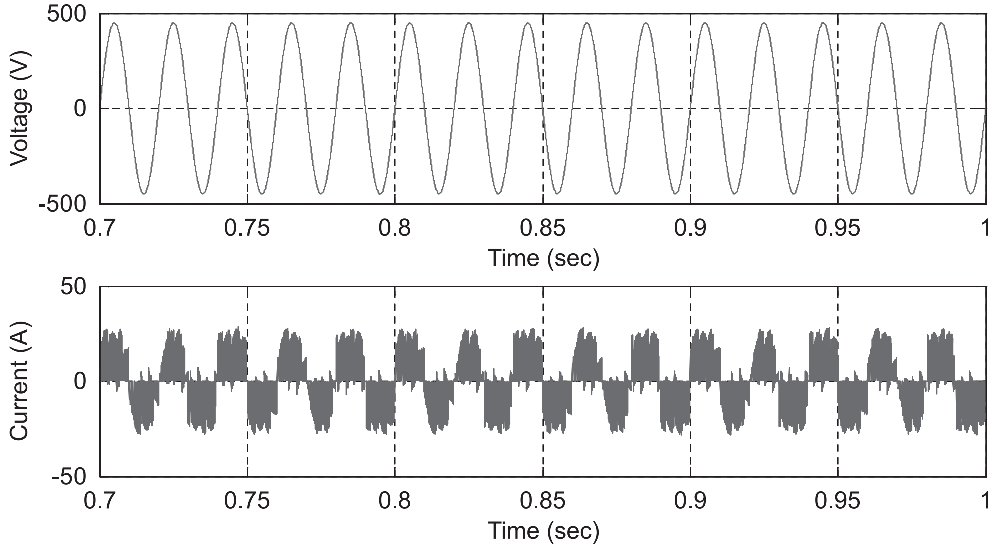

Figure 13: Rectifier input voltage and current (THD = 84.78%)

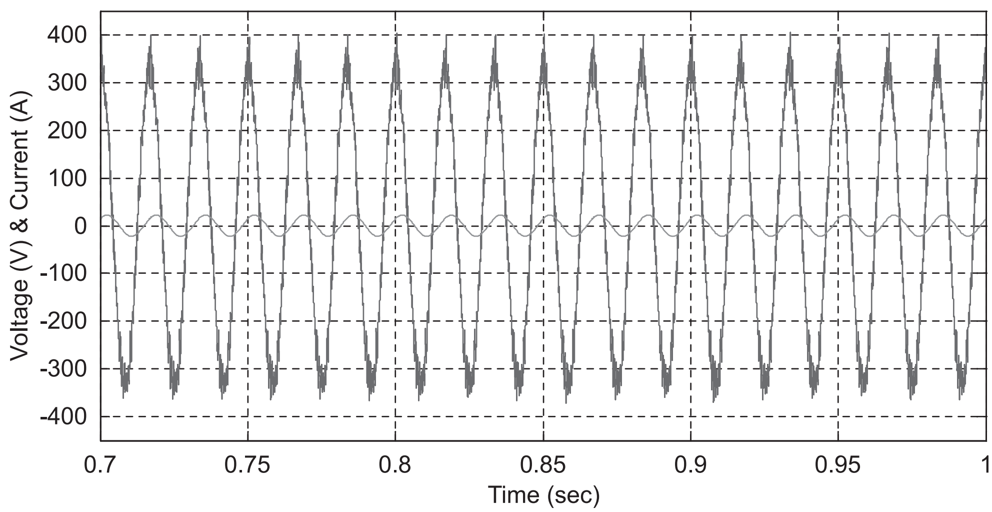

Figure 14: Inverter output voltage (THD = 8.14%) and current (THD = 0.82%)

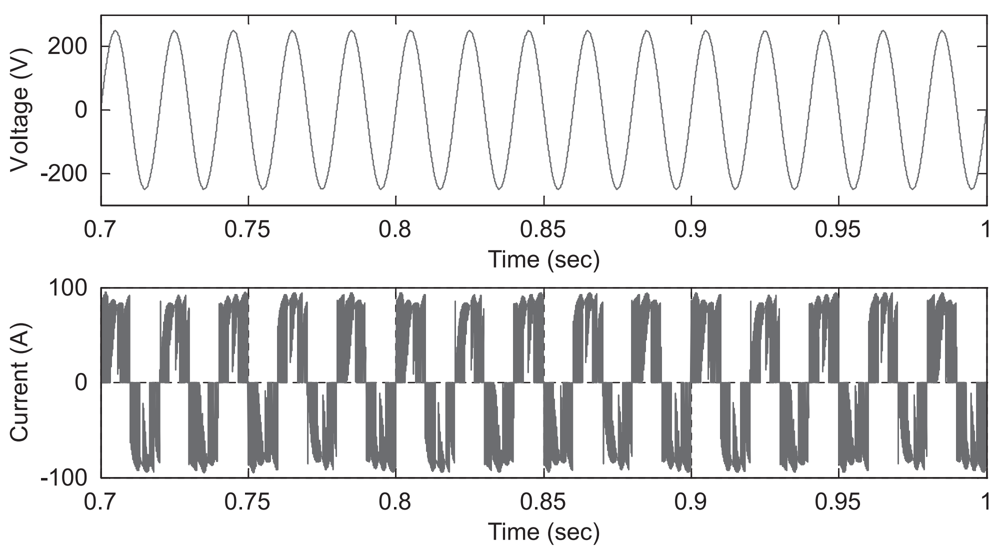

Figure 15: Rectifier output voltage and current (THD = 54.14%)

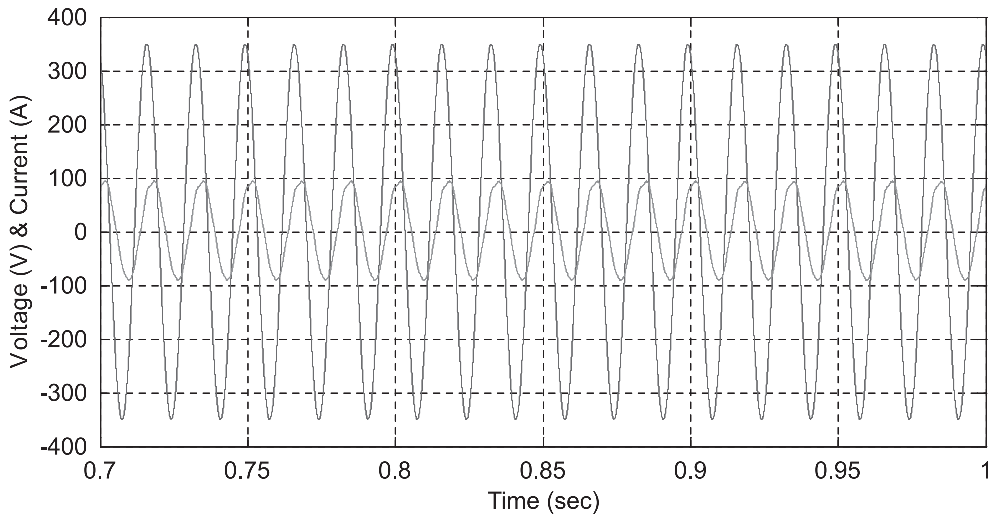

Figure 16: Inverter input voltage and current (THD = 3.98%)

Similarly, Figure 11 and Figure 15 shows the Rectifier side load voltage and current for both modified and conventional IMCs. Here also the distortions of load voltage and current (THD = 35.11%) for modified IMC are less compared to that of conventional IMC with load voltage and current (THD = 54.14%). Whereas in this case the power flow is from Inverter (60Hz) to Rectifier (50Hz). These results are compared shown in Table 3 below.

Table 3
Comparative Results for Conventional IMC and Modified IMC

S.No.	*Power Flow*	*Conventional IMC (THD's)*				*Modified IMC (THD's)*			
		Input Voltage	*Input Current*	*Output Voltage*	*Output Current*	*Input Voltage*	*Input Current*	*Output Voltage*	*Output Current*
1	Rectifier (50 Hz) to Inverter (60 Hz)	0.00%	84.78%	8.14%	0.82%	0.00%	84.23%	5.07%	0.16%
2	Inverter (60 Hz) to Rectifier (50 Hz)	0.00%	3.98%	0.00%	54.14%	0.00%	3.89%	0.00%	35.11%

5. CONCLUSION

A comparison between the modified IMC and conventional IMC is analysed in this paper. The modified IMC gives maximum *dc* link output voltage at the Rectifier as compared to that of conventional IMC. The performance of modified IMC and conventional IMC supplying power to static load in both directions of power flow is analysed and the distortions in load voltage and load current is compared for both the converters. Here, it is observed that the load voltage and load current distortions are less for modified IMC as compared with the conventional IMC. In all the above cases the fundamental input current of the Rectifier stage is kept at unity power factor for the power flow in both the directions.

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