PERFORMANCE OF INDIRECT MATRIX CONVERTER AS ASYNCHRONOUS LINK BETWEEN TWO AC SYSTEMS

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Abstract: *This paper discusses an Indirect Matrix converter(IMC) topology used to supply a three-phase load directly from three phase AC power source without using any large electrolytic capacitors in the intermediate dc link. The Indirect Matrix converter considered here, consists of an input stage and two output stages with a pair of voltage source inverters. An improved switching configurations is selected for the Inverters based on the output space vectors and its switching table is developed to minimise switching losses and output distortion. The dc link voltage for the rectifier stage is controlled by a new modulation technique to obtain maximum dc voltage with unity power factor (UPF) for the fundamental at the input side. The performance of IMC as an asynchronous link between two ac systems is proposed for different frequencies at the rectifier and inverter stages with bidirectional power flow. Also, the IMC is operated for multiple loads (active and passive loads)at variable frequencies. The performance of the IMC with the proposed modulation techniques are shown through simulation results.*

KEYWORDS: *UPF, Bidirectional power flow, Asynchronous link, Static load*

1. Introduction:

Due to the absence of energy storage elements in the dc stage, the Matrix converter power circuit is simple, cheap and reliable over the conventional rectifier/inverter systems. Through suitable control techniques the input power factor, output voltage and frequency can be controlled [1,3] . The virtual dc-link between input and output enables bi-directional power flow.

The Matrix converters (MC) are of two types: the direct matrix converter (DMC) and the Indirect Matrix converter (IMC). The IMC are more advantageous over DMC since it is possible to supply multiple loads at different voltages and frequencies at the output. The controllers for each of the output are independent whereas in the case of DMC the switching of the devices at the output depend upon the control of the switching devices at the input. Therefore, the DMC is not suitable for multiple outputs [4]. Further the control of IMC is much simpler that of DMC since the switching of output devices can be made independent of the input side switching [5,6].

Fig.1 shows the block diagram of an Indirect Matrix converter. The IMC is primarily divided into two stages that is Rectifier stage and Inverter stage. The rectifier stage consists of 6 bidirectional switches whereas the inverter stage consists 6 unidirectional switches [7,8,9]. The switching of devices in the rectifier stage is modulated to produce input current with fundamental unity power factor and keep the dc-link voltage positive. The inverter stage produces output voltages with variable amplitude and frequency. Filters are used at the input and output stages to reduce current distortion [10,11] .

In IMC, the modulation techniques for the two stages are relatively different from each other[7,9] .The switching devices at the input side of the IMC commutate using a simple modulation technique. Also, the output side of the IMC uses a new modulation strategy

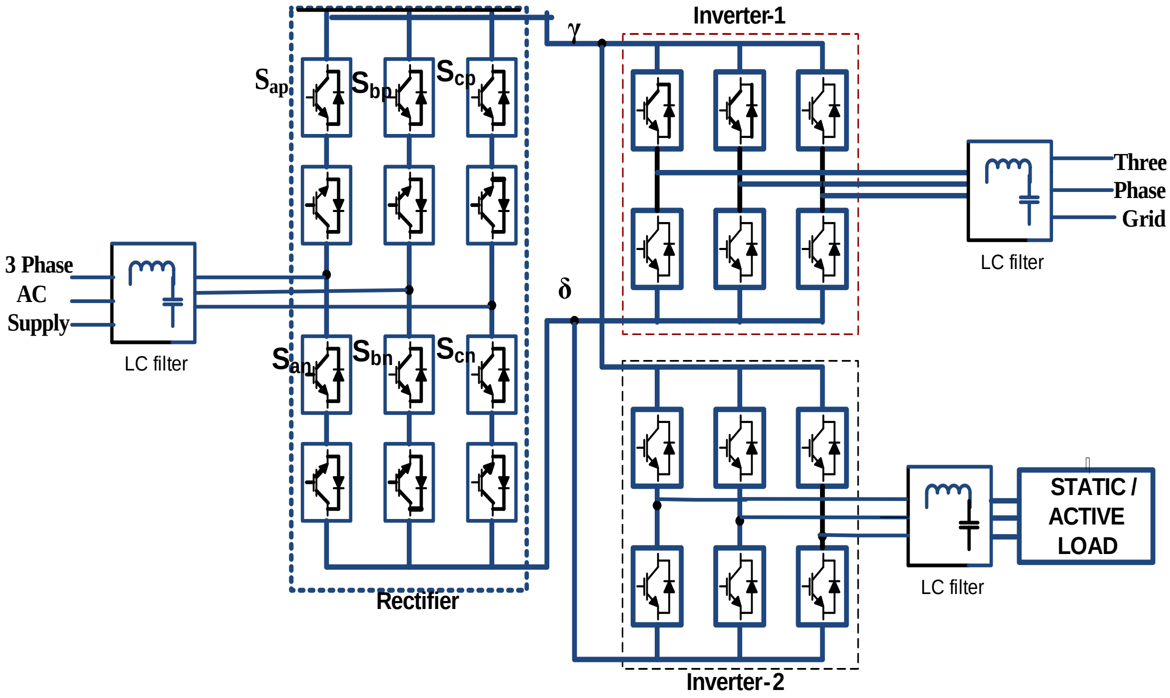

Fig 1: Block Diagram of IMC

different from that used in reference [8] to reduce the distortion in output voltage and input current. One of the disadvantages of Direct matrix converters(DMC) is its inability to supply multiple loads at different frequencies[4] since it is not having any virtual dc-link .But in the case of IMC due to its virtual dc-link capability , any number of inverters can be connected to the output of the Rectifier and hence, it can feed various loads at variable frequency. The proposed converter is used to supply both Active and passive loads at different frequencies .Also, in the proposed IMC , a new and simple technique different from that used in reference [8] to control the dc voltage from maximum to minimum by adding an offset value to the switching times of the Rectifier modulation control.

Asynchronous link for two ac systems means interconnection of systems operating at different frequencies . In the proposed IMC , the two ac systems are connected to Rectifier and the inverter stages with different operation is also discussed in Section-5. Section-6 gives the conclusions drawn.

2.0. Control Of IMC For The Rectifier Side:

The Rectifier stage of the IMC is controlled by the following modulation technique . Where the three phase supply voltages are given by

frequencies .Performance of the Asynchronous link using IMC is analysed in this paper for bidirectional power flow control, with unity power factor for the fundamental at the Rectifier side.

The principle of operation of the IMC topology is explained in the following sections. In section-2, the control logic for proposed IMC is discussed where Rectifier stage with the new modulation technique for increasing or decreasing the DC-link voltage is proposed. The performance of Rectifier alone with the proposed modulation technique is discussed in section-2. In section-3 a new switching pattern at the output stage by considering modulation of the input stage is introduced to reduce distortion of the output voltage and switching losses. Section-4 discusses the performance of the IMC as an Asynchronous link between two ac systems of different frequencies. Also, the ability of IMC to supply a static load in addition to the asynchronous

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

$v_b = V_m \sin(\omega t - 2\pi/3)$

$v_c = V_m \sin(\omega t + 2\pi/3)$

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

Table:1

Switching states						
S_{ap}	S_{an}	S_{bp}	S_{bn}	S_{cp}	S_{cn}	Voltage vectors
0	0	0	1	1	0	V_{cb}
1	0	0	1	0	0	V_{ab}
1	0	0	0	0	1	V_{ac}
0	0	1	0	0	1	V_{bc}
0	1	1	0	0	0	V_{ba}
0	1	0	0	1	0	V_{ca}

Table 1 shows the Rectifier stage having six active voltage vectors $V_{\gamma\delta}$ which appear at the output as shown in fig 1.The six switches S_{ap}-S_{cn} are also shown in fig.1.A reference vector is generated which is in phase with the voltage v_a rotating at input supply frequency. In case of sector-1 the angle θ_{in} (=ωt)of the reference vector changes from 0-π/3 with respect to voltage V_{cb}. At time t=0, θ_{in} is 0. Refer to fig.2

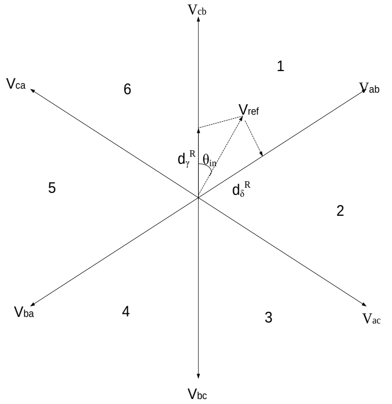

Fig.2. The sector identification and its voltage vectors for rectifier stage

In this sector the input phases "a" and "c" are connected to the positive output dc pole γ and the input phase "b" is connected to the negative pole δ of the dc link. By the switching sequence shown in Table:1 active voltage vectors, V_{cb} and V_{ab} derived from the input phases "a" and "c" are connected to the Rectifier output with the following duty cycle [8]. The modulation cycle used here as per Eqs:(1) and (2)given below is to obtain maximum dc voltage for specified ac input voltages to Rectifier and to ensure unity power factor for fundamental component of the input current. These equations are same as those used in reference [8]. However these equations are modified as explained in the following sub section 2.1 to get variable dc output voltage.

$$d_\gamma^R = \frac{\sin(\frac{\pi}{3} - \theta in)}{(\sin(\frac{\pi}{3} - \theta in) + \sin(\theta in))}$$

$$d_\delta^R = \frac{\sin(\theta in)}{(\sin(\frac{\pi}{3} - \theta in) + \sin(\theta in))}$$

$$d_\gamma^R + d_\delta^R = 1 \qquad \text{....................(1)}$$

The switching times T_1^R and T_2^R for the voltages V_{cb} and V_{ab} are given by the Eq (2) :

$$T_1^R = T_s * d_\gamma^R$$

$$T_2^R = T_s * d_\delta^R$$

$$T_1^R + T_2^R = T_s \qquad \text{.....................(2)}$$

where T_s is the sampling time interval used for simulation .

The angle θ_{in} is given by ω*t where t is the time and is incremented for each time step by $\Delta\theta_{in} = \omega * T_s$

As the reference vector moves into sector- 2 to sector -6 the duty cycles d_γ^R and d_δ^R are calculated for each sector using Eq:(3)

$$d_\gamma^R = \frac{\sin(\frac{n\pi}{3} - \theta in)}{\sin(\frac{n\pi}{3} - \theta in) + \sin(\theta in - \frac{(n-1)\pi}{3})}$$

$$d_\delta^R = \frac{\sin(\theta in - \frac{(n-1)\pi}{3})}{\sin\left(\frac{n\pi}{3} - \theta in\right) + \sin(\theta in - \frac{(n-1)\pi}{3})} \qquad \text{............(3)}$$

where n is the sector number.

Table:2 gives the sector-wise voltages appearing at the Rectifier output. Voltages in column 3 are applied for a time T_1^R and the voltages in column 4 are applied for T_2^R . The corresponding Rectifier output voltage on no-load is shown in fig:3. For an input voltage v_a=312 sin 314t, the average output dc voltage is found to be 493v.

Table:2

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

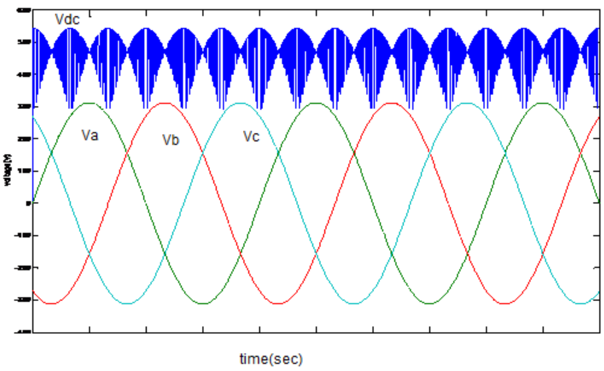

Fig.3. Three phase voltages and the DC link voltage (V_{dc})

The performance of Rectifier with a Resistive load (R=100Ω) for the same input voltage and modulation method the input current and voltage for phase "a" is shown in fig. 4. The input fundamental power factor is unity and the THD of the current is 10.93%

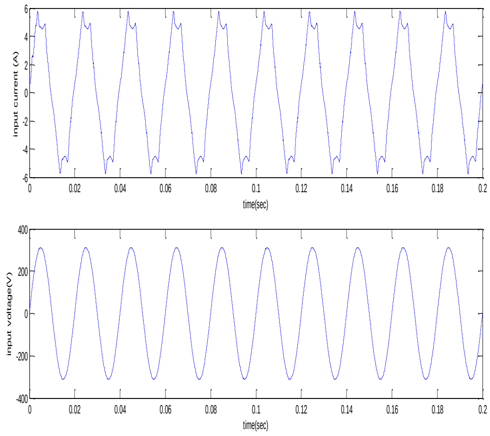

Fig.4. input current and phase voltage

2.1.Control of Dc- Link Voltage At The Rectifier Stage:

The dc voltage of the input stage of IMC is controlled by adding an offset to the switching times T_1^R and T_2^R calculated as per Eq.(2) for each sector. Unity power factor at the input is maintained for the fundamental while varying the average output dc voltage .

The new switching times are given by Eq:(4)

$T_1^{R'} = T_1^R + KN$

$T_2^{R'} = T_1^R - KN$ ....(4)

where K is an integer multiple of T_s.

The variable N is given by Eq :(5),

From $(n-1)\frac{\pi}{3} \le \theta_{in} < \frac{\pi}{6}+(n-1)\frac{\pi}{3}$, N=1

$\theta_{in} = \frac{\pi}{6}+(n-1)\frac{\pi}{3}$, N=0

$\frac{\pi}{6}+(n-1)\frac{\pi}{3} < \theta_{in} \le \frac{\pi}{3}+(n-1)\frac{\pi}{3}$, N=-1

............(5)

where n is the sector number

And, the following logic is used to ensure $T_1^{R'}$ and $T_2^{R'}$ are not negative

if $T_1^{R'}$ as per Eq:(4) is more than T_s, then $T_1^{R'}$ equal to T_s

if $T_1^{R'}$ is less than zero then $T_1^{R'} = 0$

Accordingly $T_2^{R'}$ is obtained as $T_s - T_1^{R'}$

The sum of the new switching times $T_1^{R'}$ and $T_2^{R'}$ is always equal to T_s.

The variation of average output dc voltage for different values of K , for the same ac input voltage and the load is shown in fig.5a. In fig.5b. for the value of K=0.1, the dc voltage of the rectifier and the input current for the same load of R=100 ohms and input ac voltage of v_a= 312 sin(ωt) are shown. The THD of the input current is found to be 17.73%.

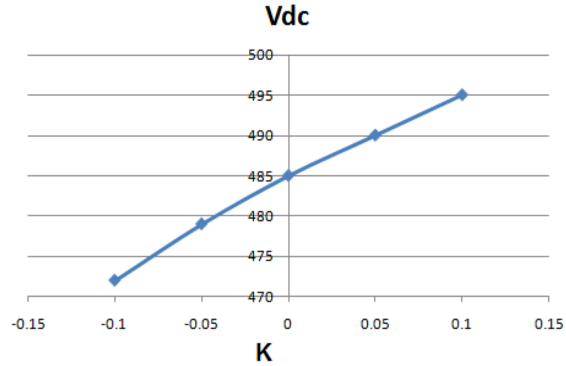

Fig.5a.Average dc voltage for different values of K

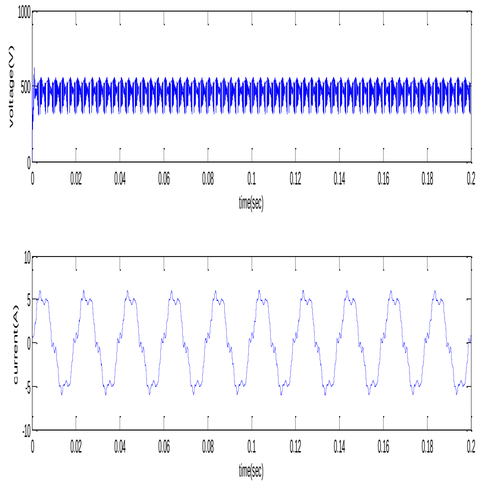

Fig.5b. Rectifier dc voltage and input current for k=0.1

Table.3 gives the THD of The Rectifier input current for different values of K

Table:3

K	Average dc voltage (volts)	THD of the input current
-0.1	471.7	11.99%
-0.05	478.1	9.89%
0.0	484.5	10.93%
0.05	490.3	14.15%
0.1	495.0	17.73%

Another method for controlling the dc voltage of the Rectifier is given by adding sinusoidally varying offset value K to the switching times $T_1^{R'}$ and $T_2^{R'}$. The new switching times are given in Eq:(6)

$T_1^{R'} = T_1^R + K\sin 6\,\theta_{in}$

$T_2^{R'} = T_1^R - K\sin 6\,\theta_{in}$ ....(6)

The main disadvantage of the second modulation method is that the dc voltage is not varying much for different values of K and the corresponding THD of the input current is found to be very high. Hence, first method is used for performance analysis of IMC in this paper.

3.0. Control Of Inverter Stage:

The inverter is controlled using Space Vector Modulation(SVM) technique. Fig.6. shows the the six active voltage space vectors V_1-V_6 and the two zero voltage vectors V_0 obtained through switching of the inverter [8]. The switching times of these space vectors depend upon the position of reference space vector V_r indicated in Fig.6. For SVM control, T_1 ,T_2 are the switching times for active voltage vectors V_1 and V_2 and T_0 is the switching time for the zero voltage vector V_0 in sector-1 .The reference voltage V_r is given by Eq:(7)

$V_r=V_m\cos(\theta)$

$\theta=\omega_0 t+\varphi$ ....(7)

where V_m and φ are chosen depending upon the requirement of power flow from inverter to the ac grid (refer to fig:1) ω_0 is the ac grid frequency. In the case when the inverter is connected to static or dynamic loads V_m and ω_0 correspond to the specified load voltage and frequency. As shown in fig.1. an improved T filter configuration is used at the output of the inverter.

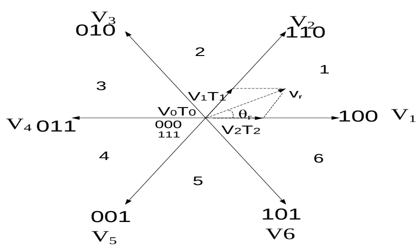

Fig.6: Space vector diagram of inverter stage

The space vectors V_1-V_6 shown in fig.6. are obtained from the switching states of the inverter. The switching states of the inverter for the different space vectors is also shown in fig.6. State 1 refers to the corresponding phase being connected to positive dc terminal and state zero corresponds to the phase being connected to the negative dc terminal. Depending on the location of V_r in the sectors 1 to 6 the corresponding adjacent vectors are used for the SVM control to generate the reference space vector V_r . The following duty cycle given by Eq:(8) for sector -1 is used

$V_r T_s=V_1 T_1+ V_2 T_2+V_0 T_0$ ....(8)

where V_0 correspond to zero states 7 and 8 of the inverter given by the switching states 111 or 000. In the above Eq.(8) T_1 ,T_2, T_0 are given by Eq:(9). The sum of $T_1+T_2+T_0=T_s$.

$T_1 =\frac{\sqrt{3}.Vr}{Vdc}\, T_s \sin(\frac{\pi}{3}-\theta)$

$T_2=\frac{\sqrt{3}.Vr}{Vdc}\, T_s \sin \theta$

$T_0= T_s- T_1-T_2$ ....(9)

where Vdc is the Rectifier output dc voltage

Similar equations can be obtained for the other sectors 2 to 6 by properly defining the angle θ.

Since the input dc voltage (V_{dc}) of the inverter is varying during each sampling interval T_s due to the switching cycle for the Rectifier, in order to reduce the output voltage distortion the duty cycle consisting of T_1,T_2 ,T_0 as given by Eq:(9) for the corresponding space vectors are modified in each sector in the proposed new SVM technique proposed here for the inverter output voltage control . The modified duty cycle is given by Eq:(10)

$T_1'=T_1 d_\gamma^R$, $T_2'=T_2 d_\gamma^R$, $T_1''= T_1 d_\delta^R$, $T_2''= T_2 d_\delta^R$ and $T_0=T_s-(T_1+T_2)$ ....(10)

$T1= T_1'+T_1''$ and $T_2= T_2'+T_2''$

where d_γ^R and d_δ^R are obtained from Eq:(3)

To reduce the switching losses in the inverter the following sequence shown in fig.7. for the duty cycle of the space vectors in each sector is used.

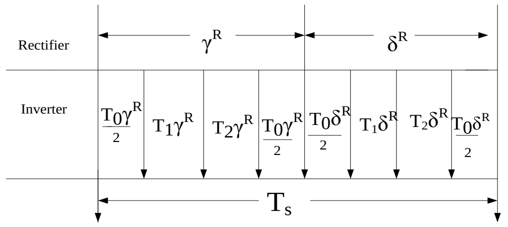

Fig.7: switching pattern for both Rectifier and Inverter stages

Fig.8.shows the output load voltage and current from the inverter operating at 45 Hz with an inductive load of R=10Ω ,L=10mH and the reference voltage V_r=312 volts. The THD of the voltage is 8.67% and that of current is 4.29%.

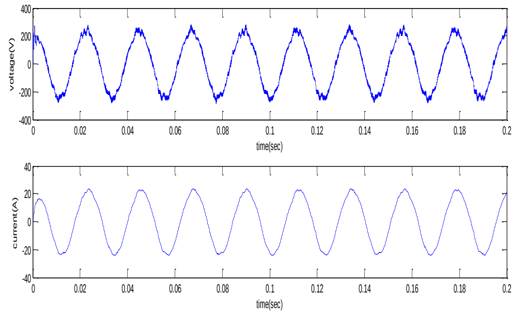

Fig.8.Inverter output load voltage and current at 45 Hz

4.0. Indirect Matrix Converter As An Asynchronous Link:

IMC as an asynchronous link means ,the two ac systems which are interconnected are operating at different frequencies. That is, the Rectifier stage is operated with one frequency and the inverter output voltage source is operated at different frequency. The power flow is bidirectional with the rectifier side controlling the dc voltage and its controller maintains unity power factor for the fundamental at the input of Rectifier. The reference voltage V_r for the inverter is adjusted in magnitude and phase angle to control the power flow between the inverter and the AC grid . The schematic diagram is shown in fig.9. The Rectifier control is as per the Eq.(3). Details are discussed in section 2.For the inverter control Eq.(9) is used and the details are discussed in section 3.

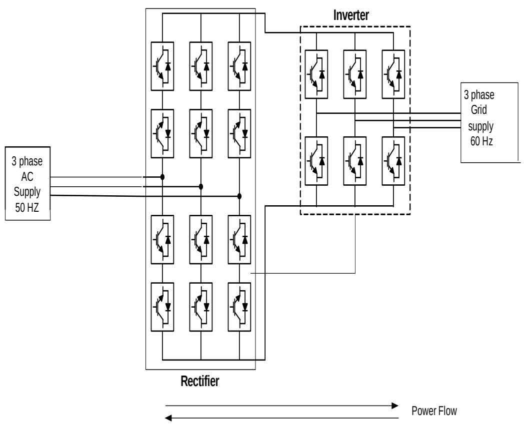

Fig.9. Asynchronous link for IMC

The performance of the IMC as an Asynchronous link between two ac systems operating at 50Hz on Rectifier side and 60 Hz on Inverter side is analysed .Fig.10 and fig.11 show the voltage and current waveforms at the Rectifier input and Inverter output and the power flow of 7.88kw is from 50 Hz system to 60 Hz system. Figures 12 and 13 show the corresponding waveforms for the power flow of 8.3kw from Inverter to Rectifier side. The THD for the Rectifier and Inverter currents are indicated in the figures.

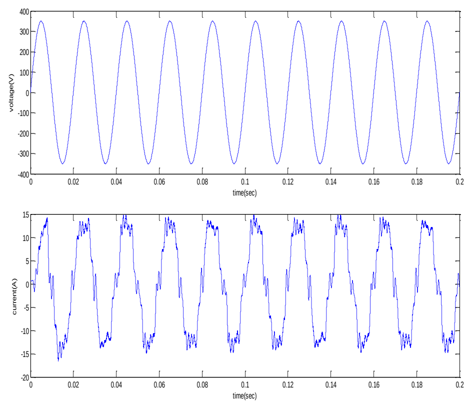

Fig.10.Rectifier input voltage and input current with THD=13.09%

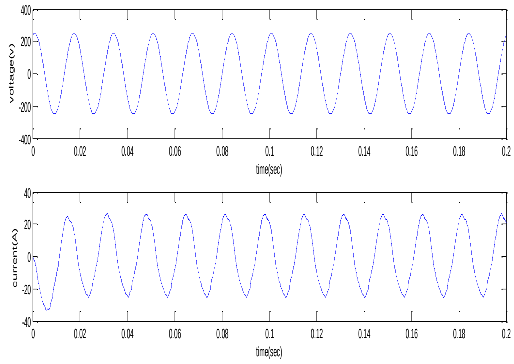

Fig.11.Inverter output voltage and output current with THD=8.02%

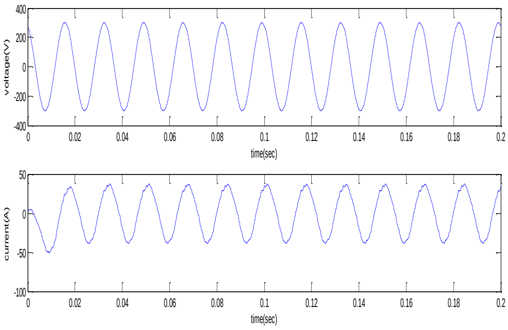

Fig.12.Inverter input voltage and current with THD=6.39%

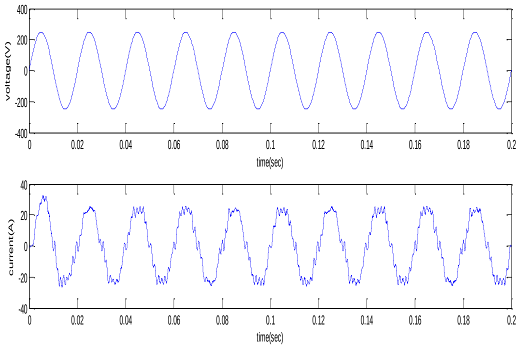

Fig.13.Rectifier output voltage and current with THD=17.14%

5.0. Performance Of IMC Supplying Power To Static Load In Addition To The AC Grid:

The schematic diagram for this application of IMC is shown in fig.1. The Rectifier side frequency is 50Hz and the input voltage is v_a= 350sinωt . The Rectifier control is as per Eq.(3).This ensures UPF for the fundamental input current. The first inverter is connected to the ac grid of frequency 60 Hz and voltage v_A=250cosω_it. The Reference voltage V_r for the inverter control using Eqs:(9) and (10) is adjusted for power flow of 13.4kw from Rectifier to Inverter side. The switching sequence used for the switching devices in the inverter-1 and inverter-2 is as per Fig.7. to reduce the switching losses.Inverter-2 is used to supply power to the static load of R=10Ω and L=10mH at frequency 45 Hz. Same controls are used for both Inverters derived from Eqs:(9) and (10).

Fig.9. shows the resulting Rectifier input current waveform. Fig.10.shows the Inverter-1 output current waveform and Fig.11. shows Inverter-2 voltage and current. The corresponding THD values are also indicated in the figures.

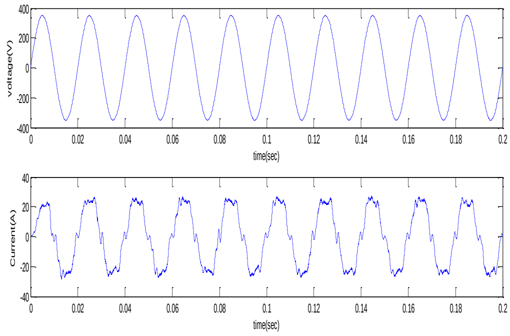

Fig.9. Rectifier input voltage and current with THD= 16.21%

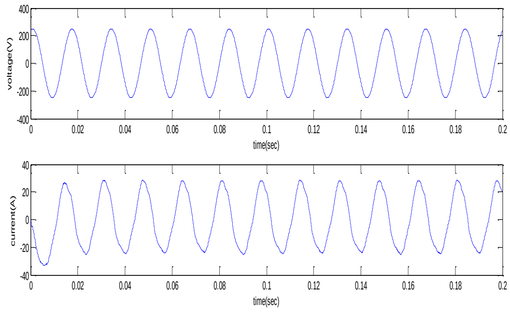

Fig.10. Inverter-1 output voltage and current with THD= 10.21%

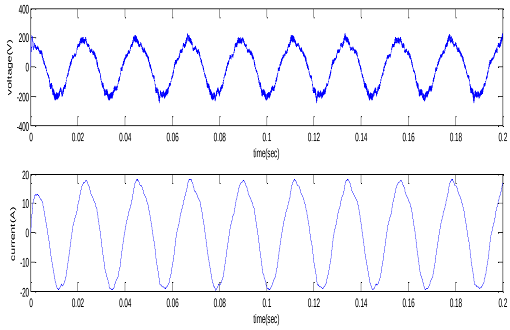

Fig.11. Inverter-2 voltage with THD= 14.27% and current with THD= 9.65%

6.0. CONCLUSION:

IMC with a new modulation strategy at the Rectifier stage to control the dc voltage from maximum to minimum with constant AC input voltage and maintain unity power factor for the fundamental input current has been proposed and a new switching pattern for the Inverter stage to reduce output voltage distortion and switching losses is discussed. The performance of the IMC as an Asynchronous link between two ac systems of different frequencies with bidirectional power flow has been analysed. The performance of the IMC with the new modulation techniques proposed are shown through simulation results for various modes of operation. The performance of the IMC supplying power to multiple loads operating at different frequencies is also studied. From the performance analysis it is observed that the THD levels of output currents of inverters are within the acceptable limits but the Rectifier input current has a higher THD level inspite of using a filter . Hardware implementation of the IMC with one Rectifier and two inverters supplying a static and a dynamic load at different frequencies is under progress. The proposed control techniques for Rectifier and inverter discussed in this paper will be used for the hardware model of the IMC.

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