

## Single phase to three phase ac Matrix Converter for Traction Drives

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**Abstract:** The paper presents the converter topology for single to three phase matrix converter for the ac traction drives. The converter analysis is presented with source separation and link approach. The conventional carrier based control is employed for the converter to control the output voltage and frequency. The operational feasibility with the three phase ac traction motor (850 kW) is presented. The performance of the converter with the motor is simulated in the PSIM. The results indicate the feasibility of the matrix converter application to retrofit the existing (AC-DC-AC) to (AC-AC) traction drive system.

**Index Terms:** Matrix Converters, Sinusoidal Pulse Width Modulation, Traction Motors, Variable Speed Drives.

### I. Introduction

Electric traction in most of the country have single phase 25 kV, 50 Hz AC or 3kV DC power supply systems. The conventional locomotives have a transformer with a tap changer or a step-down transformer with semiconductor devices, like power diodes, GTOs, IGBTs, etc.

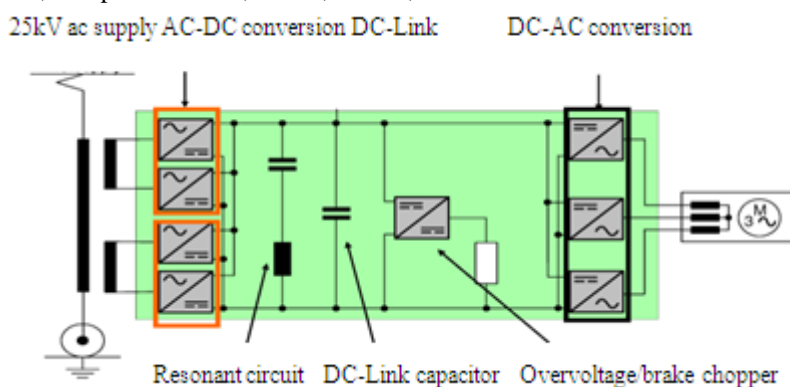


Fig. 1: Conventional Single-to-three phase ac Traction.

Those are used for ac- to- dc and dc-to-three-phase ac power conversion and to charge the intermediate dc-link capacitors for energy storage elements. The locomotives have Bo-Bo (4-TM on 4 axles) or Co-Co (6-TM on 6 axles) type bogie arrangements. The traction motor (TM) is a three phase induction motor operated with variable voltage and frequency converter in conventional speed control mode as shown in figure 1.

The converter without dc link will be preferred over the two stage ac-dc-ac conversion in the existing power conversion arrangements in the ac traction drives. The matrix converters (MC) is a direct ac-to-ac converter, replaces the multiple conversion stages and the intermediate energy storage elements (dc-link) thus being a single stage converter as shown in figure 2. The different topologies, single phase to single phase and three phase to three phase with bi-directional switches are analyzed and results are presented [1]-[2]. The phase transformation from single to three phase with three legged six bi-directional switch converter having simple control given for the three phase balanced loads [3]-[6]. This control suffers lower voltage utilization and requires additional matching transformer. The matrix converter topology could be analyzed through the separation and link technique [4]. This analysis incorporates the back-to-back common emitter bi-directional switch cells configuration is shown in figure 2 with fictitious dc link to understand the operation of matrix converter [5].

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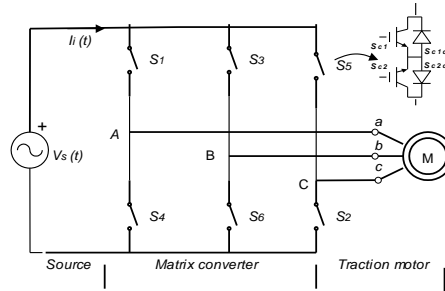


Fig. 2: Proposed single-to-three phase ac Traction converter.

The paper proposes the single phase to three phase matrix converter topology for traction drives. The operation of the converter is analyzed using the separation and link approach. The control is built by using the sinusoidal pulse width modulation (SPWM) for the bi-directional switches in this converter. This single phase to three phase converter has following merits.

- This replaces the conventional ac-dc-ac stages so the effective energy conversion is efficient.
  - The control is conventional carrier based SPWM.
- The known pattern of harmonics predicts the de-rating and operational efficiency of the induction motor.

## II. Matrix Converter Analysis

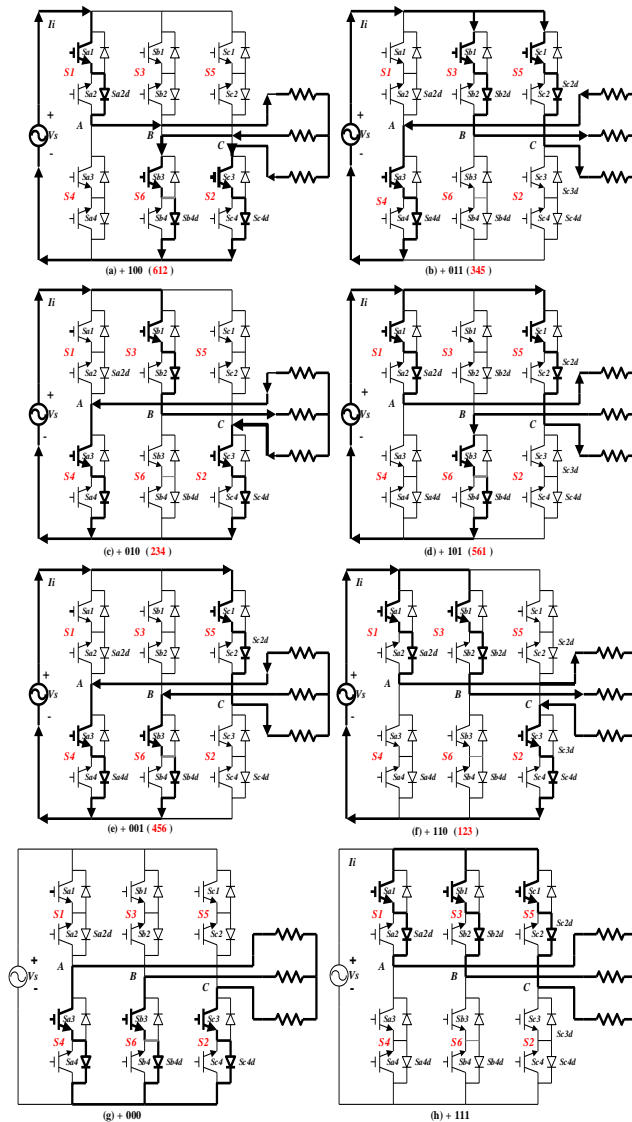
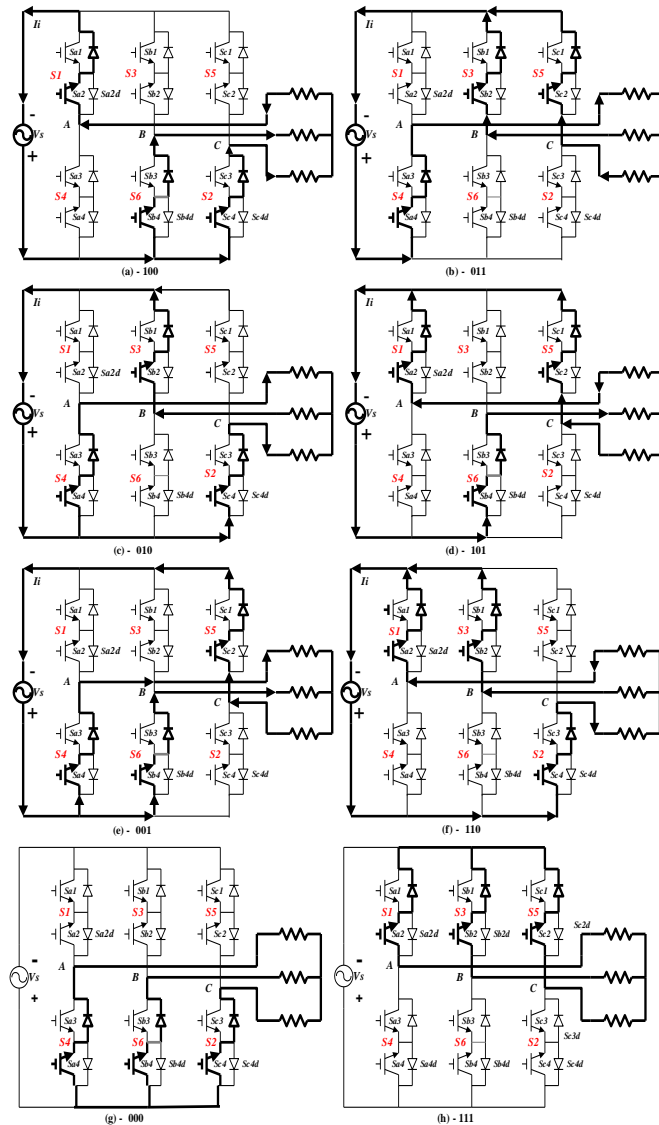


Fig.3 (a): Operation states for single to three phase matrix converter for Positive source period.



**Fig.3 (b):** Operation states for single to three phase matrix converter for Negative source period.

The single stage ac-ac converter for single phase to three phase ac conversion with six bi-directional switches are  $S1(Sa1, Sa2), S2(Sc3, Sc4), S3(Sb1, Sb2), S4(Sa3, Sa4), S5(Sc1, Sc2)$  and  $S6(Sb3, Sb4)$  is analyzed with separation and link method. The separation in Source positive period is shown in figures 3(a) and the separation in Source negative period in figures 3(b) and which are then linked, found equal to the results of the 1-3MC circuit. The sine pulse width modulation (SPWM) control technique is used to obtain the desired output results of single-to-three phase ac matrix converter.

Figure 2 configuration is the adopted configuration of the single phase to three-phase ac matrix converter. In one source voltage period can be divided into two source voltages. One is bigger than zero called positive source period and other is less than zero is negative source period. The single to three phase ac matrix converter can be regarded as two equivalent circuits.

Take A-phase for example, when the source voltage  $V_s$  during positive period, following the principle of no short circuit for source side switches  $S_{a1}$  &  $S_{a3}$  must not be ON at the same time and no open circuit for load side one of the switches  $S_{a1}$  and  $S_{a3}$  must be ON. Considering the resistive load, when switch  $S_{a1}$  is ON and  $S_{a3}$  is OFF then switch  $S_{a2}$  must be ON to provide path for current through its diode from source to load. Similarly, when switch  $S_{a1}$  is OFF and  $S_{a3}$  is ON then switch  $S_{a4}$  should be ON to provide path for current flow through its diode from load to source.

When the source voltage  $V_s$  is in the positive period, the switches  $S_{a1}, S_{a3}$  &  $S_{b1}, S_{b3}$  &  $S_{c1}, S_{c3}$  should be controlled to keep energy flowing from source to load and switches  $S_{a2}, S_{a4}$  &  $S_{b2}, S_{b4}$  &  $S_{c2}, S_{c4}$  are kept ON through its diodes to provide the current path from source to load whenever necessary.

When the source voltage  $V_s$  is in negative period, the single to three phase ac matrix converter is simplified to the configuration shown in figure 3(b) with the same analysis as that in the source positive periods,

the switches  $S_{a2}$ ,  $S_{a4}$  &  $S_{b2}$ ,  $S_{b4}$  &  $S_{c2}$ ,  $S_{c4}$  should be controlled to keep energy flowing from load to source and switches  $S_{a1}$ ,  $S_{a3}$  &  $S_{b1}$ ,  $S_{b3}$  &  $S_{c1}$ ,  $S_{c3}$  are kept ON through its diodes to provide the current path from load to source whenever is necessary.

There are total 16-operating states shown in TABLE-I for one complete cycle of operation. The six operating states (+100 to +110) and two null states (+000 and +111) during source positive period are shown in figure 3(a). Similarly, we can draw another six operating states (-100 to -110) and two null states (-000 and -111) for source negative period, but the direction of current flow should be reversed are shown in figure 3(b). Similarly, all analysis for phase B and C is adopted.

**Table-I: Switching Operation States For 1-3MC**

States	$V_{ab}$	$V_{bc}$	$V_{ca}$	Switching Operation
+(100)	$V_s$	0	$-V_s$	$S_{a1} S_{a2d} S_{b3} S_{b4d} S_{c3} S_{c4d}$
+(101)	$V_s$	$-V_s$	0	$S_{a1} S_{a2d} S_{b3} S_{b4d} S_{c1} S_{c2d}$
+(001)	0	$-V_s$	$V_s$	$S_{a3} S_{a4d} S_{b3} S_{b4d} S_{c1} S_{c2d}$
+(011)	$-V_s$	0	$V_s$	$S_{a3} S_{a4d} S_{b1} S_{b2d} S_{c1} S_{c2d}$
+(010)	$-V_s$	$V_s$	0	$S_{b1} S_{b2d} S_{a3} S_{a4d} S_{c3} S_{c4d}$
+(110)	0	$V_s$	$-V_s$	$S_{a1} S_{a2d} S_{b1} S_{b2d} S_{c3} S_{c4d}$
+(000)	0	0	0	$S_{a3} S_{a4d} S_{b3} S_{b4d} S_{c3} S_{c4d}$
+(111)	0	0	0	$S_{a1} S_{a2d} S_{b1} S_{b2d} S_{c1} S_{c2d}$
-(100)	$V_s$	0	$-V_s$	$S_{b4} S_{b3d} S_{c4} S_{c3d} S_{a2} S_{a1d}$
-(101)	$V_s$	$-V_s$	0	$S_{b4} S_{b3d} S_{a2} S_{a1d} S_{c2} S_{c1d}$
-(001)	0	$-V_s$	$V_s$	$S_{a4} S_{a3d} S_{b4} S_{b3d} S_{c2} S_{c1d}$
-(011)	$-V_s$	0	$V_s$	$S_{a4} S_{a3d} S_{b2} S_{b1d} S_{c2} S_{c1d}$
-(010)	$-V_s$	$V_s$	0	$S_{a4} S_{a3d} S_{c4} S_{c3d} S_{b2} S_{b1d}$
-(110)	0	$V_s$	$-V_s$	$S_{c4} S_{c3d} S_{a2} S_{a1d} S_{b2} S_{b1d}$
-(000)	0	0	0	$S_{a4} S_{a3d} S_{b4} S_{b3d} S_{c4} S_{c3d}$
-(111)	0	0	0	$S_{a2} S_{a1d} S_{b2} S_{b1d} S_{c2} S_{c1d}$

‘1’ Upper arm switch ON, ‘0’ Lower arm switch ON  
 ‘+’ period source voltage, ‘-’ period source voltage  
 Subscript ‘d’ denotes diode to that switch.

Considering the states of the controlled switches, it can be defined as,

$$S_{xn} \left( \begin{matrix} x = a, b, c \\ n = 1, 2, 3, 4 \end{matrix} \right) = \pm \begin{cases} '1' \text{ the upper arm switch is ON} \\ '0' \text{ the lower arm switch is ON} \end{cases}$$

where ‘+’ denotes the source positive period and ‘-’ denotes the source negative period.  $S_{x1}$ ,  $S_{x2}$ ,  $S_{x3}$  and  $S_{x4}$  are the controlled switches of the three phases A, B and C respectively. The subscript ‘d’ denotes the anti-parallel diodes to that switches written as  $S_{x1d}$ ,  $S_{x2d}$ ,  $S_{x3d}$  and  $S_{x4d}$  as shown in TABLE-I.

### III. SPWM Control Of Matrix Converter

When sine pulse width modulation (SPWM) is adopted, as usual, the analysis for conventional converter, the switch control signals for single phase to three phase ac matrix converter can be understood from figure 4. Suppose  $A = 1$  denotes the source is during the positive period and  $A = 0$  denotes the source is during the negative period.  $B = 1$  denotes SPWM signal is positive and  $B = 0$  denotes SPWM signal is zero. The switch controls signal are shown in TABLE-II are deduced from Figure 5. Take A-phase generation, for example,  $x = a$ , during the source positive or negative periods. Switches  $S_{a1}$ ,  $S_{a2}$ ,  $S_{a3}$  and  $S_{a4}$  are controlled with SPWM signals and its anti-parallel diodes  $S_{a1d}$ ,  $S_{a2d}$ ,  $S_{a3d}$  and  $S_{a4d}$  will provide current paths as and when needed.

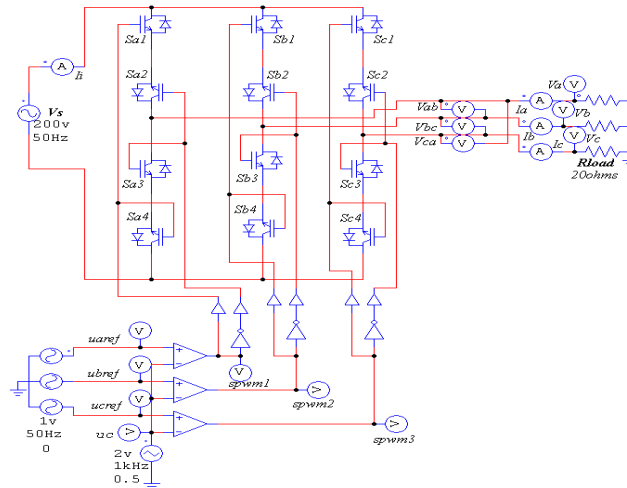


Fig.4: Single -to- three phase MC with R-load.

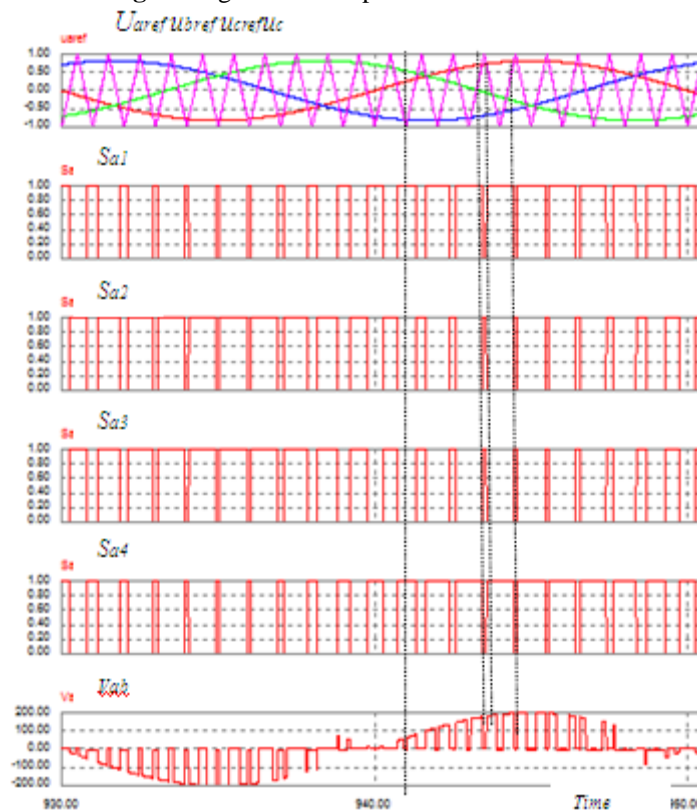


Fig.5: Output voltage  $V_{ab}$  - SPWM control at  $f_c = 1kHz$

Table-II: Switch Controls Signal For 1-3 MC

SWITCH $S_x$ ( $x = a, b, c$ )	PWM switching signals			
	A=1 B=1	A=1 B=0	A=0 B=1	A=0 B=0
$S_{x1}$	1	0	0	1
$S_{x2}$	0	1	1	0
$S_{x3}$	0	1	1	0
$S_{x4}$	1	0	0	1

The results of line voltage  $V_{ab}$  are obtained as shown in Figure 5 and also the same results can be obtained for other phase  $B$  and  $C$ .

#### IV. Operation With A Traction Motor

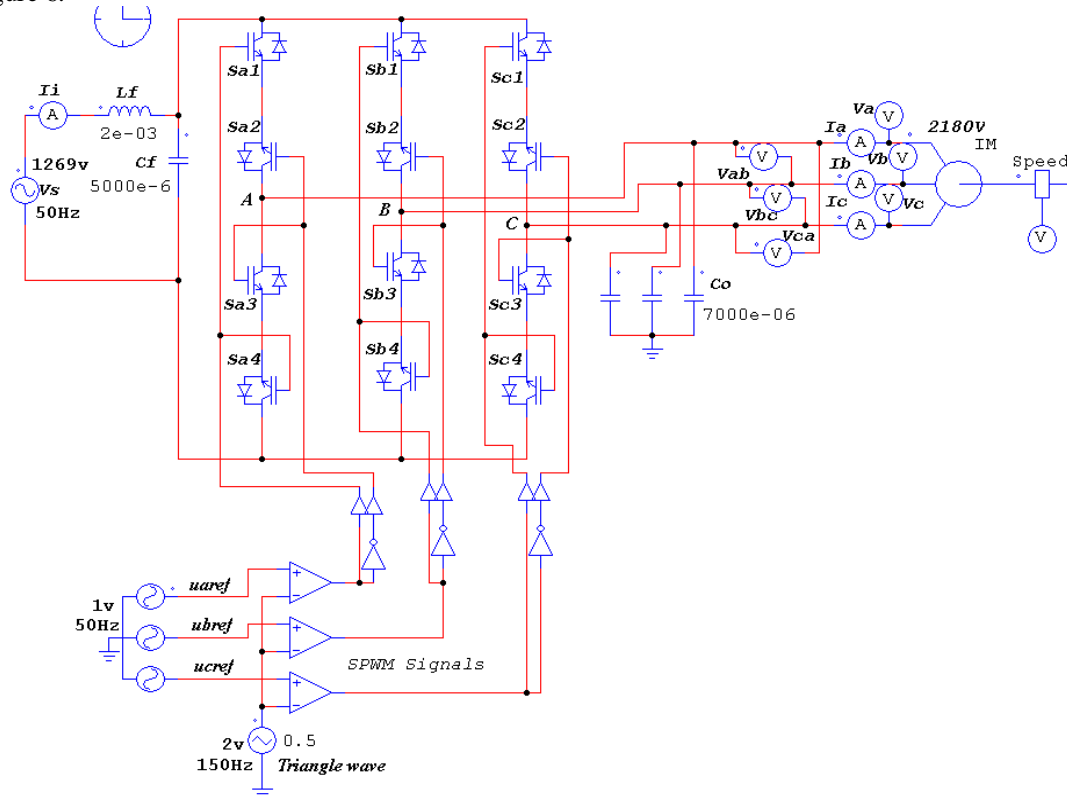
To verify the operation strategy, the proposed 1-3 phase ac matrix converter with a three-phase asynchronous traction motor (TM), Type [ABB-6FRA6068] is simulated by PSIM software. The three-phase

resistive load is changed to three-phase star wounded induction motor. The traction motor parameters are given in TABLE-III.

**Table-III:** Traction Motor Parameters

Type: ABB-6FRA6068		
Parameters	Symbols	Rating
Supply Voltage	$V_{ab}$	2180 V
Supply Frequency	$f_i$	50 Hz
Output Frequency	$f_o$	65 – 170 Hz
Speed	$N$	1283 rpm
Power (KW)	$P$	850 Kw
current	$I$	270 A
Max. Current	$I_{max}$	393 A
Stator Resistance	$R_s$	0.0727 $\Omega$
Stator Inductance	$L_s$	1.312 m H
Rotor Resistance	$R_r$	0.0641 $\Omega$
Rotor Inductance	$L_r$	2.716 m H
Mutual Inductance	$L_m$	41.982 m H
Motor Inertia	$J$	19.1 $\text{Kgm}^2$

The single-to-three phase ac Matrix Converter circuit is three legged  $A$ ,  $B$  and  $C$  with Six bi-directional switches are  $S1$  ( $S_{a1}$ -  $S_{a2}$ ),  $S2$  ( $S_{c3}$ -  $S_{c4}$ ),  $S3$  ( $S_{b1}$ -  $S_{b2}$ ),  $S4$  ( $S_{a3}$ -  $S_{a4}$ ),  $S5$  ( $S_{c1}$ - $S_{c2}$ ) and  $S6$  ( $S_{b3}$ -  $S_{b4}$ ). The simulation circuit is shown in Figure 6.



**Fig.6:** Simulation circuit for 1-3 MC with a TM.

The simulation is presented by using SPWM control technique. The Simulation of circuit is simulated with traction motor parameters by PSIM/MATLAB software packages. The single phase ac source voltage  $V_s$  taken as 1269V and source frequency  $f_i$  is 50Hz. When 150 Hz output frequency is demanded, the simulated results are obtained shows the three phase output voltages found approximately equal to 2180 V and three phase output currents are nearly 270 A and also following 120 degree phase sequence. The input current  $I_i$  is found nearly sinusoidal as expected is shown in Figure 7. Where,  $V_{ab}$ ,  $V_{bc}$  and  $V_{ca}$  are the line voltages and  $V_a$ ,  $V_b$  and  $V_c$  are phase voltages.  $I_a$ ,  $I_b$  and  $I_c$  are the output currents

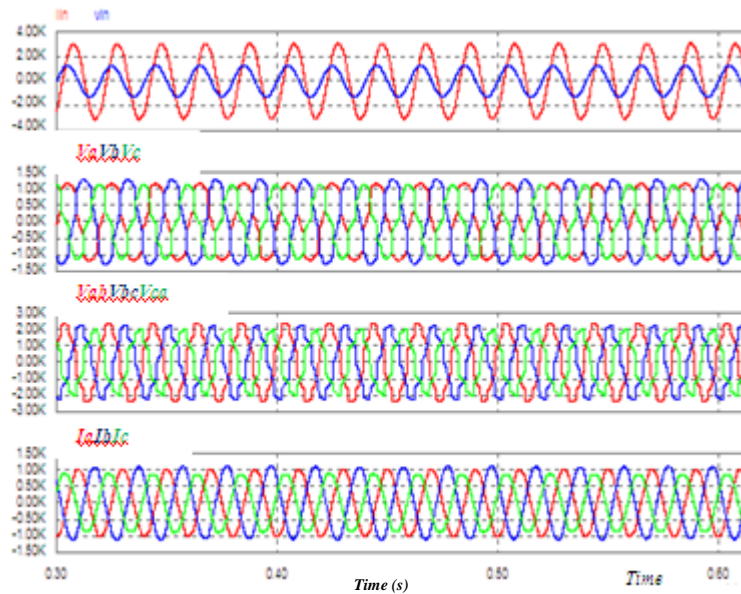


Fig. 7: Output waveforms of 1-3 MC with Traction Motor.

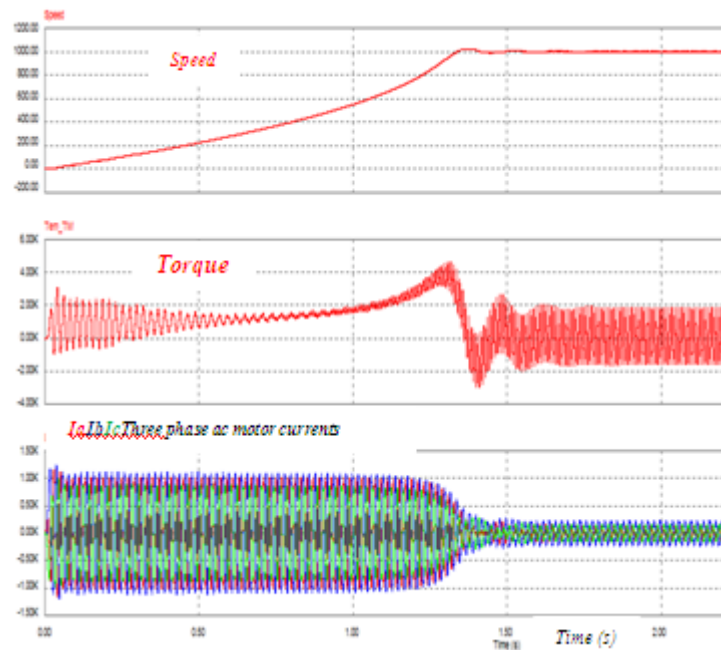


Fig. 8: Speed-torque-load currents of 1-3 MC with Traction Motor.

It can be seen that the Torque-Speed response of the Traction Motor during motoring operation, the shaft torque  $T_{em}$  and speed  $N$  is shown in Figure 8 at an accelerating mode.

It is also found that the output voltage parts at the frequencies  $|f_o - 2f_i|$  and  $|f_o + 2f_i|$  possess big proportions besides the frequency  $f_o$ , where,  $f_o$  is the fundamental frequency of the output voltage and  $f_i$  is the frequency of the source voltage, which implied the influence of the input supply frequency.

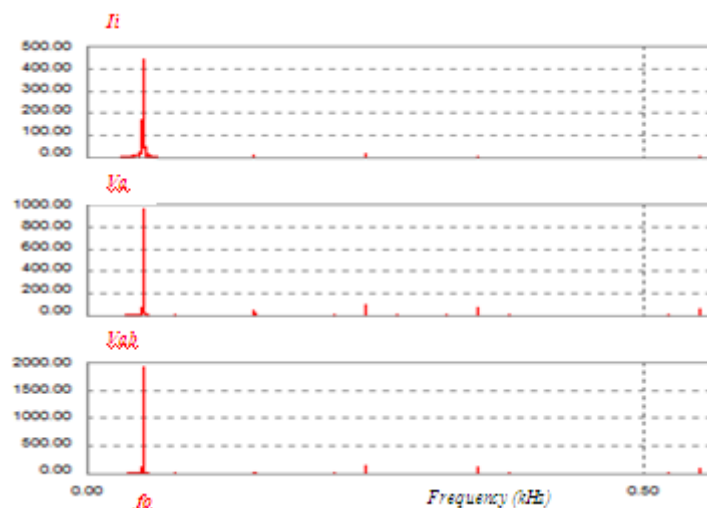


Fig. 9: FFT of input current and output voltages of 1-3 MC

At the same time the amplitudes of the output voltages fluctuate at about 100Hz, the FastFourierTransform (FFT) taken after simulation is shown in Figure 9, which is twice the source frequency  $f_i$ . This fluctuating is due to the SPWM control signals having relation only with the sign of the source voltage but not with the instantaneous value of the source voltage. The instantaneous value of the source voltage influences the output voltage directly. The low voltage ratio is the weakness of the matrix converter, which should be improved with some other efficient methods like SVPWM (space vector PWM), Fuzzy logic, etc.

## V. Conclusion

The proposed matrix converter topology for single phase to three phase ac conversion is used for traction drives. This is analyzed to indicate the operational features of MC with six bidirectional switches. The operation of this MC with SPWM is verified with simulation. This simplified control approach is suitable for general purpose implementation. The three phase traction motor drives performance indicates the satisfactory operation of this converter. This 1-3MC is a direct single stage ac-ac converter topology could be used to retrofit the existing two stage ac-dc-ac converter with dc link traction drives. This is also suitable for conversion of single phase transmission lines into three phase ac lines for Domestic, Industrial and Agricultural applications at remote places.

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