A review of Indirect Matrix Converter Topologies

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Abstract— Matrix Converter (MC) is a modern direct AC/AC electrical power converter without dc-link capacitor. It is operated in four quadrants, assuring control of the output voltage, amplitude and frequency. The matrix converter has recently attracted significant attention among researchers and it has become increasingly attractive for applications of wind energy conversion, military power supplies, induction motor drives, etc. Recently, different MC topologies, which have their own advantages and disadvantages, have been proposed and developed. Matrix converter can be classified as direct and indirect structure. In this paper, the indirect MCs are reviewed. Different characteristics of the indirect MC topologies are mentioned to show the strengths and weaknesses of such converter topologies.

Keywords— Matrix converter; AC/AC conversion; topologies; bidirectional switches;

I. INTRODUCTION

Matrix converter is a new generation of the direct power converter controlling the output voltage, amplitude and frequency. It has an adjustable power factor to control the input, regardless of the load. The absence of heavy and susceptible-to-failure capacitors, matrix converters can perform operations at high temperature, gain reliability, control input and output current and adjust voltage sine waves with an adjustable phase shift. These are considered some advantages of this type of converters. The controlling of output voltage, amplitude and frequency represents one more advantage over the previously mentioned advantages and over other types of converters as well. Those advantages promote the integration of this new topology in several areas of industrial applications. For example, aerospace industries have a great interest in that converter [1], [2], marine propulsion industries, electrical drive machines with variable speed [3]-[10], embedded systems and other fields of renewable energy which are based on wind and fuel cells [11]-[14].

Various research works on the topologies of matrix converters, led to the discovery of appropriate structures that minimize the number of semi-conductors. Two types of topologies for the matrix converter have been established by researchers including direct and indirect matrix converter topologies [15]-[26]. It has been shown that the indirect topology is handled easier. Other studies have been published on the design of multilevel and Z-Source Matrix Converters.

In previous work [24], authors showed the primary concerns of the MCs on bidirectional switches as well as the direct MC topologies and associated modelling. In this paper, the indirect topologies for MCs are investigated. Various features of those topologies are studied and a brief summary of the research will be shown at the end.

II. INDIRECT MATRIX CONVERTER TOPOLOGY

A new topology, developed in the early 2000s, can be proposed as an alternative to the matrix converter. This configuration consists of a combination of two conventional converters through a fictitious intermediate floor without capacitive storage element. It is called "double stage converter". The first floor is a controlled rectifier directly connected to the second floor, which consists of a voltage inverter, traditionally used in variable speed AC machines as presented in figure 1.

This indirect converter topology has two stages:

- Rectifier stage and inverter stage

The rectifier stage is formed of two switching cells, denoted (R) and (R'), modeled by the (1). One switch is closed at each switching time for both cells; this condition is expressed by the relation (2).

$$[S_{rect}] = \begin{bmatrix} S_A & S_B & S_C \\ S'_A & S'_B & S'_C \end{bmatrix} \quad (1)$$

Where …. $[S_{red}]$ is the connection matrix of the rectifier.

$$\begin{cases} S_A + S_B + S_C = 1 \\ S'_A + S'_B + S'_C = 1 \end{cases} \quad (2)$$

The operation of the rectifier is described by (3) and (4).

$$\begin{bmatrix} v_p \\ v_o \end{bmatrix} = [S_{rect}] \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = [S_{rect}]^T \begin{bmatrix} i_{dc} \\ -i_{dc} \end{bmatrix} \quad (4)$$

The inverter stage of the indirect matrix converter consists of three switching cells called a, b, c as shown in figure 1. This floor is modeled by equation (5) and satisfies the constraints described by (6).

$$[S_{inv}] = \begin{bmatrix} S_a & S'_a \\ S_b & S'_b \\ S_c & S'_c \end{bmatrix} \quad (5)$$

Where … $[S_{inv}]$ is the connection matrix of the inverter stage.

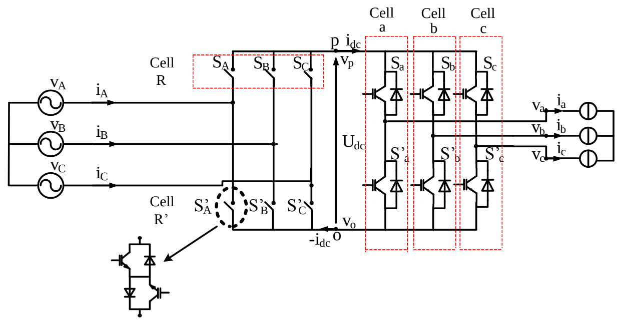


Fig. 1. Dual-stage indirect matrix converter

Every rectifier switch may be one of the following switches Fig. 2

$$\begin{cases} S_a + S'_a = 1 \\ S_b + S'_b = 1 \\ S_c + S'_c = 1 \end{cases} \quad (6)$$

The inverter operation is set by the relations (7) and (8).

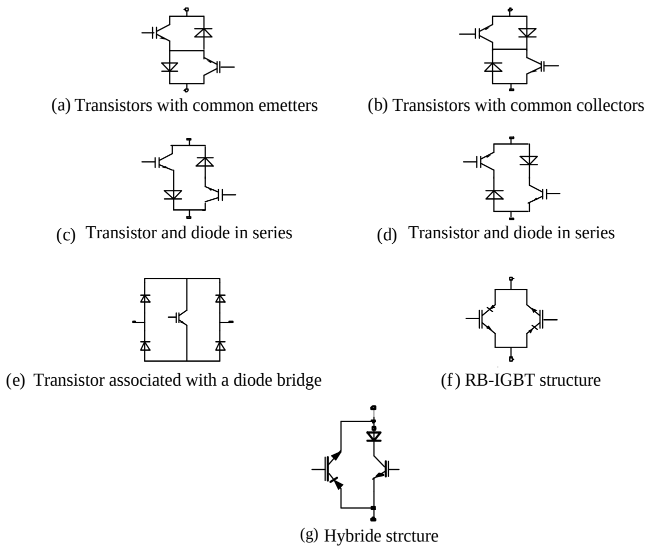


Fig.2. Different topologies of the bidirectional switches

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = [S_{inv}] \begin{bmatrix} v_p \\ v_o \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} i_{dc} \\ -i_{dc} \end{bmatrix} = [S_{inv}]^T \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (8)$$

The connection matrix of two-stage matrix converter named $[S_{DE}]$ is obtained by the product of the connecting matrices of the inverter and rectifier, as shown in equation (9).

$$[S_{DE}] = [S_{inv}].[S_{rect}] = \begin{bmatrix} S_a & S'_a \\ S_b & S'_b \\ S_c & S'_c \end{bmatrix} . \begin{bmatrix} S_A & S_B & S_C \\ S'_A & S'_B & S'_C \end{bmatrix} \quad (9)$$

A tie between two matrices connections can be established as shown in (10).

$$[S] = [S_{DE}] \Rightarrow \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{Cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} = \begin{bmatrix} S_a & S'_a \\ S_b & S'_b \\ S_c & S'_c \end{bmatrix} . \begin{bmatrix} S_A & S_B & S_C \\ S'_A & S'_B & S'_C \end{bmatrix} \quad (10)$$

In the same manner as the direct matrix converter, a formulation based on modulation of the switches may also be set for the dual stage matrix converter. The equations described above in "connection function" are transposed in "modulation function" and the conversion matrices defined by the modulation functions of each stage of "dual-stage" matrix converter are described by (11), (12) for the rectifier stage and (15), (16) for the inverter stage.

$m_i = \frac{t_i}{T}$ where t_i represents the conduction time of switch (S_i) during the commutation period T .

$$[M_{rect}] = \begin{bmatrix} m_A & m_B & m_C \\ m'_A & m'_B & m'_C \end{bmatrix} \quad (11)$$

$$\begin{cases} m_A + m_B + m_C = 1 \\ m'_A + m'_B + m'_C = 1 \end{cases} \quad (12)$$

The laws of conversion of electrical values, whatsoever voltage/voltage or current/current are set by relations (13), (14) for the recovery block and (17), (18) for the inverter stage.

$$\begin{bmatrix} v_p \\ v_o \end{bmatrix} = [M_{rect}] \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = [M_{rect}]^T \begin{bmatrix} i_{red} \\ -i_{red} \end{bmatrix} \quad (14)$$

$$[M_{inv}] = \begin{bmatrix} m_a & m'_a \\ m_b & m'_b \\ m_c & m'_c \end{bmatrix} \quad (15)$$

$$\begin{cases} m_a + m'_a = 1 \\ m_b + m'_b = 1 \\ m_c + m'_c = 1 \end{cases} \quad (16)$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = [M_{inv}] \begin{bmatrix} v_p \\ v_o \end{bmatrix} \quad (17)$$

$$\begin{bmatrix} i_{dc} \\ -i_{dc} \end{bmatrix} = [M_{inv}]^T \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (18)$$

Product conversion matrices of inverter and rectifier stages are the conversion matrix of "double stage" matrix converter, denoted $[M_{inv}]$. It is expressed by (19).

$$[M_{DE}] = [M_{inv}].[M_{rect}] = \begin{bmatrix} m_a & m'_a \\ m_b & m'_b \\ m_c & m'_c \end{bmatrix} . \begin{bmatrix} m_A & m_B & m_C \\ m'_A & m'_B & m'_C \end{bmatrix} \quad (19)$$

As explained before; there is a relationship between "modulation functions" of the direct matrix converter and the indirect matrix converter, which is the equality of two conversion matrices according to (20).

$m_{ij} = \frac{t_{ij}}{T}$ where t_{ij} represents the conduction time of switch (S_{ij}) during the commutation period T .

$$[M] = [M_{DE}] \Rightarrow \begin{bmatrix} m_{Aa} & m_{Ba} & m_{Ca} \\ m_{Ab} & m_{Bb} & m_{Cb} \\ m_{Ac} & m_{Bc} & m_{Cc} \end{bmatrix} = \begin{bmatrix} m_a & m'_a \\ m_b & m'_b \\ m_c & m'_c \end{bmatrix} . \begin{bmatrix} m_A & m_B & m_C \\ m'_A & m'_B & m'_C \end{bmatrix} \quad (20)$$

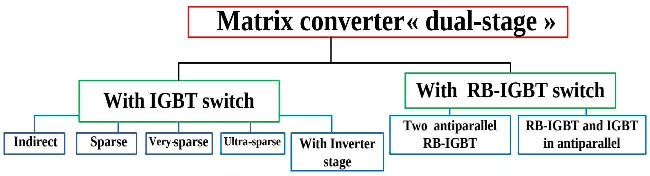


Fig. 3. Different indirect MC topologies

This two-stage indirect matrix converter structure developed by “J.W. Kollar” has a major advantage which is the ability to minimize the number of power transistors. The different topologies derived from indirect dual-stage MC have been shown in figure 3. Based on the two-stage indirect MC configuration, the following topologies have been derived:

A. Indirect matrix converter:

The configuration shown in figure 4 includes a rectifier stage comprising six bidirectional switches connected to a common emitter or common collector. This configuration generates less switching and conduction losses compared to other configurations. It has a complex control for the number of switches to handle. All this leads to the development of other configurations with the aim of reducing the number of required transistors which facilitates the monitoring and control of the matrix converter.

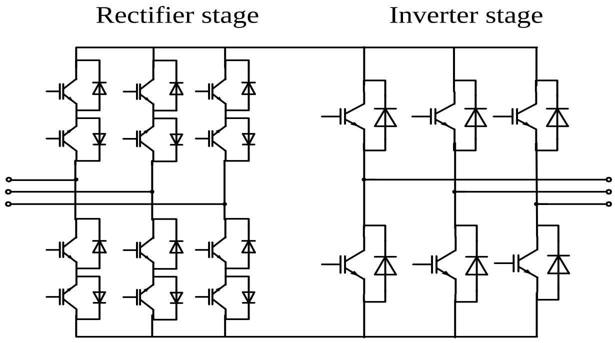


Fig. 4. Indirect matrix converter

B. Sparse matrix converter:

The configuration shown in figure 5, leads to remove an IGBT from each arm of the rectifier, so three components will be eliminated totally compared to the previous configuration, which facilitates the development of control algorithm of the converter. Conduction losses will be greater than those generated by the first configuration since three transistors and diodes are working during the feeding phase of the load as well as two transistors and two diodes in the feedback phase to the network.

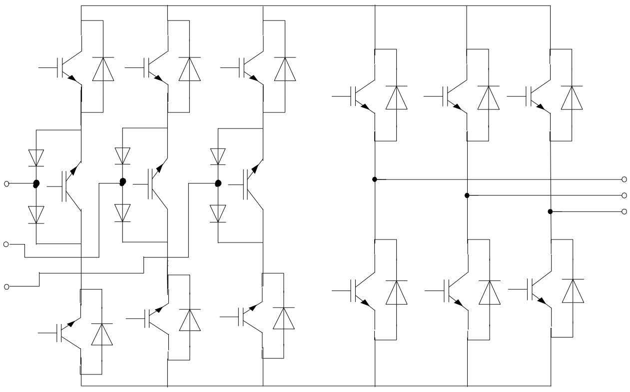


Fig. 5. Sparse Matrix converter

C. Very-Sparse matrix converter:

The structure of this topology illustrated in figure 6 is based on the implementation of bidirectional IGBT switches connected to a diode bridge, where the number of the controlled components in the rectifier is reduced compared to the two configurations mentioned above. Each active element of the rectifier requires the activation of a transistor with two diodes in each commutation phase, the rectifier requests two transistors and four diodes, bearing in mind that conduction losses are then a matter of importance.

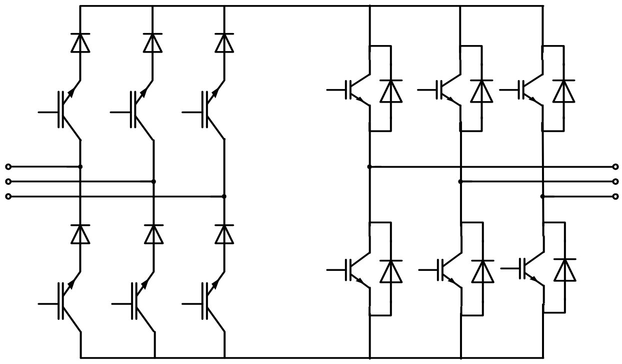


Fig. 6. Very-Sparse Matrix Converter

D. Ultra-Sparse Matrix Converter:

In this configuration, the least number of switches is employed. There is a single switch via input phase as shown in figure 7. In each arm, one transistor and two diodes are controlled. This structure generates similar conduction losses to those produced by the "Very- Sparse" structure. Yet, this configuration does not allow bi-directional power flow which limits its practical application.

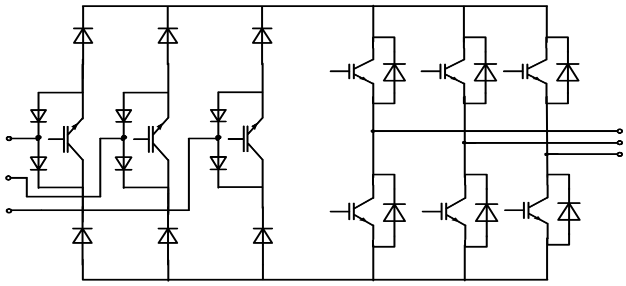


Fig. 7. Ultra-Sparse matrix converter

E. Matrix Converter "to inverter stage"

The first stage of this configuration includes a rectifier in cascade with an inverter circuit as shown in figure 8. This structure has many controlled components than the "Sparse" topology. It creates additional switching losses and has a high complexity level in control. Consequently, this configuration will not be an objective study.

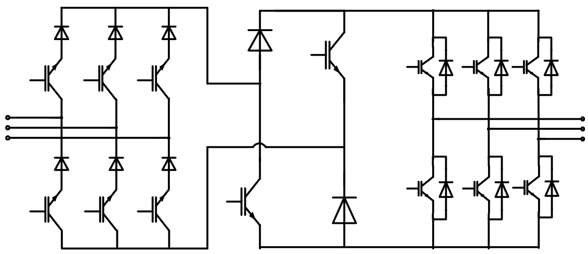


Fig. 8. Matrix converter with rectifier stage

F. Matrix Converter based on RB-IGBT:

The structure shown in figure 9 incorporates RB-IGBTs into the rectifier stage with advantages like reduction of conduction losses. The poor diode recovery behavior of the RB-IGBT is of less concern here than in a matrix converter because it is possible to switch the rectifier stage at zero current as soft switching pattern. At low switching frequencies, a matrix converter built with RB-IGBTs will be more efficient than the one built with IGBTs.

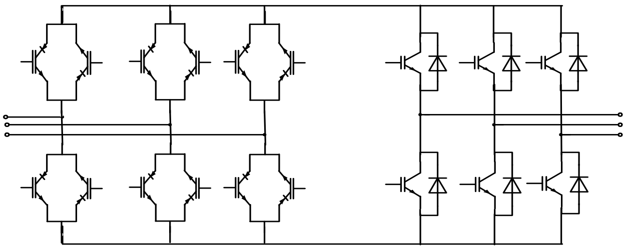


Fig. 9. Matrix converter or rectifier unit switches are based on RB-IGBT

G. Matrix Converter based hybrid switches:

The topology of matrix converter using hybrid bi-directional switches in the rectifier stage (as shown in figure 10), provides low conduction losses in motoring operation as well as soft turn-on commutation of the RB-IGBTs, whereas in the rectifier stage the standard IGBTs and diodes provide low switching losses in regenerative operation.

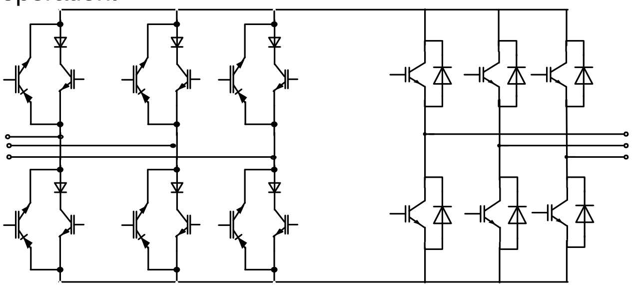


Fig. 10. Matrix converter or rectifier unit switches are based on a RB-IGBT on anti-parallel to an IGBT with a series diode

Table 1 shows the summary of the above-mentioned MC topologies considering various points including some elements such as a number of components, power losses, control strategy complexity and reversibility.

III. SIMULATION RESULTS

The SimPowerSystem toolbox of MATLAB has been used as the simulation tool. The simulation results before and after compensation of the three-level sparse matrix converter feeding an RL load as illustrated in Fig.11, also shown in Figs.12 to 17. Table II gives the system parameters used in the simulations.

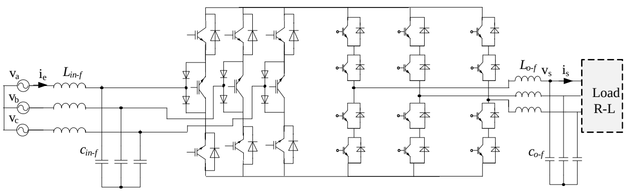
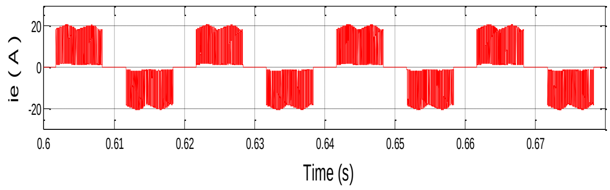


Fig. 11. Three-level Sparse Matrix Converter

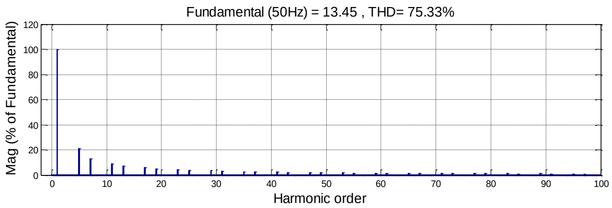
Table 1. Summary of the indirect topologies features

Topology	Number of transistors	Number of diodes	Energetic losses	Reversibility power	Control
Indirect Matrix	18	18	low	yes	fairly complicated
Sparse	15	18	important	yes	fairly complicated
Very-Sparse	12	12	low	yes	easy
Ultra-sparse	9	18	low	No	easy
With Stage inverter	14	14	important	yes	complicated
Based on RB-IGBT	18	18	low	yes	fairly complicated
Based-on Hybrid switches	18	18	average	yes	easy

Figs.12 (a)-(b) show the phase a input current (ie) and its harmonic spectrum, respectively. The input current has a THD of 75.33%. The output voltage (vs) of phase (a), and its harmonic spectrum (output voltage THD of 92.21%) are shown in figs.13 (a)-(b), respectively. Figs.14 (a)-(b) show the phase (a) output current (is) and its harmonic spectrum. The output current THD is 2.43%. An input and output LC filters are necessary to compensate the high-frequency ripple from the input currents and output voltages. Thus, an LC filter is connected at the input side to avoid overvoltage and to filter the high-frequency ripple from the input currents. Similarly, on the other side, an output LC filter is connected between the converter and the load which allows controlling the output voltage and mitigates its harmonics. Figs. 15 (a) and (b) show the phase (a) input current and its harmonic spectrum after filtering. The measured THD of the input current in phase (a) is reduced from 75.33% before compensation to 1.78% after compensation. It is important to notice that the input current is kept free of harmonics.

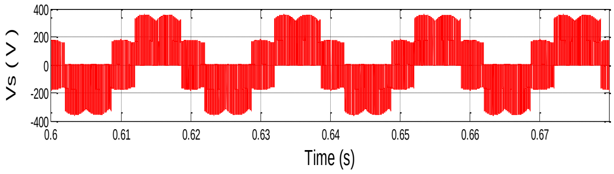


(a)

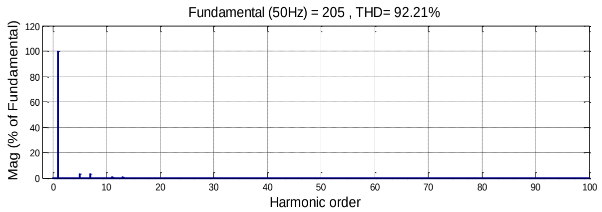


(b)

Fig. 12. (a) Waveform of phase a input current (ie) of three-phase three-level sparse matrix converter before filtering, (b) Harmonic spectrum of input current.

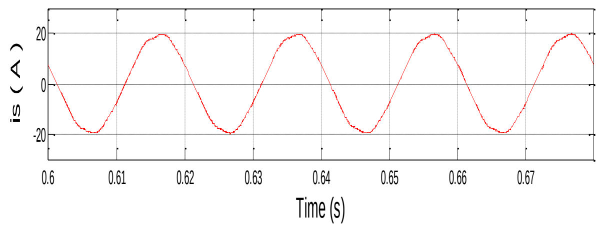


(a)

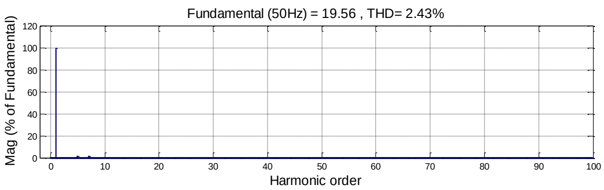


(b)

Fig. 13. (a) Waveform of phase a output voltage (vs) of three-phase three-level sparse matrix converter before filtering, (b) Harmonic spectrum of output voltage

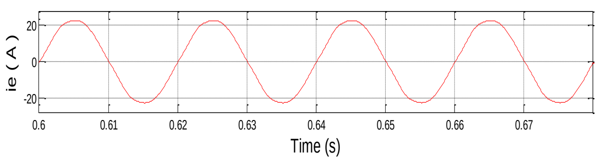


(a)

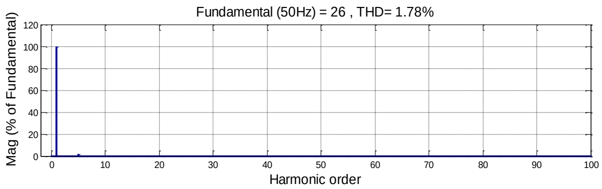


(b)

Fig. 14. (a) Waveform of phase a output current (is) of three-phase three-level sparse matrix converter before filtering, (b) Harmonic spectrum of output current.



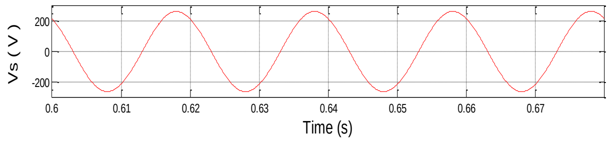
(a)



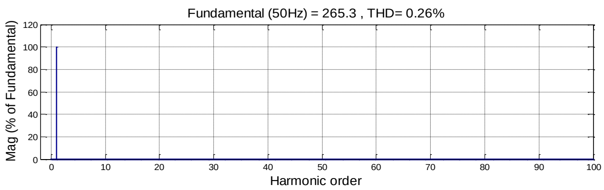
(b)

Fig. 15. (a) Waveform of phase a input current of three-phase three-level sparse matrix converter after filtering, (b) Harmonic spectrum of input current.

The waveforms and harmonic spectra of output voltage and current waveforms after filtering are shown in (figs.16 and 17) respectively. The output filter reduces the THD in the output voltage from 92.21% to 0.26%. The THD of the output current in phase (a) is therefore reduced from 2.43% without output filter to 0.15% after filtering. These results show the output LC filter capability to compensate harmonics of output voltages and output currents.

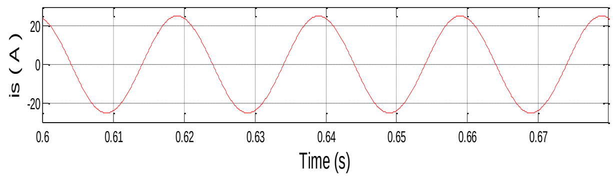


(a)

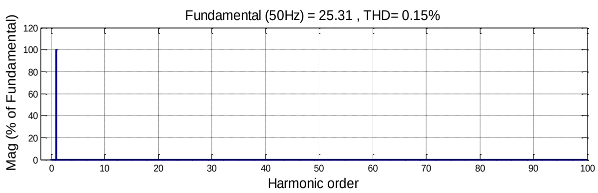


(b)

Fig.16. (a) Waveform of phase a output voltage of three-phase three-level sparse matrix converter after filtering, (b) Harmonic spectrum of output voltage



(a)



(b)

Fig.17. (a) Waveform of phase a output current of three-phase three-level sparse matrix converter after filtering, (b) Harmonic spectrum of output current

Table 2. Specification Parameters

Circuit Specifications	Value
Input side	$V_{in-max} = 311\ V$, $f_{in} = 50Hz$
Load	$R = 10\Omega$, $L = 10mH$
Input filter	$R_{in-f} = 0.1\Omega$, $L_{in-f} = 40mH$, $C_{in-f} = 100\mu F$
Output filter	$R_{o-f} = 0.1\Omega$, $L_{o-f} = 27mH$, $C_{o-f} = 200\mu F$
Output side	$V_{o-max} = 256.8\ V$, $f_o = 50Hz$
Ratio	0.825
Switching frequency	$f_{sw} = 10KHz$

IV. CONCLUSION

This paper proves that the dual stage MC topology has been studied and analyzed. Different topologies based on dual stage configuration of MC have been illustrated. The brief summary at the end shows some facts and characteristics of the afore-mentioned topologies which would be useful for future applications on MC topologies and control aspects. As mentioned before, MC has two main topologies including direct and indirect ones. The comparison between these two topologies made it clear that the two-stage matrix converters have advantages over the direct or conventional ones. For example, the possibility of reducing the number of switches forming the converter enables consumers to reduce the switching power losses and manufacturing cost as well. Less switching difficulties occurs because switches of the input stage (rectifier) can be turned on by the application of the zero vector current. The second stage is controlled as a standard inverter and the Clamp circuit can be simplified only by a capacitor in series with a diode which is not compatible with the direct matrix converter topology. Simulation results for an RL load supplied via a sparse matrix converter with the PWM modulation show that output voltage is controllable with corresponding improvements in power quality and the unity displacement power factor is achieved at the input stage. Eventually, these studies offer a very wide field of research, especially in the study of reliability, maintainability, availability; faults tolerances and stability of these types of converters.

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