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CONFIGURATIONS COMPARISON OF MULTI DIRECTIONAL MATRIX CONVERTER FOR LOW POWER APPLICATION

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Abstract

Four different topologies of Multi Directional Matrix Converters (MDMC) are compared for use in low power applications. In the proposed small-scale power system the MDMC configuration with 12 bidirectional switches combined the desirable characteristics of the AC/AC conventional Matrix Converter (MC) and AC/DC single phase to single phase matrix converter. The indirect method with Space Vector Pulse Width Modulation (SVPWM) technique applied to the proposed MDMC configurations in order to control the power direction from power sources to loads. These four configurations have been simulated by MATLAB software and results are presented and discussed. Analyses and simulation results show that the MDMC with 12 bidirectional switches can run over a large input voltage and frequency range while controlling the power flow direction, compensate the fluctuating power and maintaining the excellent quality of output waveform in case of THD and DC current ripple.

Keywords: Matrix converter, Multi directional matrix converter, SVPWM, Small-scale power system.

1. Introduction

With increasing demand of electricity in the recent decade, renewable energy is become interesting as significant alternative sources of energy. Many factors such as impact of fossil-fuel resource on environmental, increasing the cost of fuel oil and diminishing fossil-fuel resource are responsible for this development [1-2].

Nomenclatures

d_α, d_β	Duty cycle of current vector I_α and I_β respectively
d_μ, d_γ	Duty cycle of voltage vector v_μ and v_γ respectively
f_i	Input frequency of the MDMC
f_o	Output frequency of the MDMC
I_α	Closest clockwise state vector to reference current vector
I_β	Closest anticlockwise state vector to reference current vector
L_l	Output load inductance
m_c	Modulation index of current source rectifier
m_v	Modulation index of voltage source inverter
R_l	Output load resistance
T_α, T_β	Time spent in vector I_α and I_β respectively
T_μ, T_γ	Time spent in vector v_μ and v_γ respectively
T_0	Time spent in zero vector
V_{ab}, V_{bc}, V_{bc}	Input line-to-line voltage
V_{od}	d-axis input voltage
$V_{ors}, V_{ost}, V_{otr}$	Output line-to-line voltage
V_{oq}	q-axis input voltage
$V_{s\text{-}RMS}$	Input line-to-line voltage in RMS

Greek Symbols

θ_{CSR}	The angle between the reference vector and the closest clock-wise state vector in current source rectifier
θ_{VSI}	The angle between the reference vector and the closest clock-wise state vector in voltage source inverter

One of the major requirements for small scale power generation system is to ensure continuous power flow by storing excess energy from the energy source [3]. Small scale power systems with battery storage and power converter are efficient and reliable stand-alone system for remote areas [4]. In recent years, the matrix converter become popular in the category of AC/AC converters due to its desirable features such as sinusoidal input and output current, generating of load voltage with arbitrary amplitude and frequency and ability to controlled input power factor for any load [5]. The principle of MC control proposed by Venturini and Alesina in the early 1980's which known as a "direct transfer function" approach with voltage transfer ratio restriction to 0.5 [6]. The term direct transfer function means that the energy does not appear in the form of dc in the conversion process.

The "indirect transfer function" was derived by Rodriguez in 1983 [7]. In this method, the matrix converter was described as virtual configuration of pulse width modulation (PWM) rectifier and inverter with "fictitious dc link". Switching is arranged in this method, so most positive and most negative input lines will be connected to each output line by using PWM technique, as conventionally used in standard voltage source inverter (VSIs) [8].

Between direct and indirect method, the indirect method, have the capability to implementing Pulse Width Modulation (PWM) and Space Vector PWM (SVPWM) techniques to the switches of the MC which can reduced THD and losses in system. the voltage ratio of MC can reach to the 0.866 with taking the advantage of SVPWM technique [9].

The multi directional matrix converter for 2kW standalone power system with battery storage is expected to be a breakthrough towards new technological advancements, in the area of sustainable energy. Therefore, four possible configurations have been proposed based on conventional Matrix converter configuration [6], and all configurations simulated by MATLAB software and results are presented and discussed.

2. System Structure

In the proposed small-scale power system, the Variable speed turbine is connected to the three phase 2 kW permanent magnet generator which can generate voltage up to 80 V, the output of generator is connected to the input side of MDMC. In another side the DC output of MDMC used for battery charging and AC output connected to transformer with ratio of 1:10 in order to top up the voltage amplitude based on the Malaysia standard (240 V). The Schematic diagram of the proposed stand-alone system with battery and MDMC is shown in Fig. 1.

The proposed MDMC configurations are made based on the MC structure. Performance of matrix converter is strictly depending on the high switching frequency switches topology and the modulation strategy employed to control theses bidirectional switches. The indirect method is Appropriate method In order to implement the Pulse Width Modulation (PWM) and Space Vector pulse width modulation (SVPWM) techniques to the MC [9]. Therefore, the proposed MDMCs should be able to control the power flow from generator or battery to the AC load regarding to the concept of fictitious rectifier-inverter pair and dc-link of indirect method. In another hand the DC output voltage of the MDMC should deliver a clean regulated voltage output with sinusoidal input current.

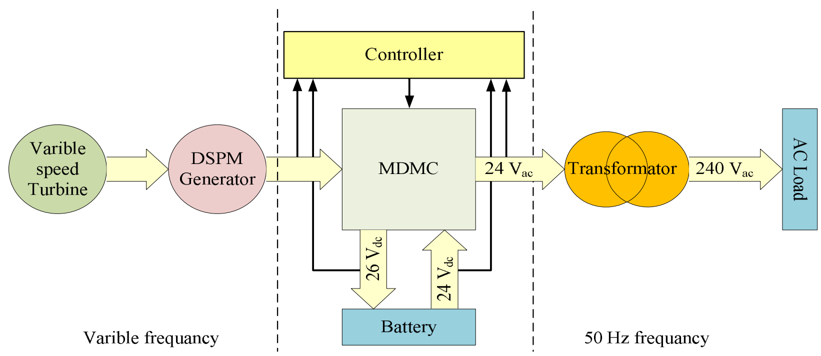


Fig. 1. Schematic Diagram of the Proposed Stand-Alone System.

The proposed MDMC concept structure with four input and three outputs are illustrated in Fig. 2. The input side of the MDMC is connected to the three phase generator and imaginary battery when the system is on discharging mode. In another side the output of MDMC is connected to the single phase AC load and the real battery when the system is on charging mode.

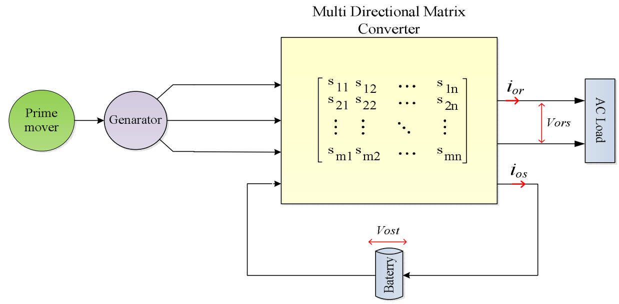


Fig. 2. Schematic Diagram of Multi Directional Converter.

3. MDMC Modulation Methods

Different imaginary stages of transformation are considered in indirect switching matrix approach. This transfer switching matrix, are considered as: rectification stage and inverter stage. In the rectification stage, a fictitious dc link with a dc voltage of constant local average will be provided. Then, the fictitious dc voltage is connected to the battery in case of battery charging as well as converted to the single-phase AC voltage in the case of AC load on inverter stage.

The SVPWM technique is a renowned method in control of DC/AC inverters and also AC/DC converters [10]. The SVPWM reduced the number of switching in each time sequence and represent the voltages and currents in two-dimension reference frames instated of three-dimensional *abc* frames. Firstly, Huber and Borojevic applied the SVPWM to the matrix converter in the same way that it is applied to DC/AC converter with taking advantage of indirect matrix switching approach [11, 12]. The concept of the indirect method for all proposed MDMC structure have been illustrate in imaginary switches part of Tables 1(a) and 1(b), with six imaginary switches for the rectifier part and six imaginary switches for the inverter. Furthermore, Tables 1(a) and 1(b) indicates the current flow through the inverter stage during the two 180^o sectors.

The first part of all multi directional converters can be considered as a current source rectifier (CSR) with an imaginary dc-link voltage, *Vpn*, which is illustrated in Fig. 3. The implementation of SVPWM for the current source rectifier is similar in all configuration of MDMC. Any of the three-phase quantities in abc-frame can be transforming to the *dq* coordinate with accomplished of *dq*-frame transformation. Three-phase output ac voltages of generator V_{ab}, V_{bc} and V_{ca} are a set of quantized values in *abc* coordinate at each state which is transformed to the fixed two-dimensional *dq*-frame as shown in Eq. (1) [13].

$$\begin{bmatrix} V_{0q} \\ V_{0d} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & cos(\frac{2\pi}{3}) & cos(-\frac{2\pi}{3}) \\ 0 & sin(\frac{2\pi}{3}) & sin(-\frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \quad (1)$$

By calculating the switching state vector for allowed input currents of the current source converter in each switching state, will result, eight space current vectors consist of six non-zero space switching current vectors, I_1, I_2,...,I_6, and two zero current space current vectors, I_0 and I_7. Figure 3 illustrates the eight Input current space vector in complex plane where the two zero space current vectors, are located at the origin of the frame and the rest six vectors can form a hexagon centred at the origin of the dq frame [14].

The continuous desired input currents should be synthesized using the two active vectors next to the reference vector and a zero vector. If the reference vector located in sector 1, between non-zero vectors, $\overline{I_1}$ and $\overline{I_6}$, the $I_{s\text{-}ref}$ can be represented as Fig. 4. During each switching period, T_s, the $I_{s\text{-}ref}$ is calculated by T_α ,T_β and T_0 where T_α is the time spent in vector I_α and T_β is the time spent in vector I_β and the rest is the time T_0 which dedication to a zero vector. These three time periods can be stated by duty cycles using trigonometric identities as shown in Eq. (2) where the m_c is the modulation index of the current source converter.

$$\begin{cases} T_\alpha = m_c \sin\left(\frac{\pi}{3} - \theta_{CSR}\right).T_s = d_\alpha T_s \\ T_\beta = m_c \sin(\theta_{CSR}).T_s = d_\beta T_s \\ T_{0c} = d_{0c} T_s = T_s - (T_\alpha + T_\beta) \end{cases}$$
$$\Rightarrow \begin{cases} d_\alpha = m_c \sin(\frac{\pi}{3} - \theta_{CSR}) \\ d_\beta = m_c \sin(\theta_{CSR}) \\ d_{0c} = 1 - (d_\alpha + d_\beta) \end{cases}, \quad 0 \le m_c \le 1 \tag{2}$$

The second part of imaginary switches of MDMCs can be considered as voltage source inverter (VSR). It is necessary to replace θ_{CSR} in Fig. 4 with output space vector θ_{VSI} angle voltage and subscripts α and β in duty cycles with subscripts μ and γ, three duty cycles of VSR of MDMC can be described by Eq. (3) as follow.

$$\begin{cases} T_\mu = m_v \sin\left(\frac{\pi}{3} - \theta_{VSI}\right).T_s = d_\mu T_s \\ T_\gamma = m_v \sin(\theta_{VSI}).T_s = d_\gamma T_s \\ T_{0v} = d_{0v} T_s = T_s - (T_\mu + T_\gamma) \end{cases} \Rightarrow \begin{cases} d_\mu = m_v \sin(\frac{\pi}{3} - \theta_{VSI}) \\ d_\gamma = m_v \sin(\theta_{VSI}) \\ d_{0v} = 1 - (d_\mu + d_\gamma) \end{cases}, \quad 0 \le m_v \le 1 \tag{3}$$

In all configurations of MDMC with indirect method, it is supposed to have a target constant current space vector, for the rectifier part which contains six 60° sectors. Furthermore, in inverter stage there are two 180° sectors for AC and DC outputs. In this study, 12 sectors in total have been determined for MDMCs outputs. By considering these 12 sectors and regarding to the three phase to three phase matrix converter modulation proposed by Huber et.al in 1995 [12], the proposed modulation process can be perform by using five combined duty cycles as shown in Eq. (4). These combinations can be considered in each sequence.

$$\begin{aligned} d_{\alpha\mu} &= d_\alpha \times d_\mu \\ d_{\beta\mu} &= d_\beta \times d_\mu \\ d_{\alpha\gamma} &= d_\alpha \times d_\gamma \\ d_{\beta\gamma} &= d_\beta \times d_\gamma \\ d_0 &= 1 - (d_{\alpha\mu} + d_{\beta\mu} + d_{\beta\gamma} + d_{\alpha\gamma}) \end{aligned} \tag{4}$$

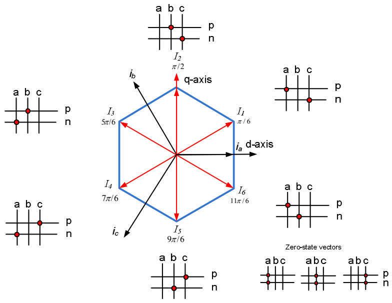


Fig. 3. Input Current Space Vector in Complex Plane.

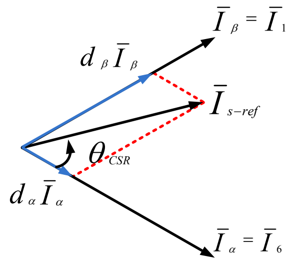


Fig. 4. $I_{s\text{-}ref}$ Synthesis Using Vectors $\bar{I}_1$ and $\bar{I}_6$.

Table 1a. MDMC Configurations and SVPWM Switching Method (Inverter Stage).

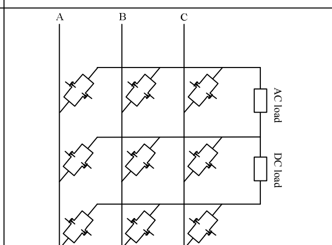
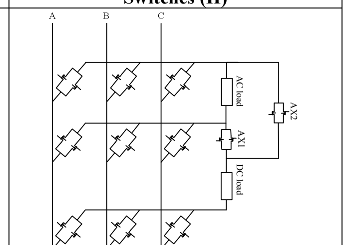
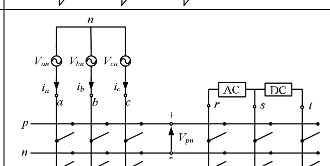
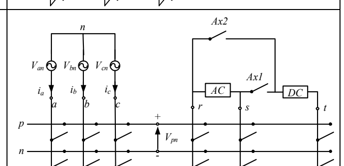
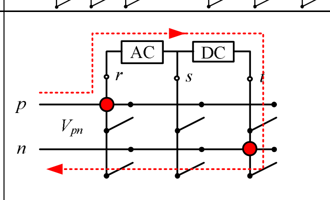
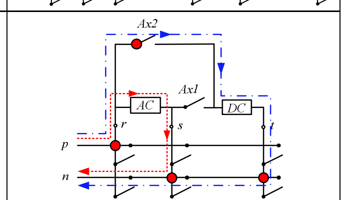
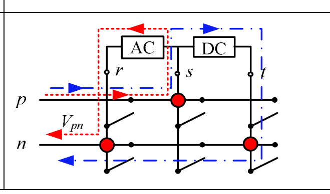
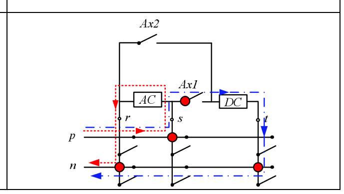
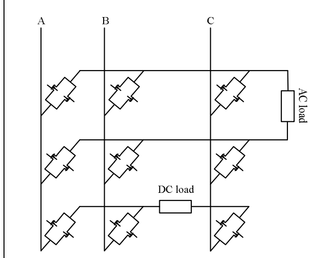
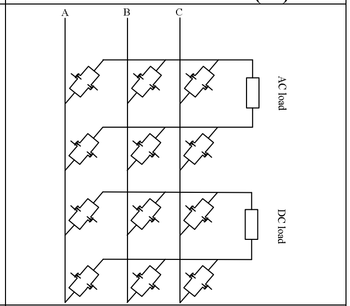
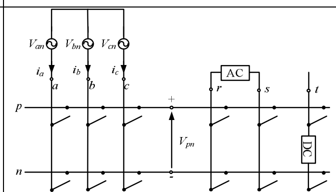
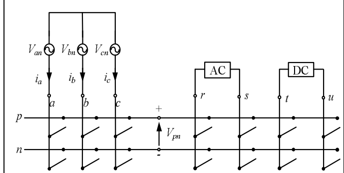
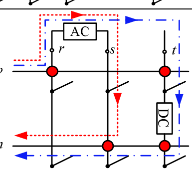
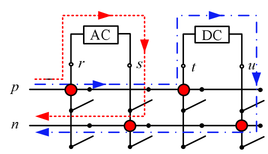
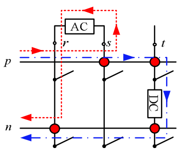
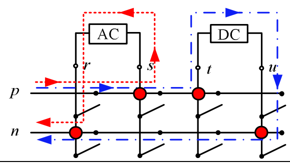
MDMC Name		MDMC with Conventional MC Structure (I) [7].	MDMC with Conventional MC Structure and Two Auxiliary Switches (II)
Schematic Diagram of MDMC			
Imaginary Switches			
Sector	0 - π		
	π - 2π		

Table 1b. MDMC Configurations and SVPWM Switching Method (Inverter Stage).

MDMC Name		MDMC with DC Load inside of MC Structure (III)	MDMC with 12 Bidirectional Switches (IV)
Schematic Diagram of MDMC			
Imaginary Switches			
Sector	0 - π		
	π - 2π		

4. Results and Discussion

Simulation of MDMC configurations I, II, III and IV are performed by using MATLAB and the result are shown in Figs. 5-8 respectively. The simulation parameters are shown in Table 2. The switching period T_s is 166 µs, and battery's charging is *SOC*=95%, thus power injected from generator to the DC and AC loads.

Table 2. Simulation Parameters.

Parameters	Value
R_l - L_l load	R_l=2.4 Ω , L_l=10 mH
Input voltage (line-to-line RMS) $V_{s\text{-}RMS}$	28 V
Input frequency f_i	180 Hz
Output frequency f_o	50 Hz

Figures 5-8 illustrate the output AC-side line-to-line voltage v_{ors} which connected to the AC load in all configuration, r-phase output ac-side current i_{or}, output battery-side voltage v_{ost} and t-phase output current i_{ot}. The total harmonic distortion (THD) of the output currents is processed by FFT analysis feature of MATLAB and result expressed in Table 3**.** Finally all configurations compared to each other based on Table 3 contents such as number of bidirectional switches which directly affect to the total cost of system and efficiency, total harmonic distortion and ability of configuration to inject power from DC side to the system when the power of generator is not sufficient to supply the AC load.

Regarding to output wave form result and contents of the Table 3, the configuration IV have the lowest THD in the case of AC current output and lowest ripple in DC current output with ripple of 1.4% average DC current. in another hand the quality of waveform is acceptable for the configuration III with *THD* = 1.67% in the case of AC current output, but the ripple in DC current is not acceptable for battery charging when it's around 61% of average DC current.

In point of view of injecting power from the battery source to the system based on Table 3 and wave form result of simulation, configuration IV have the best performance and more freedom to control the power flow in all direction. The simulation results in Figs. 7 and 8 illustrate that configuration IV can inject the power to/from DC continuously when the configuration III is be able to transfer power to the DC side in 60^o of each period at desired output frequency.

Number of the switches has direct effect on system losses and price. Therefore, in point of view of losses and price, configuration I and II with 9 and 11 bidirectional switches respectively are more cost efficient than configuration IV. Furthermore, configuration III has lower losses compare to the configuration IV. With using indirect method and SVPWM technique, MATLAB simulation result revealed that the configuration I and II are not capable to inject power from DC side to system, since several vectors are utilized in one switching period. In addition, the output DC current has been distorted in configuration I and II due to the connection point of the battery. This distortion is happen when the voltage cannot apply to the DC load continuously.

Three-phase to single-phase converters always pay attention to how to compensate the fluctuating power. In this paper, the MDMCs compensate the fluctuating power with draw the fluctuating power from the generator, i.e., the inertia of the generator acts as an energy buffer for compensating the fluctuating power.

Table 3. Comparison of MDMC Configurations.

Configuration	I	II	III	IV
THD	15.02%	19.14%	1.67%	1.61%
DC Current ($I_{ave}\pm$ percentage of ripple)	1.24 ± 95%	2.75 ± 15%	1.15 ± 61%	2.74 ± 1.4%
Number of bidirectional switches	9	9	9	12
Extra switches	0	2	0	0
Ability to flow power from DC side to AC side	No	No	Yes	Yes

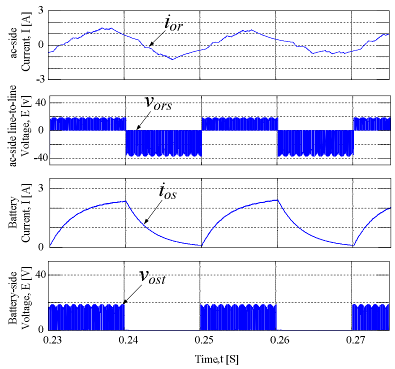


Fig. 5. Output Wave Form of MDMC Configuration (I).

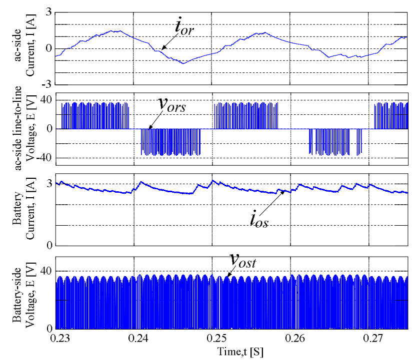


Fig. 6. Output Wave Form of MDMC Configuration (II).

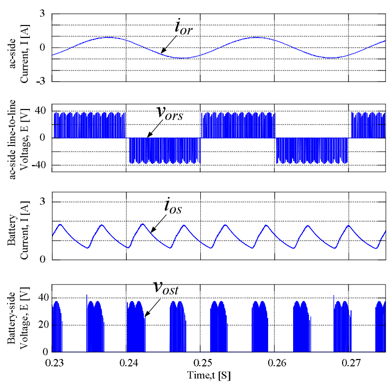


Fig. 7. Output Wave Form of MDMC Configuration (III).

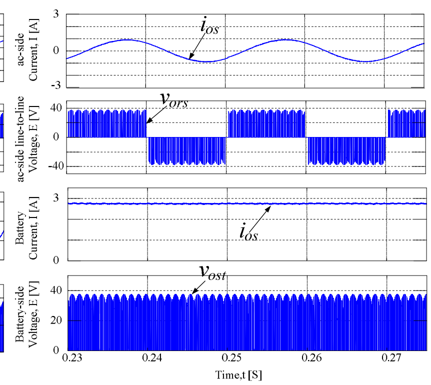


Fig. 8. Output Wave Form of MDMC Configuration (IV).

5. Conclusions

The multi directional matrix converter offers superior technical characteristics for low power system with battery storage, especially without bulky DC-bus capacitors at the DC-side. This study also presents a SVPWM method for all proposed configuration and compared the result in terms of quality of waveform, losses and efficiencies. The presented results show, that the output voltages and currents of proposed configurations can be synthesize by using the indirect method and taking the advantage of the SVPWM technique.

The feasibility of the proposed MDMC structures and SVPWM technique has been verified by MATLAB simulation. Analyses and simulation results shows that the MDMC with 12 bidirectional switches can run over a large input voltage and frequency range while controlling the power flow direction, compensate the fluctuating power, and maintaining the excellent quality of output waveform in case of THD and DC current ripple.

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