SINGLE STAGE POWER CONVERSION FOR WIND ENERGY SYSTEM USING AC-AC MATRIX CONVERTER

R.Bharani Kumar and K.T.Maheswari

Bannari Amman Institute of Technology, Sathyamangalam, Erode 638 401
Tamilnadu, India
E.Mail. bharanikumar.rbk@gmail.com

Abstract- *Matrix converter is one of the latest single stage AC-AC converters. It can convert fixed ac voltage into variable amplitude and variable frequency ac voltage and vice versa. In this paper, the ability of the matrix converter to deliver a constant voltage at desired frequency from a permanent magnet generator (PMG) driven by wind turbine is connected to the three phase matrix converter. The Space Vector Pulse Width Modulation (SVPWM) technique is used to generate the pulses to control the matrix converter as it provides the output AC voltage with very less harmonics. The SVPWM pulse pattern is varied using an FPGA control circuit according to varying .wind velocity and generated voltage. The simulation and hardware results are presented to validate the concept.*

Keywords: *Matrix converter, Space Vector Pulse Width Modulation, Permanent Magnet Generator, Wind Turbine, Total Harmonic Distortion*

I. Introduction

Around the world the demand for electrical energy is going on increasing and hence the need for taping renewable energy is also increasing. Predictions by scientists indicate that the global energy demand will almost be doubled by 2025. So to meet out the future needs wind energy is one of the choices which is renewable, ecofriendly and cheaper. The magnetization of the wind electric generator is provided by a Permanent Magnet pole system or a dc supply on the rotor, providing self-excitation property of the Permanent Magnet generators and it differs from the induction generator [1]. For the PM generators allows operation at high power factors and high efficiencies. [2].

Generally, the power electronics devices used in Wind Energy Conversion System (WECS) include matrix converter, has lots of advantages such as bidirectional energy flow, sinusoidal input and output current, as well as absence of huge - energy storage components. Particularly, Single stage matrix converter has virtually the same function with conventional converter [3].

Matrix converter is a direct AC-AC converter topology that is capable of transforming energy from an AC source to load directly without the need of a huge and restricted lifetime energy storage element. Because of the major advantages such as capability of regeneration, high quality sinusoidal input and output waveforms and adaptable power factor [4], matrix converter has been one among the AC – AC topologies that receive widespread attention for being a substitute for the ancient AC-DC-AC converters in the variable voltage and variable frequency AC drive applications.

The main objective of this paper is to provide constant voltage and frequency from the variable wind turbine PMSG system. Novelty of this paper is to reduce the number of power conversion stages by using matrix converter. The matrix converter increases the efficiency of power conversion and reduces the Total Harmonic Distortion(THD) . The paper is organized as Section I which describes the introduction of variable speed wind energy conversion system with conventional and proposed ac-ac converter. Section II presents the single stage power conversion wind energy system using AC-AC Matrix converter. Section III explains the PMSG and its types. Section IV gives the operation and mathematical analysis of matrix converter. Section V presents the SVPWM technique. Section VI presents the simulation and experimental results of proposal converter. Finally section VII gives the conclusion.

II. Single Stage Power Conversion Wind Energy System Using AC-AC Matrix Converter

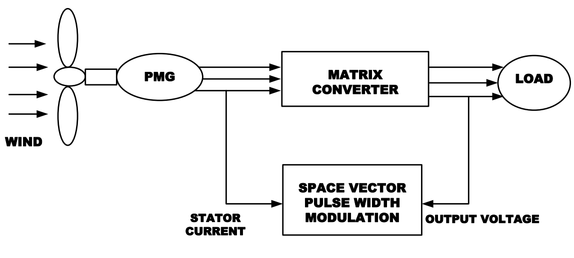


Fig 1 Block Diagram of Single Stage Power Conversion Wind Energy System Using AC-AC Matrix Converter

PMSG which is driven by the wind turbine is connected to the matrix converter as shown in Fig.1. The mechanical energy from the wind turbine is connected into electrical energy by permanent magnet generator. The output is given to the matrix converter. The matrix converter involves single stage conversion that is AC-AC. It converts the AC Voltage of fixed frequency into AC voltage of variable frequency.[6] The gating pulses to the matrix converter are generated by Space vector pulse width modulation. Stator current and output voltage are given as inputs to the SVPWM.[7] The SVPWM switching pattern for matrix converter is generated from FPGA controller.

III. Permanent Magnet Generator

The permanent magnet machine has permanent magnets instead of field windings. The permanent magnet machines can be classified into two main groups such as Surface Mounted Permanent Magnet (SMPM) machines and Interior Permanent Magnet (IPM) machines according to the installation of the permanent magnetic materials on the rotor [5]. The magnets will be mounted on the rotor surface or they will be interior to the rotor. In surface mounted permanent magnet machines, the permanent magnets are located on the outer surface of the rotor core. Another name for the rotor magnetic axis is direct axis (d-axis) or field flux axis and the principal path of the flux is through the magnets. The axis of rotor which is orthogonal to the direct axis regardless of the manner of mounting the permanent magnets on the rotor is called torque axis (quadrature axis or q-axis) [1].

The basic operation principles of these machines are the same as the normal machines. There exists an important difference between the direct and quadrature axes inductances for different types of permanent magnet machines [1]. The SMPM machines consist of many small permanent magnets that are placed on the surface of the rotor**.** Therefore, they have symmetrical reluctance in both axes and they are non-salient pole type machines. Literally, the d and q axes reactance of SMPM machines are equal ($L_q = L_d$). The arrangement of the permanent magnets on the rotor surface provides highest air gap flux density as it directly faces the air gap without the interruption of any other medium such as part of rotor laminations [6]. Lower structural integrity and lower mechanical robustness are the drawbacks of such an arrangement. Moreover the interior construction relieves the problem of retaining the magnets against centrifugal force. Therefore it is suitable for high-speed applications. The wind turbine extracts a little of wind power (P wind power) from the swept area and converts it into mechanical power (P_m) as given by the following equation.

$$P_m = {}^1/_2 \cdot \rho . A . \omega_{wind}^3 . C_p \quad (1)$$

Where ρ is the air density (1.225 kg/m^3), A is the swept area of the rotor (m^2), and ω_{wind} is the free wind speed (m/s). The power coefficient (C_P < 0.593) can be maximized for a given wind speed by adjusting the values of tip speed ratio and blade pitch angle optimally, using the data supplied by the manufacturer [5]. Through the optimal choice of C_P for a given speed, P_m and ω_m are assumed to be known values and are used as inputs to the generator.

The induced EMFs in the PMSG are considered sinusoidal and the saturation of magnetic core and the effect of rotor saliency are neglected. The generator rotor shaft is directly coupled to the wind turbine such that they have a mechanical speed of ω_m. The electrical speed (ω_e), rotor mechanical speed (ω_m), and the number of pair of poles (P) are related as $\omega_e = p.\ \omega_m$. The PMG is assumed to be balanced and its induced phase voltage is expressed as:

$$E_{ph} = 4.44. \emptyset . N . \frac{\omega_e}{2\pi} \quad (2)$$

Where $\emptyset_r$, the magnetic flux is a constant in a PMSG and N is the number of coil turns. Therefore the generator terminal phase voltage can be obtained as

$$V_{t-ph} < \varphi_{t-ph} = E_{ph} < \varphi_{s-ph} - I_{s-ph} < \theta_{s-ph} . (R_s + jX_s) \quad (3)$$

Where R_s is the winding resistance and X_s is the reactance. Also $\varphi_{s\text{-}ph}$, $\varphi_{t\text{-}ph}$ and $\theta_{s\text{-}ph}$ are the phase angles of E_{ph}, V_{t-ph} and phase current I_{s-ph} respectively for the phase $_{ph}$. The generator's input mechanical power can be calculated by:

$$P_m = 3E_{ph} . I_{s-ph} . \cos(\varphi_{sph} - \theta_{sph}) \quad (4)$$

IV. Matrix Converter

In the AC-AC converter family the most common type of converter is matrix converter. The AC-AC converter, which is an alternative of AC-DC-AC converter, called as direct or single stage converter is shown in Fig. 4.1. The matrix converter is a single-stage converter which has an array of m×n bidirectional power switches to connect an m-phase voltage source to an n-phase load directly [11]. The switching function of a switch is defined as:

$$S_{ij} = \begin{cases} 1, S_{ij} & \text{closed} \\ 0, S_{ij} & \text{open} \end{cases} \quad i\ \varepsilon \{A, B, C\}, j\ \varepsilon\ \{a, b, c\} \quad (5)$$

The Constraints can be expressed as:

$$S_{ia} + S_{ib} + S_{ic} = 1 \tag{6}$$

The AC-DC-AC converter also called as indirect matrix converter or two stage power converters is shown in Fig.2. The matrix converter is a forced commutated converter and it uses an array of controlled bidirectional switches as the main power element to create variable output voltage system with unrestricted frequency [9][10]. It does not have any DC-link circuit and does not need any massive energy storage elements. The major element in a matrix converter is the fully controlled four-quadrant bidirectional switch that permits high-frequency operation. The converter consists of 9 bi-directional switches arranged as three sets of three switches and controlled four-quadrant bidirectional switch that permits high-frequency operation. Since the converter consists of 3 sets of three switches,

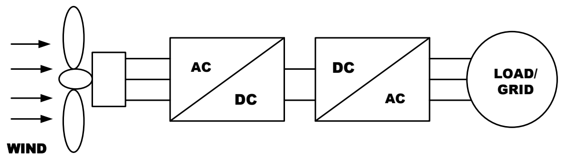


Fig. 2 Two Stage Power Conversion System

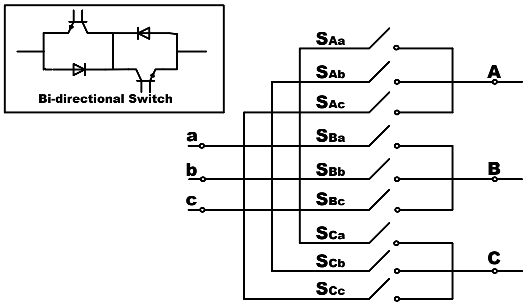


Fig. 3 Switching arrangement of Matrix Converter

any of the 3 input phases may be connected to any of the 3 output lines as shown in Fig.3. The switches are then controlled in such a way that the average output voltages are 3- phase sinusoids of the desirable frequency and magnitude. The matrix converter will act in accordance with four quadrants of motor operations, while generating no higher harmonics within the three-phase AC power supply [11]. The circuit is essentially capable of bi-directional power flow and also offers almost sinusoidal input current, with no harmonics. These switches help to acquire voltages with variable amplitude and frequency at the output side by switching input voltage with various modulation techniques [12]. These modulation techniques are to vary the voltage transfer ratio of the matrix converter. Out of the available modulation techniques, the Venturini modulation technique and the space vector pulse width modulation technique [13] are the mostly referred ones. SVPWM principles were applied to the matrix converter modulation problem that uses the space vectors within the analysis and control the matrix converters.

V. Implementation of Space Vector Pulse Width Modulation

The space vector algorithm is mainly based on the representation of the three phase input current and three phase output line voltages on the space vector plane. There are 27 different switching combinations for connecting output phases to input phases if the above mentioned combinations can be analyzed in three groups. Each output phase is directly connected to the three input phases in turns with six switching combinations in the first group [2]. In this case, the phase angles of output voltage vector and input voltage vector depend on each other. Similar condition is valid for current vectors too. For the space vector modulation technique, these switching states are not used in the matrix converter because the phase angle of both the vectors cannot be controlled independently [14]. There are 18 switching combinations in the second group in which the active voltage vector is created at variable amplitude and frequency [9]. Amplitude of the output voltages depend on the chosen input line voltages. In this case, the phase angles of the output voltage space vector and the input voltage space vector are independent of each other. Similar condition is applicable for current vectors too. The last group with 3 switching combinations consists of zero vectors. In this case, all the output phases are connected to the same input phase [15].

In the application of the space vector control technique of the matrix converter Output line voltages and input current space vectors are used. Fig.5.1 shows the representation of the input currents and Fig 5.2 shows output line voltage space vectors. Wherever |Vi| and |Vo| represent instantaneous input and output voltage vectors respectively [11], α_i and α_o represent the phase angles of input and output voltages respectively. So as to determine the switches that are conducting, the sectors of input currents and output line voltages of α_i and α_o got to be decided. There are 36 sectors based on the position of α_i and α_o. Table 5.1 show the combination of the switches which will be turning-on for each sector [10]. The switching combinations for turning on are resolute according to the specified vector also the duty period of each switch is determined by considering the common switching combinations of each vectors that is necessary to obtain the required voltage amplitude and frequency at the output of matrix converter [7]. The space vector representation supported by the SVM strategy becomes very fashionable and attributable to its simplicity. In contrast to sinusoidal PWM, SVM treats the 3 phase quantities as one equation referred to as space vector [8]. Where the phase voltages are represented as V_a, V_b and V_c. If V_a, V_b and V_c are balanced 3 phase sinusoidal voltage, then the locus of space vector is circular with a radius which is equal to the amplitude of the phase voltage.

$$V_S = {}^{2}\!/_{3}\left\{V_a(t) + V_b(t)e^{j2\pi/3} + V_c(t)e^{j2\pi/3}\right\} \quad (7)$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = {}^{2}\!/_{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \end{bmatrix}\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (8)$$

$$\alpha = \tan^{-1}\left({}^{V_\beta}\!/_{V_\alpha} \right) \quad (9)$$

a	b	c	V_A	V_B	V_C	V_{AB}	V_{BC}	V_{CA}
0	0	0	0	0	0	0	0	0
1	0	0	2/3	-1/3	-1/3	1	0	-1
1	1	0	1/3	1/3	-2/3	0	1	-1
0	1	0	-1/3	2/3	-1/3	-1	1	0
0	1	1	-2/3	1/3	1/3	-1	0	1
0	0	1	-1/3	-1/3	2/3	0	-1	1
1	0	1	1/3	-2/3	1/3	1	-1	0
1	1	1	0	0	0	0	0	0

Table 1 Switching States and Corresponding Outputs of Matrix Converter

Table 1 shows the switching patterns and the corresponding output voltage magnitudes of the matrix converter. For example, if the reference voltage is located in sector 1, voltage vectors V1, V2, V0 and V7 would be selected and applied within a sampling period. Fig. 4 and 5 shows the input current and output voltage switching vector respectively.

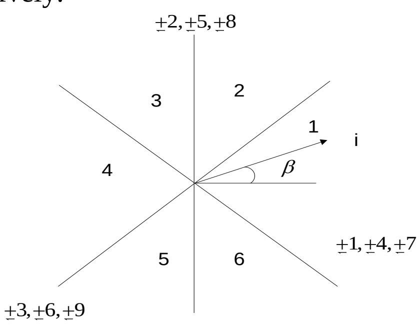


Fig. 4 Input currents switching vector

The space vector concept is derived from the rotating field of ac machine which is used for modulating the converter output voltage. In this modulation technique the three phase quantities can be transformed to their equivalent two phase quantity either in synchronously rotating frame or stationary d-q frame [6]. The reference vector magnitude can be found from this two phase component and it can be used for modulating

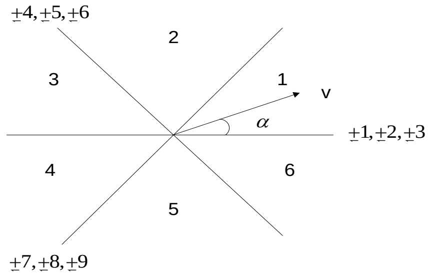


Fig. 5 Output line voltages switching vector

VI. Results and Discussions

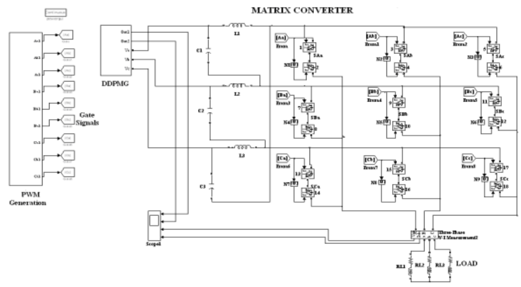


Fig. 6 .MATLAB/SIMULINK simulated model of AC-AC Matrix Converter

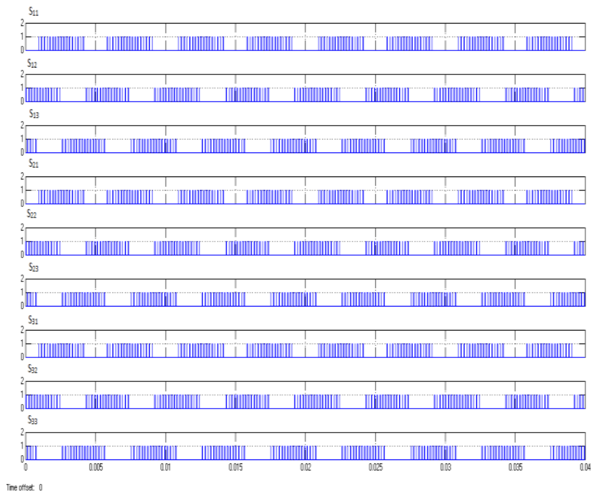


Fig. 7 Simulated Switching Pulses for matrix converter power switches

The Simulation is carried out in the MATLAB Software package and the simulation circuit is shown in Fig. 6. Fig.7 shows the pulses synthesized using SVPWM scheme to control the nine bidirectional switches of the matrix converter. The output voltage of the matrix converter obtained at different wind velocities under open loop condition is shown in the Fig.8. In Fig.8 it can be observed that the generated voltage is maximum i.e., 400V at 12m/s and minimum (170 V) at 6m/s. The frequency of the generated voltage is at its rated value of 50 Hz at 11 m/s and 12.5Hz at 8 m/s. When the matrix converter is fed through a closed loop controller the frequency and amplitude of matrix converter is fixed as 50Hz and 415 volt respectively as given in Fig.9. The frequency and voltage variations of the matrix converter under different wind speeds and the corresponding duty ratio calculated for the closed loop controller for voltage and frequency regulation has been presented in Table II. By properly adjusting the duty ratio of matrix converter the variable frequency is converted in to fixed value as 50Hz. Fig.10 (a) shows PMG generated frequency as 12.5Hz and the matrix converter converts this in to 50Hz by proper switching which is given in Table I. Similarly the 25Hz and 50Hz PMG generated voltages are converted in to 50Hz AC as shown in Fig. 10 (b) and 10(c) respectively.

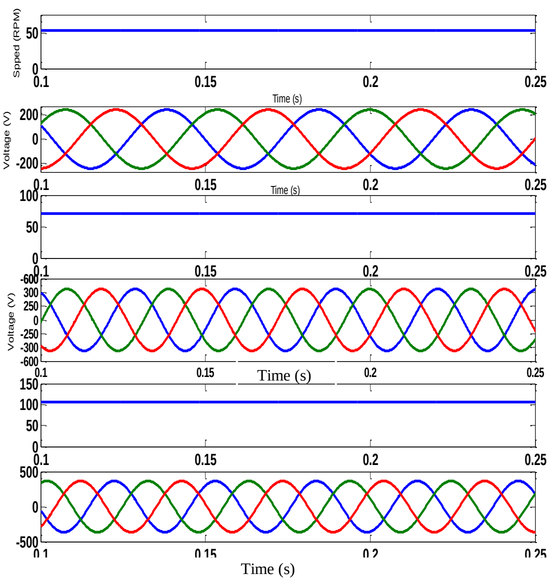


Fig.8 PMG output voltage for different wind velocities (a)8 m/s (b)9 m/s (c)11 m/s

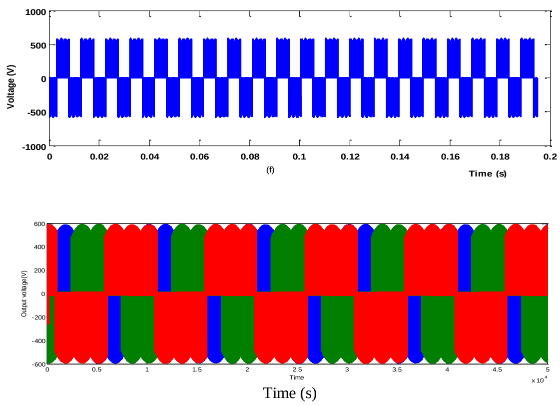
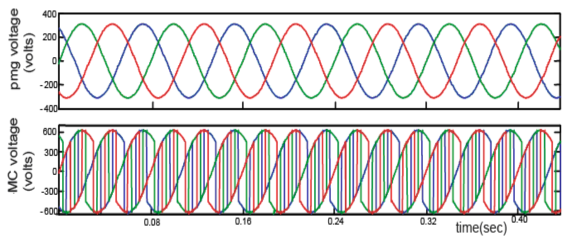


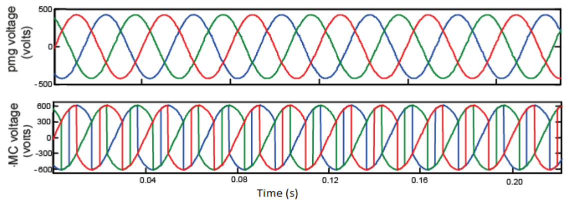
Fig 9 Simulated waveform of matrix converter output voltage

PMG Voltage (Volts)	Frequency of Generated Voltages (Hz)	Matrix Converter Output frequency (Hz)	Duty ratio
140	12.5	50	0.35
310	25	50	0.24
440	50	50	0.12

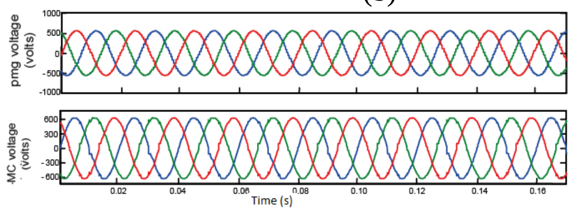
Table II PM generator frequency, voltages and matrix converter duty ratio and frequency



(a)



(b)



(c)

Fig. 10 Simulated waveforms of PMG fed matrix converter for different input frequencies (a) 12.5Hz (b) 25Hz and (c) 50Hz

S.No	Load in kW	Input Current THD %	Output Voltage THD %
1.	0.2	2.76	1.94
2.	0.4	2.60	1.86
3.	0.6	2.53	1.12
4.	0.8	2.49	0.82
5.	1	2.46	0.54

Table III Input Current and output voltage THD for different load conditions

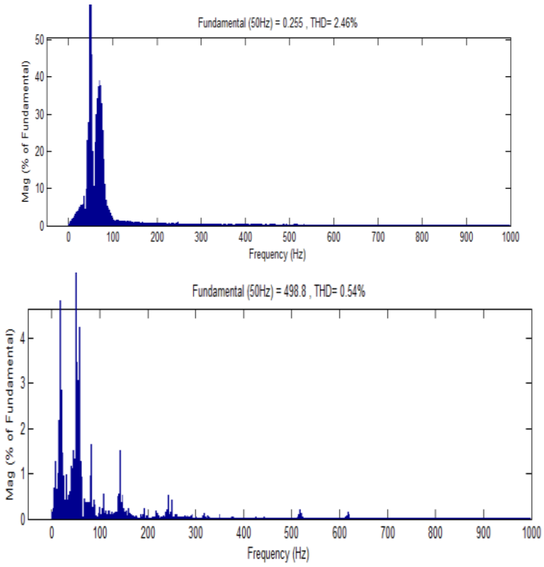


Fig .11 Input current and output voltage THD spectra for load of 1kW

Input current and output voltage THD of the matrix converter for different loading conditions are tabulated in Table III. The matrix converter provides the lower values of input current THD and output voltage THD, the harmonic spectra of input current and output voltage for a load of 1kW being illustrated in Fig 11.

VII Experimental Results and Discussion

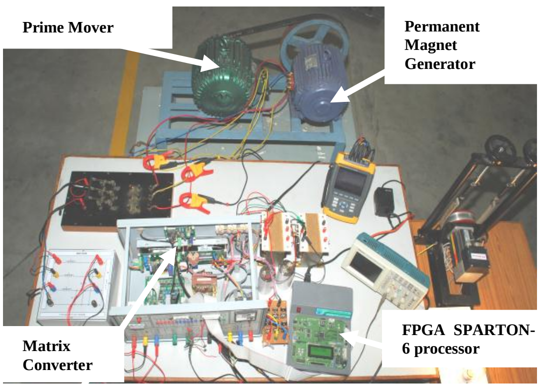


Fig. 11 Experimental setup of matrix converter with PM Generator

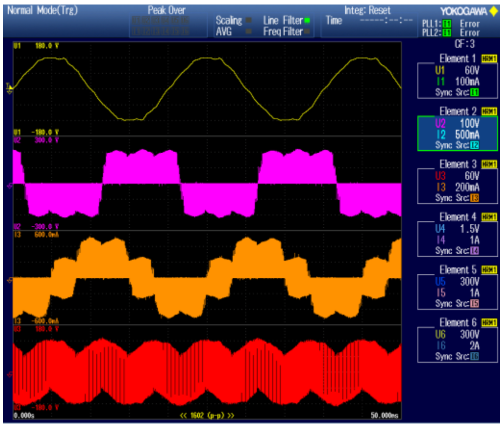
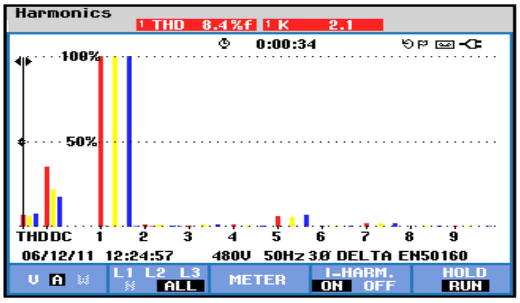
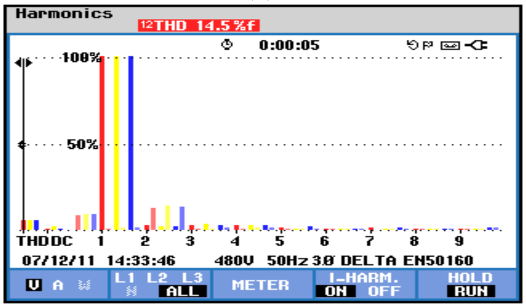


Fig. 12 Experimental wave forms of 1kW matrix converter from top to bottom PMG voltages, PWM puses, Line voltages and Phase voltages



(a)



(b)

Fig. 13 Experimental THD Spectra of (a) Load current and (b) Terminal voltage

To validate the simulation results experimental setup a 1 kW matrix converter is developed in the laboratory. The Matrix Converter is tested for different values of PM generor speed and corresponding generated frquency. Spartan-3 FPGA processor is used to generate and control SVPWM pulses for matrix converter. Fig 12 shows the experimental waveforms of PMG voltage, matrix converter line and phase voltages for a generator speed of 100 rpm and the corresponding frequency of the terminal voltage is 25 Hz. The experimenetal input and output THD is shown in Fig.13. which is 8.4 % and 14.5 % .The photograph of the experimental set up is shown in the Fig 11.

VIII Conclusion

This paper discusses a standalone wind energy conversion system using a variable speed permanent magnet generator with Matrix Converter. The output voltage of the matrix converter is analyzed for different values of input frequency. It is observed that it can deliver the rated voltage at a constant frequency of 50 Hz at its terminals under varying input conditions. The Switching Pattern is synthesized by the space vector pulse width modulation and the harmonics are eliminated and the results are presented. As far as the converter efficiency and THD are concerned, the matrix converter is more efficient than the conventional AC-DC-AC topology and the proposed design has higher efficiency and reliability.

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