Power Quality Improvement of Matrix Converter Based Wind Energy Conversion System

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1. Abstract:

With the increasing shortage in fossil fuels, and pollution problems renewable energy has become an important energy source. Among the other renewable energy sources wind energy has proven to be one of the most economical one. Wind energy, among all of the renewable energy sources, has made rapid developments and significant inroads into electrical power systems. Permanent Magnet Synchronous Generators employing these technologies have some significant advantages over conventional generators, such as no need of excitation, low volume and weight, high precision, and deletion of the gearbox. A variable-speed WECS with a permanent magnet synchronous generator and a matrix converter is proposed in this paper. Conventional Converter involves two stages of power conversion and subsequently, the efficiency of the overall WECS is reduced because of power quality issues mainly based on total harmonic distortion. The matrix converter is a simple and compact AC-AC converter. The matrix converter is mainly utilized to control the output voltage and frequency, and its input current and output voltage are closer to a sine wave. The proposed WECS with Matrix Converter has been modeled using Simulink of MATLAB software. The simulation results so obtained have validated the proposed scheme.

Keywords: PMSG, Matrix converter and WECS

2. Introduction

Wind has considerable potential as a global clean energy source, being both widely available, though diffuse, and producing no pollution during power generation. Wind energy is currently one of the most cost-competitive renewable energy technologies. Wind power has proved to be the most promising renewable energy source over the past decades which can overcome the concern of energy acquisition in future because of its environmentally amicable feature and sufficient availability. With the priority status accorded to it in many countries, the share of wind power in relation to overall installed capacity has increased significantly and in some countries, the share of wind in relation to the overall installed capacity is already approaching the 50% mark. It is predicted that by 2020 up to 12% of the world's electricity would be supplied from the wind power [2].

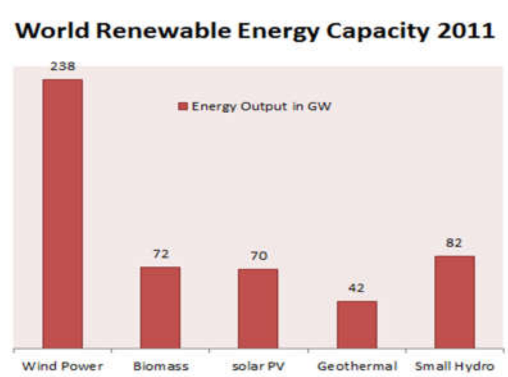


Fig. 1 World Renewable Energy Capacities in 2011[3]

Wind energy can be harnessed by a wind energy conversion system (WECS) which is composed of wind turbine, an electric generator, a power electronic converter, and a control system, as shown in Fig.2. There are different WECS configurations based on using synchronous or asynchronous machines and stall-regulated or pitch regulated systems The WECS can be classified in different types, but the functional objective of these systems is the same: converting the wind kinetic energy into electric power and injecting this electric power into the electrical load or the utility grid.

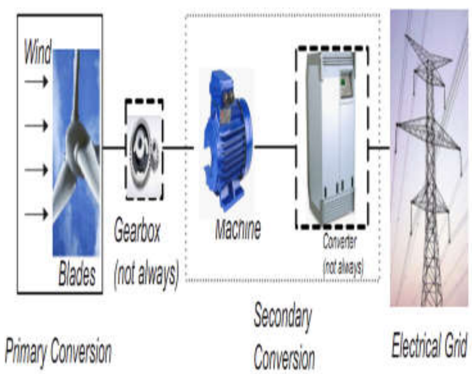


Fig.2 Block Diagram of a WECS

Permanent magnet (PM) machines are ideally suited for these applications, as they are inherently more efficient than wind-field machines. Moreover, PM machine rotors are easy to manufacture with the large number of poles required by low-speed, direct-drive WECSs.

The key feature of a direct AC – AC converter is the ability to directly perform AC – AC power conversion without the need of energy storage elements. The cycloconverter was the first direct AC – AC converter, this circuit is able to construct low frequency AC output voltage waveforms from successive segments of an AC supply of a higher frequency. However, due to the naturally commutated device characteristic, this converter topology has limited output frequency range, poor input power factor and high distortion in input and output waveforms [6]. The matrix converter (MC) provides direct AC-AC conversion and is considered an emerging alternative to the conventional two-stage AC-DC-AC converter topology. A matrix converter provides a large number of control levels that allows for independent control on the output voltage magnitude, frequency and phase angle, as well as the input power factor. When compared with the AC-DC-AC converter system, the bold feature of MC is elimination of the DC-link reactive elements, e.g. bulky capacitors and/ or inductors.

In this paper, first, a brief description of WECS is provided. Then, it is demonstrated how the wind energy can be optimally captured and converted to electric energy using a wind turbine, a permanent magnet synchronous generator and a matrix converter. Finally, the simulation results based on the proposed WECS are presented to support the theoretical expectations.

The Fig.3 shows a variable speed wind turbine is coupled with a direct drive permanent magnet synchronous generator through the Ac-Ac converter

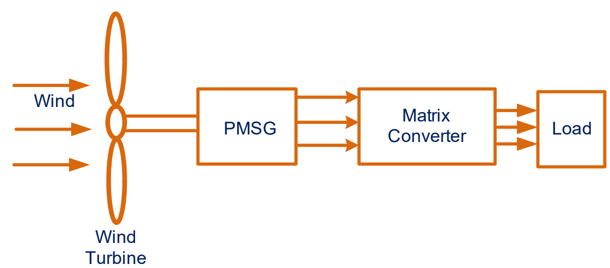


Fig.3 Block Diagram of Proposed Model of WECS

3. Designing of Wind Energy Conversion System

3.1 Modelling of Permanent magnet synchronous generator

The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind [7]. Permanent Magnet Generator provides an optimal solution for varying-speed wind turbines, of gearless or single-stage gear configuration [9]. This eliminates the need for separate base frames, gearboxes, couplings, shaft lines, and pre-assembly of the nacelle.

The output of the generator can be fed to the power grid directly. A high level of overall efficiency can be achieved, while keeping the mechanical structure of the turbine simple [9].The dynamic model of the PMSG is derived from the two phase synchronous reference frame, in which the d-axis is 90° ahead of the q-axis with respect to the direction of rotation. Fig.4 shows the d-q reference frame used in a salient-pole synchronous machine (which is the same reference as the one used in a PMSG), where θ is the mechanical angle, which is the angle between the rotor d-axis and the stator axis

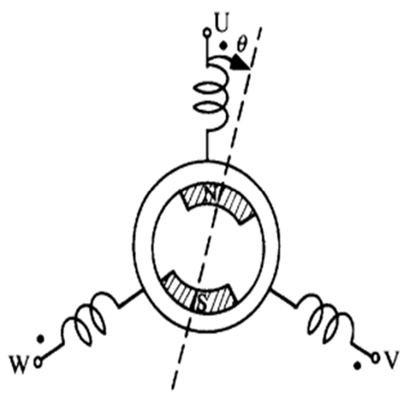


Fig.4 Analytical Model of Salient-Pole Synchronous Machine

Dynamic modeling of PMSG can be described in d-q reference system as follows [8], [5]:

$$\boldsymbol{V_q} = -\left(\boldsymbol{R_s} + \boldsymbol{pL_q}\right) \cdot \boldsymbol{i_q} + \boldsymbol{\omega_e L_d i_d} + \boldsymbol{\omega_e \Psi_f} \quad (1)$$

$$\boldsymbol{V_d} = -(\boldsymbol{R_s} + \boldsymbol{pL_d}) \cdot \boldsymbol{i_d} - \boldsymbol{\omega_e L_q i_q} \quad (2)$$

where R_s is the stator resistance, L_q and L_d are the inductances of the generator on the d and q axis, ψ_f is the permanent magnetic flux and ω_e is the electrical rotating speed of the generator, defined by

$$\boldsymbol{\omega_e} = \boldsymbol{P\omega_m}$$

Where **P** is the number of pole pairs of the generator and ω_m is the mechanical angular speed.

In order to complete the mathematical model of the PMSG, the expression for the electromagnetic torque can be described as [10]:

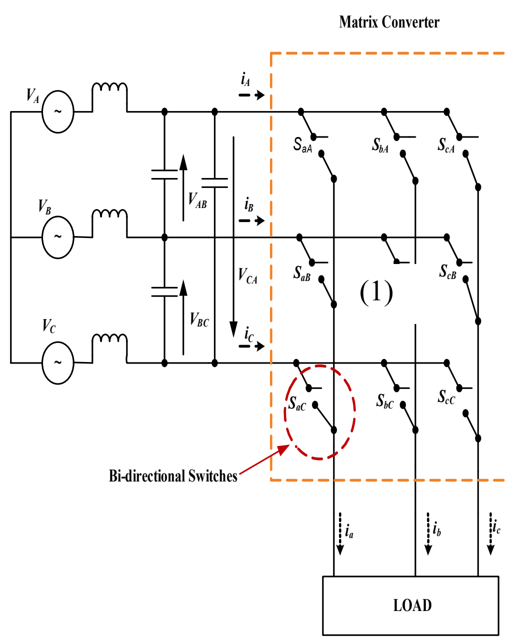
$$\boldsymbol{T_e} = \frac{3}{2}\boldsymbol{P}\left[\left(\boldsymbol{L_d} - \boldsymbol{L_q}\right)\boldsymbol{i_d i_q} - \boldsymbol{\Psi_f i_q}\right] \quad (3)$$

If $i_d = 0$, the electromagnetic torque is expressed as

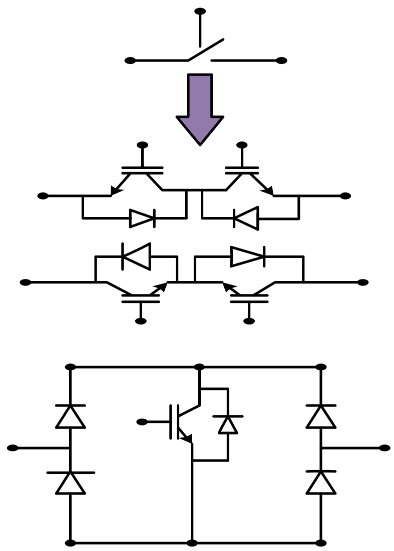
$$\boldsymbol{T_e} = -\frac{3}{2}\boldsymbol{p\Psi_f i_q} \quad (4)$$

3.2 Modelling of Matrix Converter

The matrix converter is a direct AC – AC converter that uses an array of mx n controlled bi-directional switches to directly connect m-phase inputs to n-phase outputs. The abilities of the bi-directional switch to conduct current in both directions and block voltage of both polarities enable am x n phase ideal matrix converter to generate n-phase variable output voltages with unrestricted frequency from m-phase AC supply voltages. Fig.5 shows the circuit configuration of a conventional matrix converter with an array of 3 x 3 bi-directional switches.



(a)



(b)

Fig.5 (a) Conventional Three-Phase to Three-Phase Direct Matrix Converter

(b) Typical Bi- directional switches

For the analysis of a three phase system, the instantaneous space vector representation can be utilized according to the following transformation:

$$\bar{x} = x_d + jx_q = \frac{2}{3}(x_a + \bar{a}x_b + \bar{a}^2 x_c) \qquad (5)$$

Where

$$\bar{a} = e^{j\frac{2\pi}{3}}$$

With the condition $x_a + x_b + x_c = 0$, the inverse transformation is

$$\left.\begin{aligned} x_a &= \bar{x}\cdot 1 \\ x_b &= \bar{x}\cdot\bar{a} \\ x_c &= \bar{x}\cdot\bar{a}^2 \end{aligned}\right\} \qquad (6)$$

Where (•) denotes the scalar product.

If the three phase system is supposed to be periodical with period $T = 2\pi/\omega$, the space vector components are periodical too and can be decomposed in the complex Fourier series [4] given by

$$\bar{x}(t) = \sum_{k=-\infty}^{+\infty} \bar{x}_k e^{jk\omega t}$$

where

$$\bar{X}_k = \frac{1}{T}\int_0^T \bar{x}(t)e^{-jk\omega t}\,dt \;, \quad k = 0, \pm 1, \pm 2, \dots\dots, \infty \qquad (8)$$

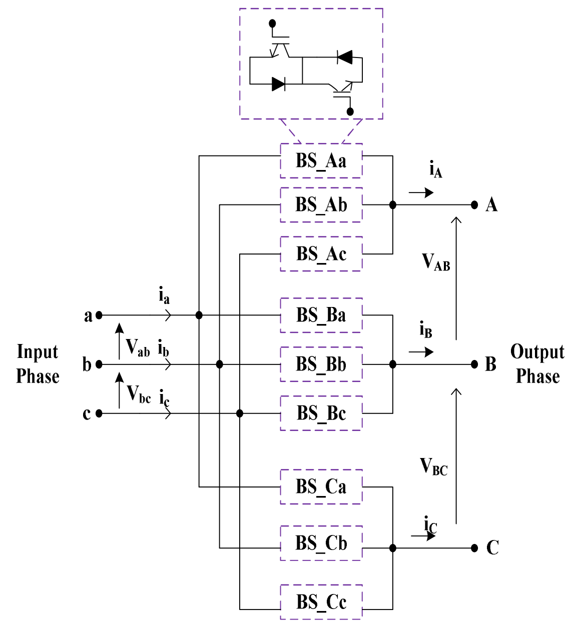


Fig.6 Schematic Diagram of Three-phase to Three-Phase Matrix Converter

With reference to the matrix converter and the relevant symbols shown in Fig.6 and accordingly to equation (4), it is possible to define the following space vectors:

$$\bar{v}_i = \frac{2}{3}(v_{ab} + \bar{a}\,v_{bc} + \bar{a}^2 v_{ca}) = v_i(t)e^{j\alpha_i(t)}$$

$$\bar{v}_o = \frac{2}{3}(v_{AB} + \bar{a}v_{BC} + \bar{a}^2 v_{CA}) = v_o(t)e^{j\alpha_o(t)}$$

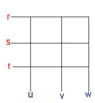
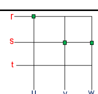
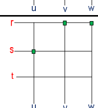
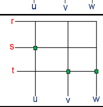
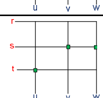
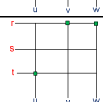
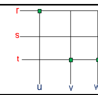
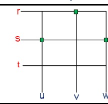
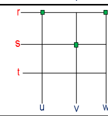
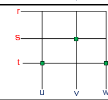
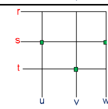
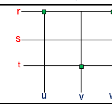
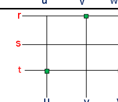
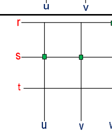
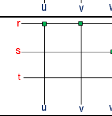
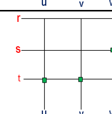
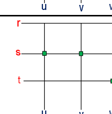
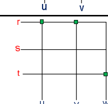
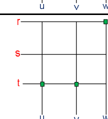
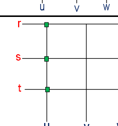
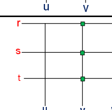
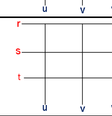
$$\bar{i}_i = \frac{2}{3}\left(i_a + \bar{a}i_b + \bar{a}^2 i_c\right) = i_i(t)e^{j\beta_i(t)}$$

$$\bar{i}_o = \frac{2}{3}\left(i_A + \bar{a}i_B + \bar{a}^2 i_C\right) = i_o(t)e^{j\beta_o(t)}$$

where $v_i\ (t)$, $v_o\ (t)$, $i_i(t)$ and $i_o(t)$are the time dependent magnitudes of the space vectors while $\alpha_i(t)$,$\alpha_i(t)$,$\beta_i(t)$ and $\beta_o(t)$ are the corresponding time dependent phase angles.

The space vector modulation technique is based on the spontaneous space vector representation of input and output voltages as well as current. Among the 27 possible switching configurations available in three phase matrix converter in which, only 21 switching strategies can be efficiently applied in space vector modulation algorithm, is represented in the following table (Table 1) which shows the 18 matrix converter active states. It can be noted that each active state uses only one input "phase to phase" voltage. Matrix converter vector modulations (SVM) can use three vector families to create the output voltage and the input current-3 null vectors (freewheeling of the load), 18 active vectors (with a fixed angular position and proportional to an input "phase to phase" voltage) and 6 rotating vectors (each input phase (r,s,t) is connected to a different output phase (u,v,w)). Most matrix vector modulations use only the two first vector families, as the third family has a position varying with time and are not useful to create the references.

Table.1 Switching Combinations used in the Space Vector Modulation

Switch Configuration	Matrix State	v_0	α_0	i_i	β_i
					
+1	 122	$2/3 v_{rsi}$	0	$2/\sqrt{3} i_{0r}$	-π/6
-1	 211	$-2/3\ v_{rsi}$	0	$-2/\sqrt{3} i_{0r}$	-π/6
+2	 233	$2/3\ v_{sti}$	0	$2/\sqrt{3} i_{0r}$	π/2
-2	 322	$-2/3\ v_{sti}$	0	$-2/\sqrt{3} i_{0r}$	π/2
+3	 311	$2/3\ v_{tri}$	0	$2/\sqrt{3} i_{0r}$	7π/6
-3	 133	$-2/3\ v_{tri}$	0	$-2/\sqrt{3} i_{0r}$	7π/6
+4	 212	$2/3\ v_{rsi}$	2π/3	$2/\sqrt{3} i_{0s}$	-π/6
-4	 121	$-2/3\ v_{rsi}$	2π/3	$-2/\sqrt{3} i_{0s}$	-π/6
+5	 323	$2/3\ v_{sti}$	2π/3	$2/\sqrt{3} i_{0s}$	π/2
-5	 232	$-2/3\ v_{sti}$	2π/3	$-2/\sqrt{3} i_{0s}$	π/2
+6	 131	$2/3\ v_{tri}$	2π/3	$2/\sqrt{3} i_{0s}$	7π/6
-6	 313	$-2/3\ v_{tri}$	2π/3	$-2/\sqrt{3} i_{0s}$	7π/6
+7	 221	$2/3\ v_{rsi}$	4π/3	$2/\sqrt{3} i_{0t}$	-π/6
-7	 112	$-2/3\ v_{rsi}$	4π/3	$-2/\sqrt{3} i_{0t}$	-π/6
+8	 332	$2/3\ v_{sti}$	4π/3	$2/\sqrt{3} i_{0t}$	π/2
-8	 223	$-2/3\ v_{sti}$	4π/3	$-2/\sqrt{3} i_{0t}$	π/2
+9	 113	$2/3\ v_{tri}$	4π/3	$2/\sqrt{3} i_{0t}$	7π/6
-9	 331	$-2/3\ v_{tri}$	4π/3	$-2/\sqrt{3} i_{0t}$	7π/6
0_1	 111	0	-	0	-
0_2	 222	0	-	0	-
0_3	 333	0	-	0	-

4. Results

4.1 Simulink Model of Wind Turbine Driven PMSG Fed to the Grid through a Matrix Converter

In this section of the dissertation work PMSG has been coupled with wind turbine, which generates the variable output in voltage and frequency. This output of the PMSG is fed to a Matrix converter for improving its performance in terms of harmonic distortion and power quality. The matrix converter is coupled to a grid with RLC filter. The performance analysis of the PMSG connected to the grid through a matrix converter with RLC filter has been carried out in this section.

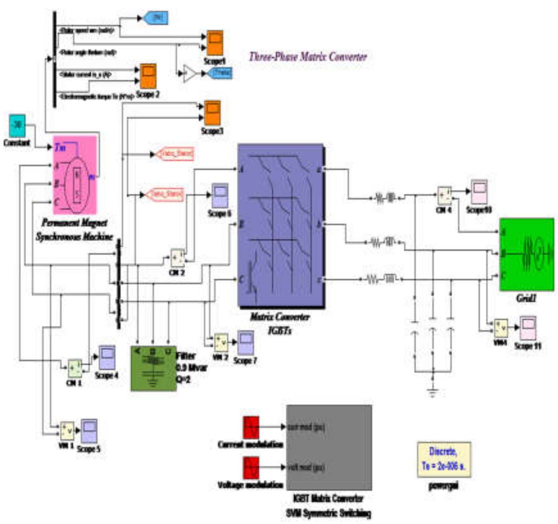
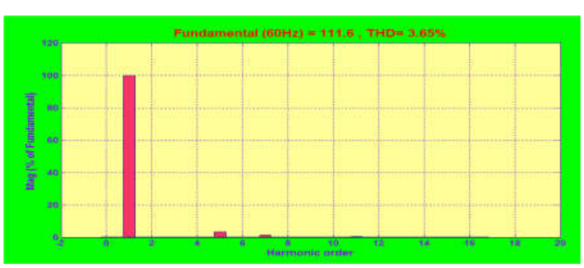
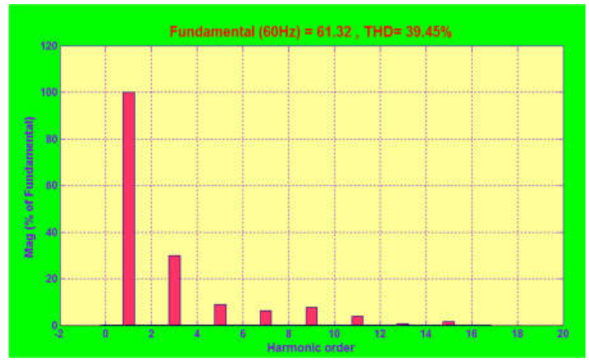


Fig.7 MATLAB Simulink Model of Proposed WECS Connected to the Grid through RLC Filter

4.2 Harmonic Analysis of PMSG Fed Matrix Converter with and without Filter



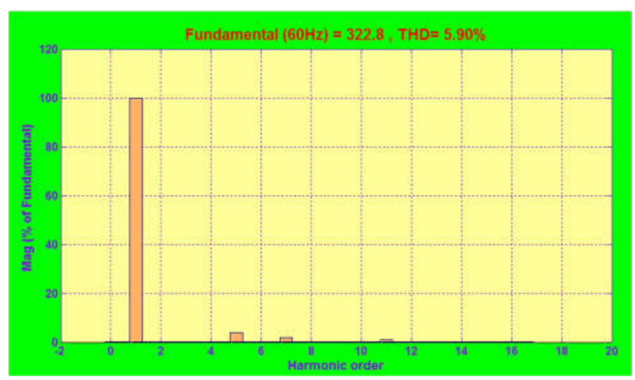
(a)



(b)

Fig.8 Total Harmonic Distortion in Input Current (a) Without Filter (b) With Filter

Figure 8 and 9 illustrates the waveforms for the total harmonic distortions of stator current and voltage without and with filter circuit, respectively. The THD analysis for stator voltage and stator currents has been carried out using the FFT block of the Simulink. From the FFT analysis it is clear that while the value of THD for the three phase stator current is sharply rising however, the value of THD for the stator voltage remains same after being filtered. Initially the value of THD in stator current is 3.65% but after filtering it becomes 39.45%.



(a)

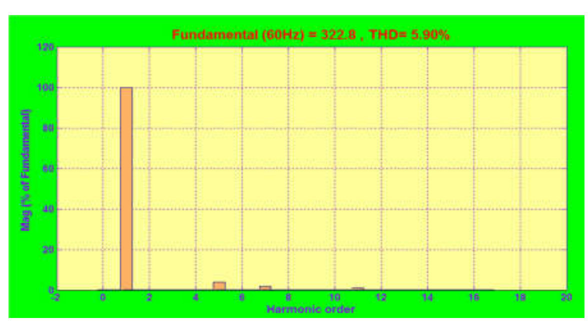
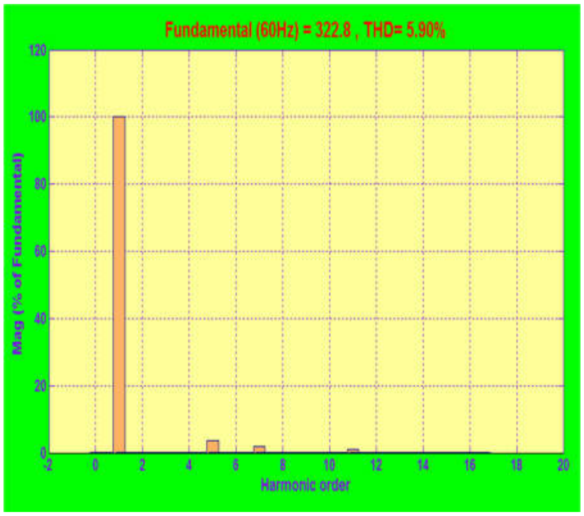


Fig.9 (a)



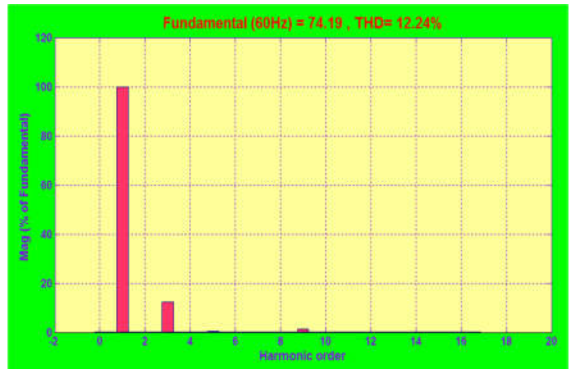
(b)

Fig.9 Total Harmonic Distortion in Input Voltage (a) Without Filter (b) With Filter

4.3 Harmonic Analysis for the O/P of Matrix Converter Fed to the Grid through the RLC Filter

The figure 7 shows the Simulink model of the PMSG feeding a three phase matrix converter. In this section the performance analysis for the output of three phase matrix converter has been carried out. The performance analysis has been done for the grid which is coupled to a matrix converter with filter having a typical value of R = 2 Ω, L = 1 mH and C=1μF. The value of RLC filter is selected to achieve the minimum value of harmonics present in the output voltage and current waveforms. The value of load current and line voltage can be observed from the scope 10 and 11 with filter respectively.

Figure 10 (a) and (b) illustrates the waveforms for the total harmonic distortions in current and voltage having filter circuit, respectively. The THD analysis for voltage and current has been carried out using the FFT block of the Simulink. From the FFT analysis it is clear that the value of THD for the current is 12.24% while the voltage is 0.76%.



(a)

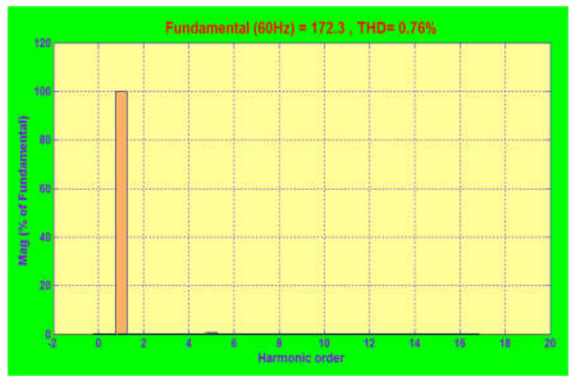


Fig.10 Total Harmonic Distortion in Output Side of Matrix Converter with RLC Filter (a) Current (b) Voltage

5. Conclusions

A three phase star connected with neutral ground filter has been used at the input of the matrix converter. The FFT analysis has been done for the input and output voltage and current of the matrix converter. The performance analysis for the input as well as output voltage and current has been done in terms of **Total Harmonic Distortion (THD**) and a Grid is also connected at the output of the matrix converter with and without RLC filter. The value of THD for the input voltage remains constant before and after filtering. The value of THD for input current increases drastically after filtering. The value of THD for input voltage is more than input current without filtering. The value of THD for input current is more than input voltage after filtering. The value of THD for the output side current of MC is reducing significantly after introducing the RLC filter between the output of MC and grid. The value of THD for the output side voltage of MC decreases drastically after filtering. The value of THD for the output current is more than the output voltage after filtering.

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