

## Space Vector Modulation Based Matrix Converter for Optimize the Reliability of Small Wind Turbine

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**Abstract:** Grid connection of small Permanent Magnet Generator (PMG) based wind turbines requires a power conditioning system. This study describes the reliability analysis of system and affecting factors on it. Due to optimize the reliability of system, a power electronic controller is used. The proposed power electronic controller in this study is AC-AC matrix converter and Space Vector Modulation (SVM) controlled technique is used for matrix converter. Comparing proposed method to other methods the advantage of this method is to have the system controlled as well as its main task, i.e., optimize reliability, eliminate open circuit and short circuit errors. The proposed method analyzed using MATLAB simulation.

**Key words:** Small wind power plant, power electronic controller, matrix converters, space vector modulation, optimize reliability

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### INTRODUCTION

The most emerging renewable energy source, wind energy, can play a major role in tackling the double challenge of energy security and global warming, because they are not depletable and produce less greenhouse-gas emissions than fossil fuels (Silva *et al.*, 2010).

Wind energy which by means of power electronics is changing from being a minor energy source to be acting as an important power source in the energy system. A wide-spread use of wind energy sources in distribution networks, the main advantages of using renewable energy sources are the elimination of harmful emissions and the inexhaustible resources of the primary energy. However, the main disadvantage, apart from the higher costs is the uncontrollability. The availability of renewable energy sources has strong daily and seasonal patterns and the power demand by the consumers could have a very different characteristic. Therefore, it is difficult to operate a power system installed with only renewable generation units due to the characteristic differences and the high uncertainty in the availability of the renewable energy sources.

The small wind turbine technology is one of the most emerging renewable technologies. It started in the 1980's with a few tens of KW production power to today with Multi-MW range wind turbines that are being installed. This also means that wind power production in the beginning did not have any impact on the power system control but now due to their size they have to play an active part in the grid.

Micro grid is a distribution system with several types of distributed resources (wind, photovoltaic, fuel cells, micro turbines, batteries, etc.) serving a set of electric loads that are residential, commercial, industrial or a combination of any of the three. A potential advantage of a micro grid is that it may have a lower cost than the existing utility service (Smallwood, 2002).

Generating energy through the Wind Energy Conversion System (WECS) is one of the most desired and updated ways in the field of renewable energy like, wind because it has no major complexity on implementation. There are mainly three types of Wind driven generators which are fixed speed and variable speed wind turbines induction generator's under the category of fixed speed and under variable speed there are two types of generators such as Doubly Fed Induction Generator (DFIG) and PMSG. PMSG is an attractive choice for variable-speed generation system. Due the following advantages, it can connected directly to the turbine without gearbox and do not require any external excitation current. So, it can operate at low speeds and reduce again weight, losses and costs (Sekhar *et al.*, 2014; Savio and Kumar, 2012).

Grid connection of small Permanent Magnet Generator (PMG) based wind turbines in the WECS requires a power conditioning system (Arifujjaman *et al.*, 2009a, b). The analysis reveals that the reliability of the power conditioning system of such PMG based wind turbines is fairly low and it reduces to 84% of initial value within 1 year.

The investigation is further enhanced by identifying the least reliable component within the power

conditioning system and found that the inverter has the dominant effect on the system reliability. The analysis also reveals that new research is required to determine a power electronics configuration for small wind turbine conversion systems (Arifujjaman *et al.*, 2009).

Because the power generated by wind generator is three-phase alternating current of variable voltage variable frequency, it must be transformed to that of fixed voltage and fixed frequency of 50 Hz which is the same as that of grid voltage. Thus, wind power which generated by the wind generator can parallel in the power grid (Liyong *et al.*, 2009).

Due to optimize the reliability of system, a power electronic controller is used. The proposed power electronic controller in this study is AC-AC matrix converter and Space Vector Modulation (SVM) controlled technique is used for matrix converter.

The matrix converter is an array of controlled semiconductor switches that connects directly the three-phase source to the three-phase load. Among the most desirable features in power frequency changers are the following:

- Simple and compact power circuit
- Generation of load voltage with arbitrary amplitude and frequency
- Sinusoidal input and output currents
- Operation with unity power factor for any load
- regeneration capability

These ideal characteristics can be fulfilled by matrix converters and this is the reason for the tremendous interest in the topology.

The matrix converter is a forced commutated converter which uses an array of controlled bidirectional switches as the main power elements to create a variable output voltage system with unrestricted frequency (Wheeler *et al.*, 2002).

Space Vector Modulation (SVM) is an algorithm for the control of Pulse Width Modulation (PWM). It is used for the creation of alternating waveform (AC) waveform. It most commonly used in inverters, 3 phase ac powered motors. There are various types of SVM that result in different quality and computational requirements (Savio and Kumar, 2012).

The SVM method represents the three-phase input currents and output line-to-line voltages as space vectors. It is based on the concept of approximating a rotating reference voltage vector with those voltages physically realisable on a matrix converter (Zhang *et al.*, 1998).

Space Vector Modulation (SVM) controlled technique is used for matrix converter switching which can eliminate the switching losses by selected switching states. Proposed work is often seen as a future concept for variable speed drives technology (Fig. 1).

Direct matrix converter shown in Fig. 2 is direct AC-AC converter which has several advantages over traditional inverters. It provides sinusoidal input and output waveforms with minimal higher order harmonics and no sub harmonics, it has inherent bi-directional energy flow capability; the input power factor can be fully controlled. Last but not least, it has minimal energy storage requirements which allows to get rid of bulky and lifetime-limited energy-storing capacitors frequency converters. It consists of consists of 9 bidirectional switches that allow any output phase to be connected to any input phase. With nine bi-directional switches the matrix converter can theoretically assume 512 (2<sup>9</sup>) different switching states combinations. But not all of them can be usefully employed. Regardless to the control method used, the choice of the matrix converter switching states combinations to be used must comply with two basic rules, they are that the converter is supplied by a voltage source and usually feeds an inductive load, the input phases should never be short-circuited and the output currents should not be interrupted. From a practical point of view by these rules imply that one and only one bi-directional switch per output phase must be switched on at any instant. By this constraint in a three phase to three phase matrix converter 27 switching combinations are the permitted switching. no energy storage components are absent between the input and output side of the matrix converter, the output voltages and current have to be generated directly from the input voltages and current. The input power factor control capability is another attractive feature of matrix. The input filter acts as an interface between the matrix converter and the AC mains to prevent unwanted harmonic currents from flowing into AC mains.

The space vector modulation technique is used to control the inverter output voltage and frequency it constructs the desired sinusoidal output three phase voltage by selecting the valid switching states of a three phase matrix converter and calculating their corresponding on time duration. The valid switching states of a matrix converter are represented as voltage space vectors. Implementation of SVM method involves two main procedures, switching vector selection and vector on time calculation.

For three phase matrix converters there are 27 valid switch combinations giving thus 27 voltage vectors. These can be divided in to three vectors, they are as follows synchronously rotating vectors, stationary vectors, zero vectors which was in Table 1 (Sekhar *et al.*, 2014; Zhang, 2015).

**Micro turbine modeling:** The proposed micro grid is an isolated system comprised of a conventional synchronous

Table 1: Switching configuration and vectors used in matrix converter (Sekhar et al., 2014)

Switching configurations				Output voltage		Input current	
SC. No.	A	B	C	$V_0$	$a_0$	$I_1$	$\beta_1$
<b>Group I</b>							
+1	a	b	b	$2/3V_{ab}$	0	$2/3A$	$-\pi/6$
-1	b	a	a	$-2/3V_{ab}$	0	$-2/3A$	$-\pi/6$
+2	b	c	c	$2/3V_{bc}$	0	$2/3iA$	$\pi/2$
-2	c	b	b	$-2/3V_{bc}$	0	$-2/3iA$	$\pi/2$
+3	c	a	a	$2/3V_{ca}$	0	$2/3iA$	$7\pi/6$
-3	a	c	c	$-2/3V_{ca}$	0	$-2/3iA$	$7\pi/6$
+4	b	a	b	$2/3V_{ab}$	$2\pi/3$	$2/3iB$	$-\pi/2$
-4	a	b	a	$-2/3V_{ab}$	$2\pi/3$	$-2/3iB$	$-\pi/2$
+5	c	b	c	$2/3V_{bc}$	$2\pi/3$	$2/3iB$	$\pi/2$
-5	b	c	b	$-2/3V_{bc}$	$2\pi/3$	$-2/3iB$	$\pi/2$
+6	a	c	a	$2/3V_{ca}$	$2\pi/3$	$2/3iB$	$7\pi/6$
-6	c	a	c	$-2/3V_{ca}$	$2\pi/3$	$-2/3iB$	$7\pi/6$
+7	b	b	a	$2/3V_{ab}$	$4\pi/3$	$2/3iC$	$-\pi/2$
-7	a	a	b	$-2/3V_{ab}$	$4\pi/3$	$-2/3iC$	$-\pi/2$
+8	c	c	b	$2/3V_{bc}$	$4\pi/3$	$2/3iC$	$\pi/2$
-8	b	b	c	$-2/3V_{bc}$	$4\pi/3$	$-2/3iC$	$\pi/2$
+9	a	a	c	$2/3V_{ca}$	$4\pi/3$	$2/3iC$	$7\pi/6$
-9	c	c	a	$-2/3V_{ca}$	$4\pi/3$	$-2/3iC$	$7\pi/6$
<b>Group II</b>							
$0_a$	a	a	a	0	$\times$	0	$\times$
$0_b$	b	b	b	0	$\times$	0	$\times$
$0_c$	c	c	c	0	$\times$	0	$\times$
<b>Group III</b>							
$x_1$	a	b	c	$\times$	$\times$	$\times$	$\times$
$x_1$	a	c	b	$\times$	$\times$	$\times$	$\times$
$x_1$	b	c	a	$\times$	$\times$	$\times$	$\times$
$x_1$	b	a	c	$\times$	$\times$	$\times$	$\times$
$x_1$	c	a	b	$\times$	$\times$	$\times$	$\times$
$x_1$	c	b	a	$\times$	$\times$	$\times$	$\times$

generator powered by a steam turbine, constant and variable loads, matrix converter and renewable sources of energy (wind) which are connected to the grid via power electronics and transformers. The micro grid in this study is connected to the main grid with the matrix converter. In this case, synchronous generator is equipped with power system stabilizer and steam governor. The renewable sources operate at maximum available power (from wind) to save costs of extra control mechanisms such as pitch control as well as to exploit the maximum natural energy. Thus, their power is subject to change as the ambient energy fluctuates. In the rest of this study we model different equipment of the proposed micro grid.

**Synchronous generator model:** The micro grid can be represented by a set of differential and algebraic equations to be solved simultaneously where the differential equations represent the synchronous generator and the algebraic equations describes the power balance in the micro grid. In this study, we model the synchronous generator using the flux-decay model (oneaxis model) given by the following equations (Sauer and Pai, 2006) as:

$$\dot{E}'_q = \frac{1}{T'_{do}} \left( -E'_q - (X_d - X'_d)I_d + E_{fd} \right) \quad (1)$$

$$\dot{\delta} = \omega_1 - \omega_s \quad (2)$$

$$\dot{\omega} = \frac{\omega_s}{2H} \left( P_m - E'_q I_q - (X_q - X'_q)I_d I_q \right) \quad (3)$$

Where:

- $T'_{do}$  = The direct axis open circuit transient time constant
- $X_d$  = The direct axis synchronous reactance of the generator
- $X'_d$  = The direct axis transient reactance of the generator
- $X_q$  = The quadrature axis synchronous reactance of the generator
- $E'_q$  = The instantaneous voltage proportional to the field flux linkage
- $\delta$  = The rotor angle deviation
- $E_{fd}$  = The field voltage
- $P_m$  = The mechanical input to the generator
- $\omega$  = The angular speed
- $H$  = The machine inertia

In addition, the following algebraic equations are used to express the model of the synchronous generator:

$$0 = R_s I_d - X_q I_d + V_d \quad (4)$$

$$0 = R_s I_q - X'_d I_d - E'_q \quad (5)$$

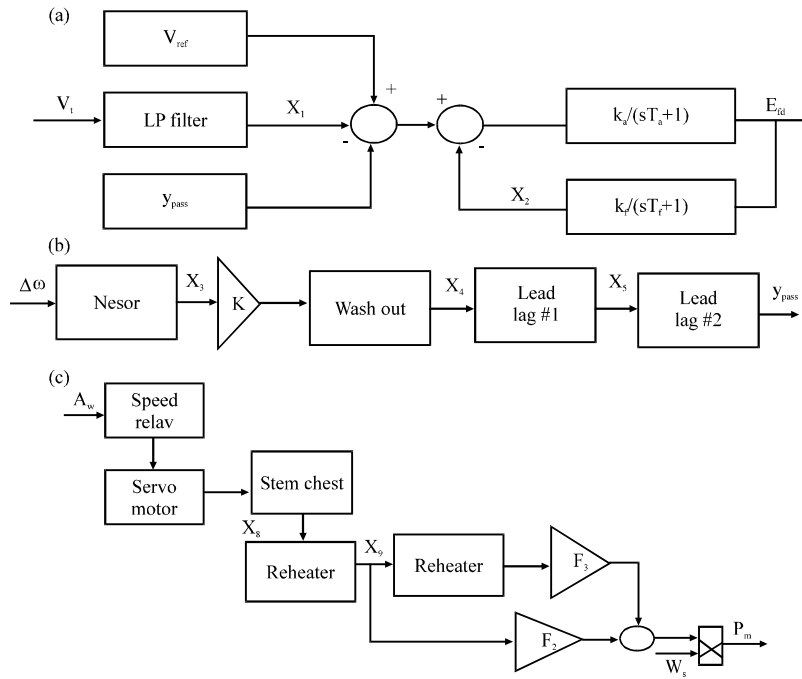


Fig. 1: a) The excitation system of the generator; b) the power system; stabilizer of the generator; c) the steam turbine governor of the generator

$$0 = V_t^2 - (V_d^2 + V_q^2) \quad (6)$$

Where:

- $R_s$  = The stator resistance
- $V_t$  = The terminal voltage
- $I_d$  and  $V_d$  = Denote d-axis stator current and voltage, respectively
- $I_t$  and  $V_q$  = The q-axis stator current and voltage

The synchronous generator is equipped with exciter, Power System Stabilizer (PSS) and governor with block diagrams shown in Fig. 1a-c. The exciter can be represented by following transfer function:

$$E_{fd} = \frac{K_a}{s.T_a + 1} \left( -\frac{V_t}{s.T_r + 1} - \frac{E_{fd}.K_f}{s.T_f + 1} + y_{pss} + V_{ref} \right) \quad (7)$$

Where:

- $T_r$  and  $T_a$  = Time constants
- $K_f$  and  $K_a$  = The gains
- $Y_{pss}$  = The stabilization signal used to control the terminal voltage  $V_t$  of the generator

Next, the power system stabilizer is represented by the following transfer function:

$$\frac{y_{pss}}{\Delta\omega} = \left( \frac{s.T_{2n} + 1}{s.T_{2d} + 1} \right) \left( \frac{s.T_{1n} + 1}{s.T_{1d} + 1} \right) \left( \frac{1}{sT_s} \right) \left( \frac{s}{sT_w + 1} \right) \quad (8)$$

Where:

- $T_s$  and  $T_w$  = The sensor and washout time constants
- $T_{1n}$ ,  $T_{1d}$ ,  $T_{2n}$  and  $T_{2d}$  = Lead and lag time constants

Finally, the steam turbine governor is used to provide and control the mechanical power to the generator. The speed governing system consists of proportional regulator, a speed relay and a servomotor while the steam turbine consists of steam chest and reheaters. The governor is represented as:

$$\frac{P_m}{\Delta\omega} = \left( \frac{1}{s.T_s + 1} \right) \left( \frac{1}{s.T_5 + 1} \right) \left( \frac{1}{sT_{sm} + 1} \right) \left( \frac{1}{sT_{sr} + 1} \right) \left( F_2 \frac{1}{sT_4 + 1} + F_3 \right) \quad (9)$$

Where:

- $T_{sr}$  and  $T_{sm}$  = Speed relay and servo motor time constants, respectively
- $T_3$ ,  $T_4$  and  $T_5$  = The steam turbine time constants
- $F_2$  and  $F_3$  = Turbine stages torque fractions

**Renewable energy source model:** Since, there is no control on the power generated by the renewable sources and these sources are connected to the micro grid through power electronics they are modeled as variable

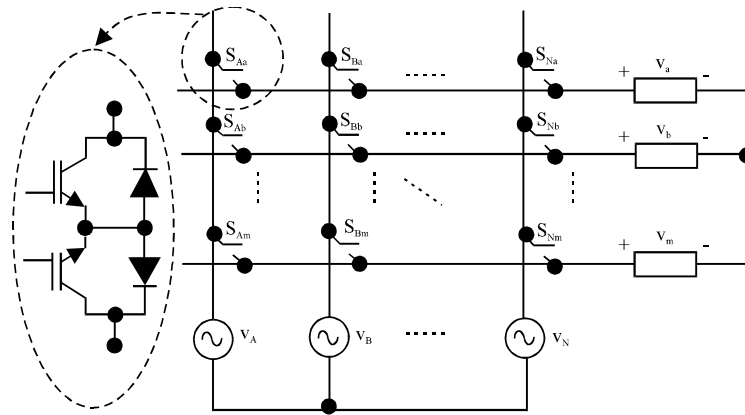


Fig. 2: AC-AC matrix converter

generations where their powers vary with the ambient energy variations such as changes in the wind speed or the solar radiation. Thus, the renewable sources can be modeled by power balance equations ( $I =$  renewable bus number) given in Eq. 10 as:

$$0 = -V_i \sum_{j=1}^N V_j Y_{ij} \cos(\theta_i - \theta_j - \phi_{ij}) + P_{Ri} \tag{10}$$

$$0 = -V_i \sum_{j=1}^N V_j Y_{ij} \sin(\theta_i - \theta_j - \phi_{ij}) + Q_{Ri}$$

where,  $P_{ij}$  and  $Q_{ij}$  The active and reactive generated powers by the renewable sources and subject to change as the ambient energy change

**The proposed structure to improve the reliability of small wind turbines**

**The used matrix converter:** Direct matrix converter shown in Fig. 2 is direct AC-AC converter which has several advantages over traditional inverters.

**Control method; svm for AC-AC matrix converter:** The space vector modulation technique is used to control the inverter output voltage and frequency it constructs the desired sinusoidal output three phase voltage by selecting the valid switching states of a three phase matrix converter and calculating their corresponding on time duration. The valid switching states of a matrix converter are represented as voltage space vectors. Implementation of SVM method involves two main procedures, switching vector selection and Vector on time calculation.

For three phase matrix converters there are 27 valid switch combinations giving thus 27 voltage vectors. These can be divided in to three vectors, they are as follows synchronously rotating vectors, stationary vectors, zero vectors which was in Table 1.

**Synchronously rotating vectors:** Switching state connecting every output phase to a different input

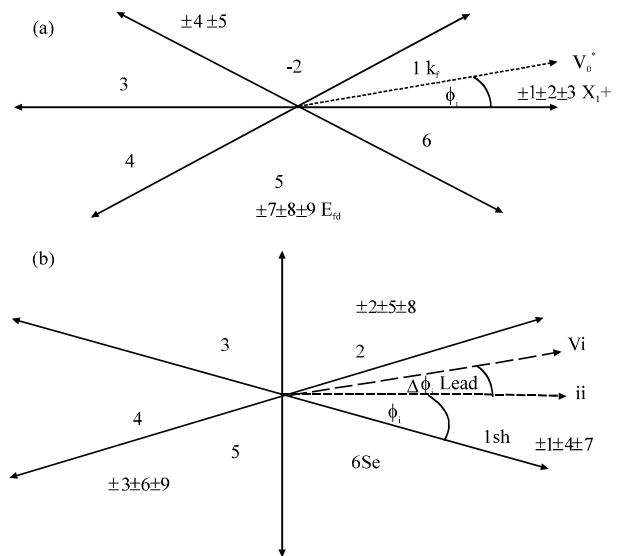


Fig. 3: a) Output line-to-neutral voltage vector and b) Input line current vector

phase. It produce voltage space vectors rotating with the input angular frequency. Constant magnitude and angular frequency.

**Stationary vectors:** It use only two input voltage at a time. It produce voltage space vectors with constant angle. Varying magnitude.

**Zero vectors:** All output phases are connected to same input phase. It produce zero output voltage. From the Fig. 3 the three-phase matrix converter module includes nine bidirectional switches a, b and c are the voltage and current at the input side of the matrix converter and the output side are denoted by A-C:

$$V_a = V_m \sin(\omega t) \tag{11}$$

$$V_b = V_m \sin(\omega t - 2\pi/3) \quad (12)$$

$$V_a = V_m \sin(\omega t - 4\pi/3) \quad (13)$$

The switching function of a switch in Fig. 3 is defined as:

$$S_{ij}(t) = 1 (S_{ij} \text{ closed}) \text{ if it is } 0 (S_{ij} \text{ opened})$$

ie(a, b, c) and jε(A, B, C) At any time, there is always only one switch connecting one output phase to one input phase:

$$S_{aj} + S_{bj} + S_{cj} = 1 \quad (14)$$

The space vector approach is based on the instantaneous space vector representation of input and output voltages and currents. We can describe the input/output current and voltage vectors as follows:

$$V_i = 2/3(v_a + v_b e^{j2\pi/3} + v_c e^{j4\pi/3}) = V_i e^{j\alpha_i} \quad (15)$$

$$V_o = 2/3(v_A + v_B e^{j2\pi/3} + v_C e^{j4\pi/3}) = V_o e^{j\alpha_o} \quad (16)$$

$$i_i = 2/3(i_a + i_b e^{j2\pi/3} + i_c e^{j4\pi/3}) = I_i e^{j\alpha_i} \quad (17)$$

$$i_o = 2/3(i_A + i_B e^{j2\pi/3} + i_C e^{j4\pi/3}) = I_o e^{j\alpha_o} \quad (18)$$

From Eq. 15-18 the output voltage vector and the current vector can be determined for each switching configuration.

**The AC-AC matrix converter:** In this power generation system, a horizontal axis wind turbine with a PMSG connected to the resistive load through a direct AC-AC matrix converter is considered. It consists of wind turbine, PMSG, direct matrix converter and feeding an resistive load as shown in Fig. 4. The permanent magnet synchronous generator is used in stand-alone energy conversion systems due to features like high efficiency and low maintenance cost. To overcome the difficulties like DC-link, AC-DC-AC conversion, energy storage elements direct matrix converter is used. Filters are used to eliminate the harmonics. The input power factor control capability is another attractive feature of matrix converters. The space vector modulation technique is used to control the inverter output voltage and frequency. By this control technique switching losses are controlled by selected switching using vector control.

### RESULTS AND DISCUSSION

The proposed micro turbine are simulated under uncertainty conditions of wind energy in this study to

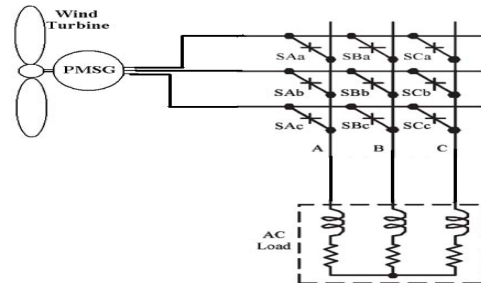


Fig. 4: Circuit diagram of the proposed method

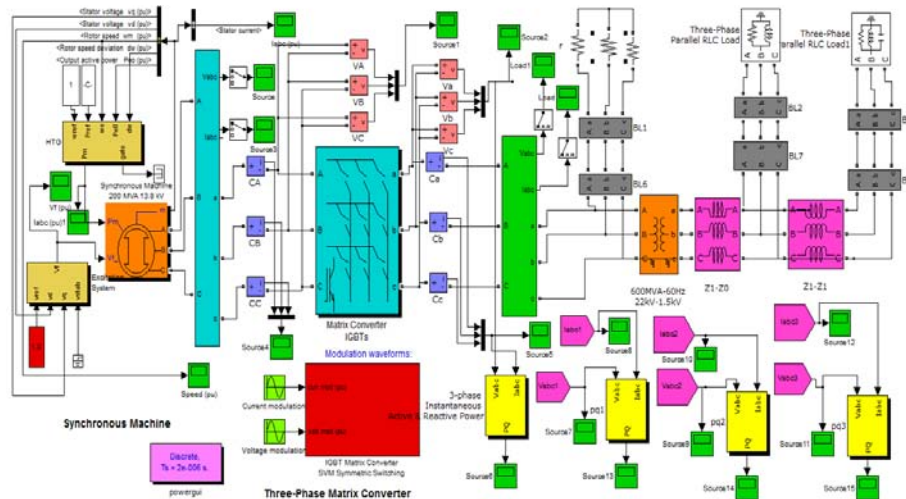


Fig. 5: Simulink model of PMSG with existence of AC-AC matrix converter

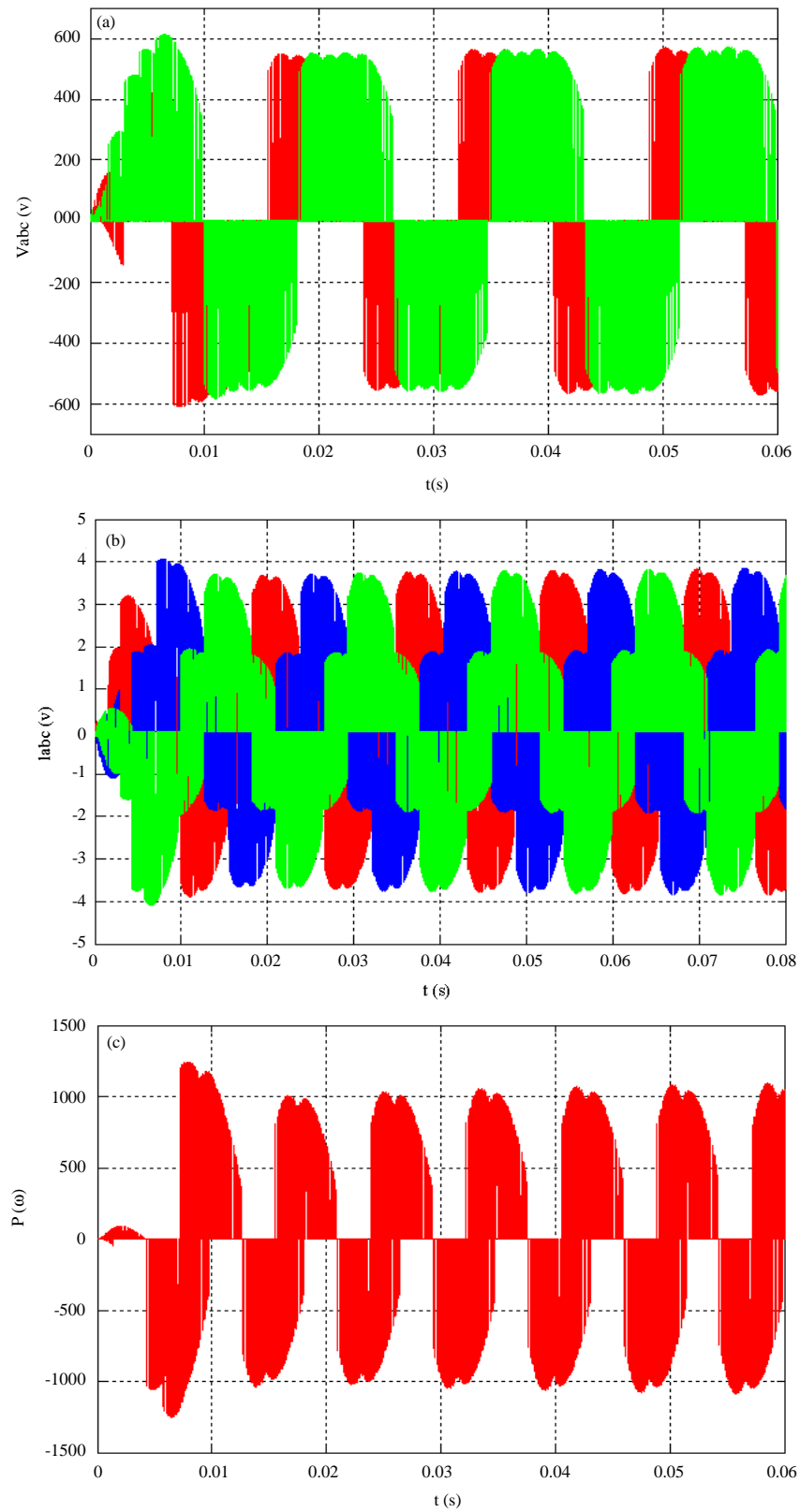


Fig. 6: a) Output voltage b) Output current (c) active power of load

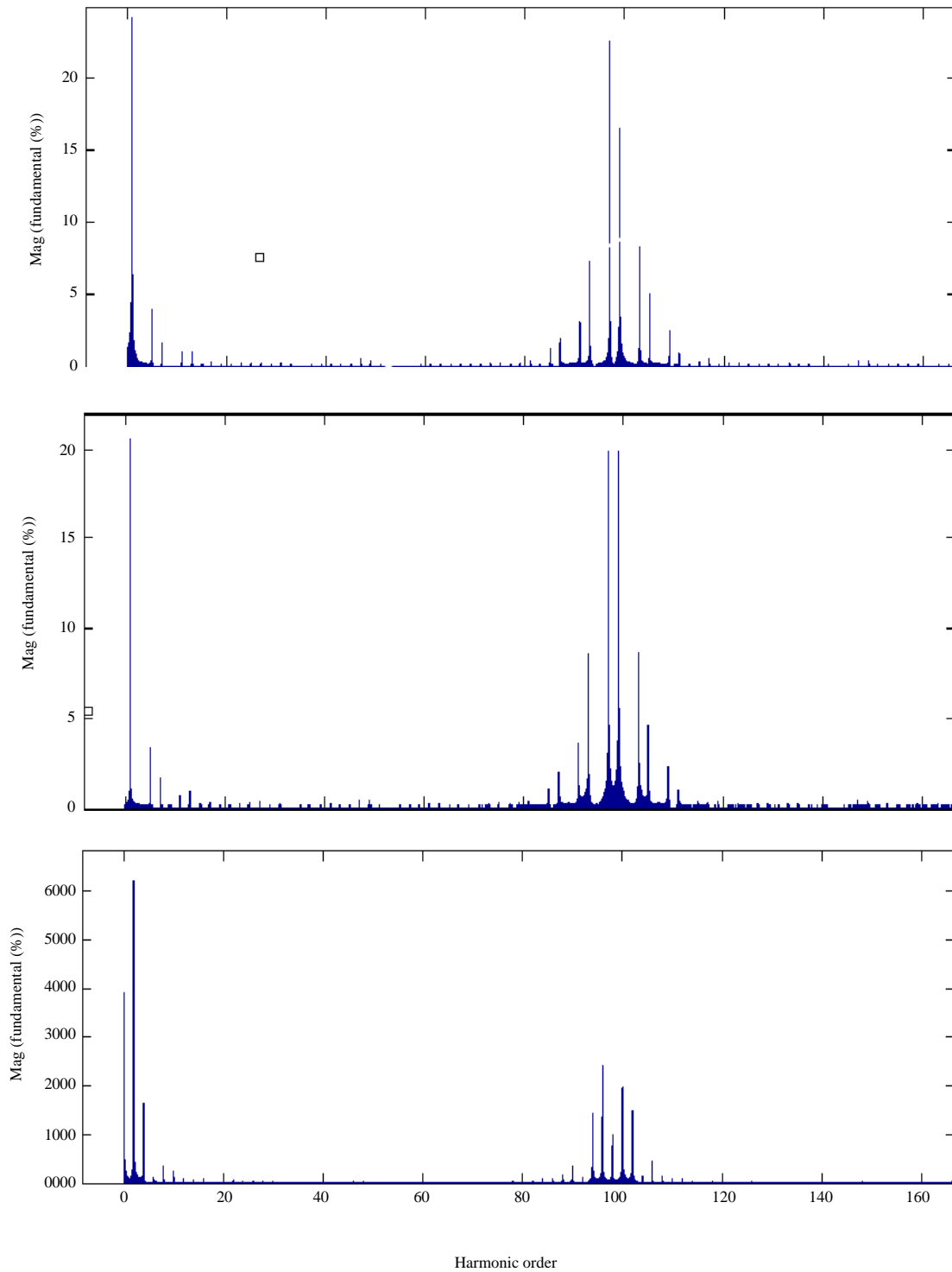


Fig. 7: The FFT analyses of the Outputs: a) voltage (Fundamental (60 Hz) = 8.39, THD = 19.35%); b) current (Fundamental (60 Hz) = 0.842, THD = 2.794%) and c) active power (Fundamental (60 Hz) = 3.64, THD = 35.04%)

evaluate the effectiveness of the wind energy and power electronic converter and the proposed control method on

the system reliability. The Matlab/Simulink Model of the PMSG fed resistive and inductive load through AC to AC



matrix converter controlled using SVM are shown in Fig. 5, respectively. Modelling of PMSG is used for power generation which was connected as source. The results analysis using proposed work in matlab are shown in Fig. 6a-c. The results of the FFT analysis given in Fig. 7a- c.

### CONCLUSION

The proposed research demonstrated the comparative analysis for varying resistance and inductance using Space Vector Modulation Techniques. The PMSG connected to a direct AC-AC matrix converter without the need of energy storage elements fed to RL load. This paper presents a model of a micro turbine and employs the AC-AC matrix converter under various circumstances to improve the micro turbine stability and power system's reliability. The simulations confirmed the results.

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