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Performance Analysis of Standalone Wind Energy Conversion Scheme

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Abstract: **Renewable energy has the advantages that it is abundant, clean, and becoming increasingly economical. Among various types of renewable energy sources, wind energy is one of the fastest growing renewable energy sources. The advancement in power electronics devices has further played an important role in the improvement of their reliability and controllability. The variable-speed wind turbines are more attractive, as they can extract maximum power at different wind velocities, and thus, reduce the mechanical stress on Wind Energy Conversion System (WECS) by absorbing the wind-power fluctuations. Recently, permanent magnet synchronous generator PMSG-based directly driven variable-speed WECS are becoming more popular due to the elimination of gear box and excitation system. The paper deals with a PMSG based WECS integration with the isolated load. The Stand Alone Wind Energy Conversion System (SAWECS) is analyzed in open loop and closed loop condition.The comparative analysis of SPWM and ISCPWM strategies for SAWECS is carried out in MATLAB/Simulink.**

Keywords: SAWECS, PMSG,DC-link voltage, ISCPWM, PWM inverter,THD.

I.INTRODUCTION

The wind turbine first came into being as a horizontal axis windmill for mechanical power generation, used since 1000 AD in Persia, Tibet and China. Transfer of mechanical windmill technology from the Middle East to Europe took place between 1100 and 1300, followed by further development of the technology in Europe. During the 19th century many tens of thousands of modem windmills with rotors of 25 meters in diameter were operated in France, Germany and the Netherlands, most of the mechanical power used in industry was based on wind energy. Further diffusion of mechanical windmill technology to the United States took place during the 19th Century [1][2].

The earliest recorded (traditional) windmill dates from the year 1191 at the Abbey of Bury St Edmunds in Suffolk. It replaced animal power for grinding grain and other farm activities like drawing water from well, the popularity of wind turbines increased tremendously and they soon dotted the landscape.

The advent of DC electric power in 1882, and introduction of 3-phase AC power production in the early 1890s, provided a technological basis for constructing wind turbines that generated electricity. The Danish scientist and engineer Poul La Cour is the most widely known pioneer of electricity generation using wind power. In 1891 in Askov, Denmark he introduced a four shuttle sail rotor design generating approximately 10kW of DC electric power. He also applied the DC current for water electrolysis, and utilized the hydrogen gas for gas lamps to light up the local school grounds [3]. La Cour's efforts started research,development and commercialization of wind electricity in Europe and thus Europe gained its leadership role in wind energy electricity generation. Though less recognized than La Cour, Charles F. Brush in 1888 introduced in Cleveland Ohio the first automatically operating wind turbine generator, a 12kW, 17-meter-diameter machine, operated for 20 years [5][6].

By 1908 there were several wind mills in operation for electricity generation, with capacities ranging from 5-25 kW. By 1930’s wind turbines with capacity of 500kW were developed which found wide spread use in inaccessible areas [1][2]. With concerns over climate change and depleting and polluting fossil fuels wind power has emerged as the most promising source of renewable energy.

The steady growth of installed wind power together with the up scaling of the single wind turbine power capability has pushed the research and development of power converters toward full-scale power conversion, lowered cost pr kW, increased power density, and also the need for higher reliability [7]. In this paper, power converter technologies are reviewed with focus on existing ones and on those that have potential for higher power but which have not been yet adopted due to the important risk associated with the high-power industry [7][1]. The power converters are classified into single and multi cell topologies, in the latter case with attention to series connection and parallel connection either electrical or magnetic ones (multiphase/windings machines/transformers). It is concluded that as the power level increases in wind turbines, medium-voltage power converters will be a dominant power converter configuration, but continuously cost and reliability are important issues to be addressed.

This paper presents an output power smoothing method by a simple coordinated control of DC-link voltage and pitch angle of a wind energy conversion system (WECS) with a permanent magnet synchronous generator (PMSG). The WECS adopts an AC-DC-AC converter system with voltage-source converters (VSC) [4][3].

The DC-link voltage command is determined according to output power fluctuations of the PMSG [5]. The output power fluctuations in low- and high-frequency domains are smoothed by the pitch angle control of the WECS, and the DC-link voltage control, respectively. By using the proposed method, the wind turbine blade stress is mitigated as the pitch action in high-frequency domain is reduced [8][10]. In addition, the DC-link capacitor size is reduced without the charge/discharge action in low-frequency domain. A chopper circuit is used in the DC-link circuit for stable operation of the WECS under-line fault. Effectiveness of the proposed method is verified by the numerical simulations.

II. STAND -ALONE WIND TURBINE SYTEM CONFIGURATION

Wind energy can be harnessed by a wind energy conversion system, composed of wind turbine blades, an electric generator, a power electronic converter and the corresponding control system. Fig shows the block diagram of basic components of WECS. There are different WECS configurations based on using synchronous or asynchronous machines, and stall-regulated or pitch regulated systems. However, the functional objective of these systems is the same: converting the wind kinetic energy into electric power and injecting this electric power utility grid.

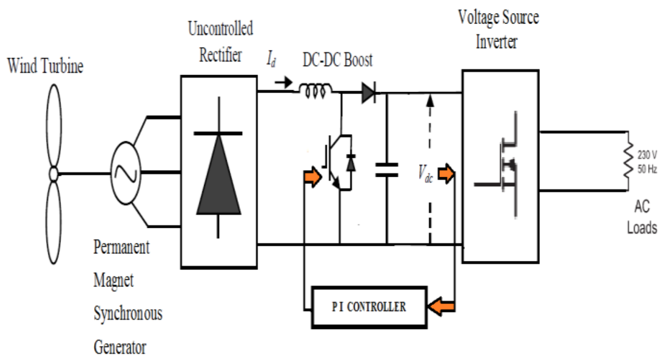

Fig.1.Block diagram for wind energy conversion

A .INTERNAL COMPONENTS OF WIND TURBINE

Anemometer: This device is used for measurement of speed. The wind speed is also fed to the controller as it is one of the variables for controlling pitch angle and yaw

Blades: These are aerodynamically designed structures such that when wind flows over them they are lifted as in airplane wings. The blades are also slightly turned for greater aerodynamic efficiency.

Brake: This is either a mechanical, electrical or hydraulic brake used for stopping the turbine in high wind conditions.

Controller: It is the most important part of the turbine as it controls

everything from power output to pitch angle. The controller senses wind speed, wind direction, shaft speed and torque at one or more points. Also the temp of generator and power output produced is sensed

Gear box: It steps-up or steps down the speed of turbine and with suitable coupling transmitting the rotating mechanical energy at a suitable speed to the generator. Typically a gear box system steps up rotation speed from 50 to 60 rpm to 1200 to 1500 rpm

Generator: It may be a synchronous or asynchronous Ac machine producing power at 50Hz

High-speed shaft: Its function is to drive the generator

Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.

Nacelle: The nacelle is the housing structure for high speed shaft, low speed shaft, gear box, generator, converter equipment etc. It is located atop the tower structure mostly in the shadow of the blades.

Pitch: This is basically the angle the blades make with the wind. Changing the pitch angle changes weather the blades turn in or turn out of the wind stream.

Rotor: The hub and the blades together compose the rotor.

Tower: Towers are basically made up of tubular steel or steel lattice. Taller the towers greater is the amount of power generated as the wind speed generally goes on increasing with height.

Wind direction: Generally erratic in nature, hence the rotor is made to face into the wind by means of control systems.

Wind vane: Basically the job of a wind sensor, measuring the wind speed and communicating the same to the yaw drive, so as to turn the turbine into the wind flow direction.

Yaw drive: This drive controls the orientation of the blades towards the wind. In case the turbine is out of the wind, then the yaw drive rotates the turbine in the wind direction

B.PERMANENT MAGNET SYNCHRONOUS GENERATOR

A typical two-pose three-phase PMSM is shown in Fig.The *as*, *bs*, and *cs* axes are the stationary windings of the stator. The *as*-axis is obtained by applying the Right Hand Rule to *as* and *as* ' windings. Respectively, the *bs*-axis and *cs*-axis are obtained using the same method.

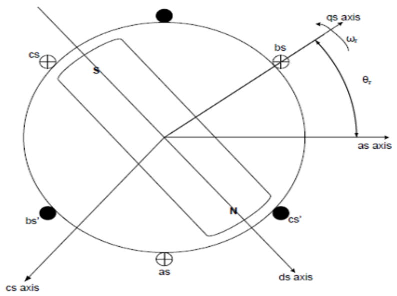

Fig 2. Two-Pose Three-Phase PMSM

The cross-section representation of the current in the windings is viewed as a solid or crossed circle. In the picture, the *as*, bs, and *cs* windings are pictured as crossed circles, which means that there is positive current flowing into the paper. On the contrary, the *as*', *bs*', and cs' windings are pictured as solid circles depicting positive current going out of the paper. For analysis purposes, two additional axes are assigned in dealing with PMSM. *d*-axis is assigned to align with the north pole of the rotor's permanent magnet and additional q-axis to be 90° ahead of the rotation. As the direction of the rotation is counter clockwise in the picture, the *q*-axis is 90° counter clockwise ahead of the *d*-axis. The rotor speed of the PMSM is defined in angular velocity ω_r. The rotor angle from the a-axis to the d-axis is indicated by θ_r. The electromagnetic torque produced (T_E) is in the direction of increasing θ_r and the load torque (T_L) is in the other direction opposing θ_r. This means that the electromagnetic torque produced is positive when the PMSM acts as a motor and negative when the machine acts as a generator.

Table.1.Simulation parameters of PMSG

Stator resistance	0.4578 Ω
D-axis inductance	0.00334 mH
Q-axis inductance	0.00334 mH
Flux induced by magnet	0.171wb
Inertia	0.0089 J kg.m^2
Friction Factor	0.001189 F(N/m.s)
Pole pair	16

C. Boost converter

There are different topologies used in PFC converters. The topology used in this study, is an ac-dc boost converter. Many applications require an ac-dc conversion from the line voltage. In its most simple form, this conversion is performed by means of a bridge rectifier and a bulk capacitor [2][3]. The bulk capacitor filters the rectified voltage and provides certain energy storage in case of a line failure. But resultant line current pulsates, causing a low power factor due to its harmonics and its displacement with respect to the line voltage [1]. In many applications, this low quality in the power usage is not acceptable above certain power levels, and the corresponding standards require improved technical solutions.

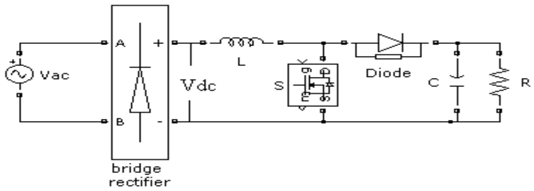

Fig. 3 .Basic boost converter

One of topologies most commonly used to deal with this problem so is called single phase boost converter [2]. The simplified boost converter circuit is shown in figure 3.

The boost inductor in the boost converter circuit is in series with the ac power line. This topology inherently accepts a wide input voltage range without an input voltage selector switch [2][1]. The equivalent circuits of the system are derived based on the "on" and "off" states of the converter switch and shown in figure 3-(a) and figure 3-(b) respectively.

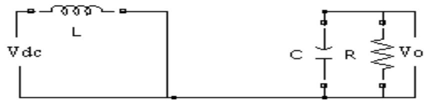

Fig.3(a) on state switching

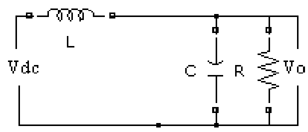

Figure 2(b) .off state switching

Table. 2.Simulation parameter of boost converter

D. Design consideration

If output voltage is represented as V_o and input voltage is represented as V_{DC}, the duty ratio (D) of a typical boost converter is given by

$$D = \frac{V_O - V_{DC}}{V_O} \quad \text{-----------} \quad (1)$$

The inductor can be designed using the equation

$$L = \frac{R.D\,(1-D)2}{2f} \quad \text{-----------------} \quad (2)$$

Where f – switching frequency and R- Load resistance.
The value of capacitance is given by

$$C = \frac{V_O.D}{f\Delta V.R} \quad \text{---------------} \; (3)$$

Where ΔV is output voltage ripple.

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E.INVERTER

The DC power available at the rectifier output is filtered and converted to AC power using a PWM inverter employing double edge sinusoidal modulation [2]. The output consists of a sinusoidally modulated train of carrier opuses, both edges of which are modulated such that the average voltage difference between any two of the output three phases varies sinusoidally [3]. Each edge of the carrier wave is modulated by a variable angle δx and can be mathematically expressed by

$$\delta x = MI \sin(\alpha x)\delta_{max} \; (x=1, 2, 3\ldots 2r+1)$$

Where MI is the modulation index and ranges from 0 to 1 [3]. subscript x denote the edge being considered, r is the ratio of the carrier to fundamental frequency at the inverter output, αx is the angular displacement of the unmodulated edge and δ_{max} is the maximum displacement of the edge for the chosen frequency ratio r.

Input voltage (V_{DC})	160V
Output voltage (V_O)	250V
Duty Ratio (D)	0.6
Inductor (L)	100mH
Capacitance(C)	20000µF
Load Resistor (R)	1500 Ω
Switching Frequency	1Khz

In the present scheme, the inverter output voltage is controlled, while its frequency is held constant at 50 Hz. In this range of operation, the PWM generator generates a carrier wave with frequency 15 times the fundamental frequency at the inverter output. Such a choice results in a line voltage waveform with 15 pulses per half cycle at the observed that the operating speed increases from inverter output. By modulating the carrier wave and hence the phase voltages, the fundamental and harmonic voltage content can be varied. There are 15 pulses and 15 slots of 12˚ each. In each slot, two edges are modulated. For 100 % that modulation (MI=1), the maximum amount by which the edge can be modulated is δ_{max}=6˚. Any further displacement of the edge will cause the pulses in the modulated phase voltage to merge, resulting in a reduction of the number of pulses in the line voltage waveform (pulse dropping phenomenon).

III. PULSE WIDTH STRATEGIES FOR WIND ENERGY CONVERSION SYSTEM

A.Introduction

The harmonic content in the output of the inverter can be reduced by employing pulse-width modulation (PWM). The PWM techniques and strategies have been the subject of intensive research since 1970's were to fabricate a sinusoidal ac output voltage [9]. Sinusoidal PWM (SPWM) is effective in reducing lower order harmonics while varying the output voltage and gone through many revisions and it has a history of three decades. The SPWM technique, however, exhibits poor performance with regard to maximum attainable voltage and power [6]. The fundamental amplitude in the SPWM output waveform is smaller than for the rectangular waveform [9]. In three-phase case the ratio of the fundamental component of the utmost line-to-line voltage to the direct supply voltage is 0.866% and this value indicates poor exploitation of the dc supply.

B. PWM STRATEGY

B.1 Sinusoidal Pulse Width Modulation

The basic single-phase full-bridge PWM inverter is shown in Fig. in which S1 and S2 will be given PWM pulses for first (positive) output half cycle and S3 and S4 are gated for the next (negative) half cycle [6][9].The unipolar PWM pulse generation with resulting pattern is represented in Fig. in which a triangular carrier wave is compared with sinusoidal reference waveform to generate PWM gating pulses. All PWM waveforms presented in this paper are assumed to be synchronous Unipolar PWM voltage switching.

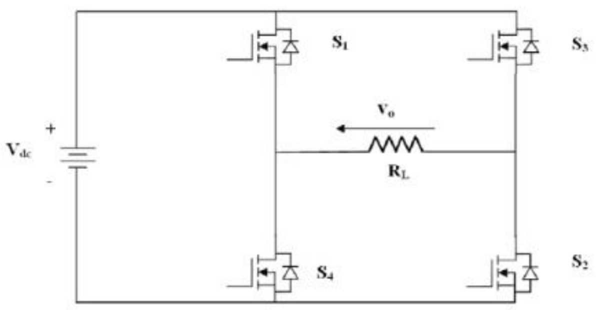

Fig.4. basic single phase e inverter

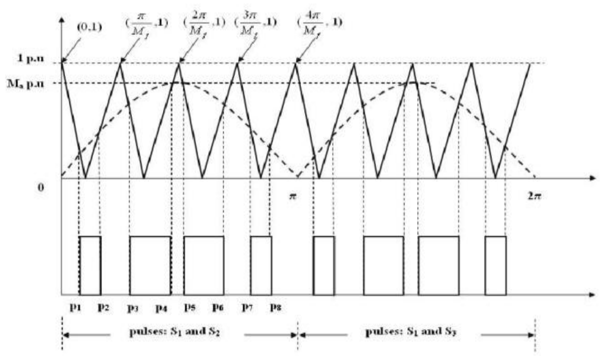

Fig. 5 .SPWM pulse generation and pattern

B.2. Proposed ISCPWM

The control strategy uses the same reference (synchronized sinusoidal signal) as the conventional SPWM while the carrier triangle is a modified one[9].

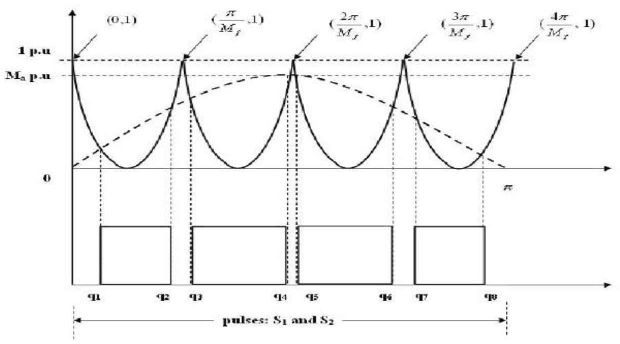

Fig.6.Inverter sine carrier PWM pulse pattern

The control scheme uses an inverted (high frequency) sine carrier that helps to maximize the output voltage for a given modulation index. Enhanced fundamental component demands greater pulse area. The difference in pulse widths (hence area) resulting from triangle wave and inverted sine wave with the low (output) frequency reference sine wave in different sections can be easily understood [9][6]. In the gating pulse generation of the proposed ISCPWM scheme shown in Fig , the triangular carrier waveform of SPWM is replaced by an inverted sine waveform.

It is worthwhile to note that both in SPWM (considered) and ISCPWM schemes, the number of pulses will be equal to M_f and hence the constant switching loss is guaranteed [6].To have conceptual understanding of wider pulse area and hence the dexterous input dc utilization in the ISCPWM, location of switching angles, duty cycle and their dependence on M_a and M_f are discussed. Fig. depicts the influence of M_a on different switching angles (four angles considered in both cases) at constant M_f of 6. From this figure, it is observed that the odd switching instants vary with negative slope and even switching instants have positive slope [9][6]. Variation of all the switching instants against M_a is a straight line and slope of each one is more than its previous one [6][9]. All the odd switching angles of ISCPWM method happen earlier than similar angles of PWM method, while the situation is reverse in case of eve switching angles and hence higher pulse area.

IV .PI CONTROL STRUCTURE

When a load is connected to the inverter output. The output voltage at the boost converter side is sensed by means sensors and it is feedback to a comparator or sub tractor which compares this boost converter output with the reference signal (desired signal) and it produces the voltage error signal. This instantaneous error is fed to a proportional-integral (PI) controller. The integral term in the PI controller improves the tracking by reducing the instantaneous error between the reference and the actual voltage. .The error is forced to remain within the range defined by the amplitude of the triangular waveform. The resulting error signal is compared with a triangular carrier signal and intersections decide the switching frequency and pulse width.

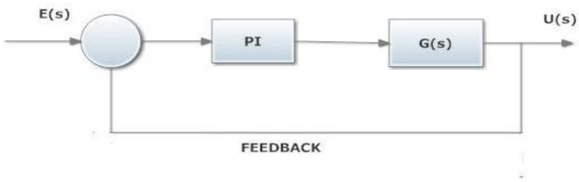

Fig 7. Block Diagram for PI Controller

PI controller is a feedback controller which detects the error value which is the difference of the output signal and the desired or reference signal. PI controller works to minimize this error by controlling the system inputs. PI controller has two elements namely Proportional (P) and Integral (I). Proportional part reduces the error while Integral part reduces the offset. P depends on present error and I depends on past errors. So, step response of a system can be improved by using PI controller.

V. SIMULATION RESULT AND DISCUSSION

A.Simulation For open Loop.

The SAWECS is analyzed through simulation and the results are presented. The turbine power characteristic for different wind velocity is shown in fig.8. It depicts that the maximum power attains at rated wind velocity of 12m/s.

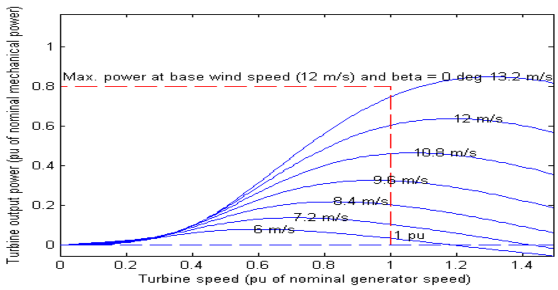

Fig.8. Turbine Power Characteristics

The simulation is first carried out in open loop condition for a resistive load and its simulink diagram is shown in fig 9. The SPWM strategy based generated inverter output voltage, boost rectifier output voltage and generator speed is shown in fig.10 to fig.12. for varying wind condition with fixed modulation index of 0.8.

The variation of output voltage and power for different modulation index is shown in fig.13 and fig.14 respectively. It illustrates that the maximum power attains at the modulation index of 0.4 and is also tabulated in table.

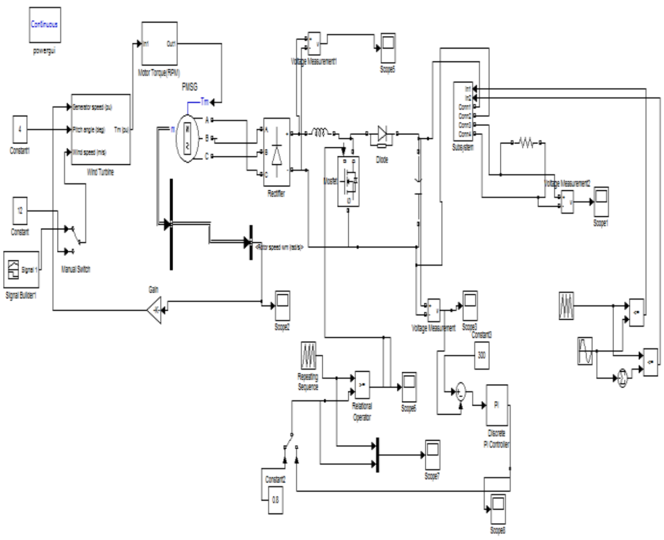

Fig 9. Simulink diagram For Open Loop

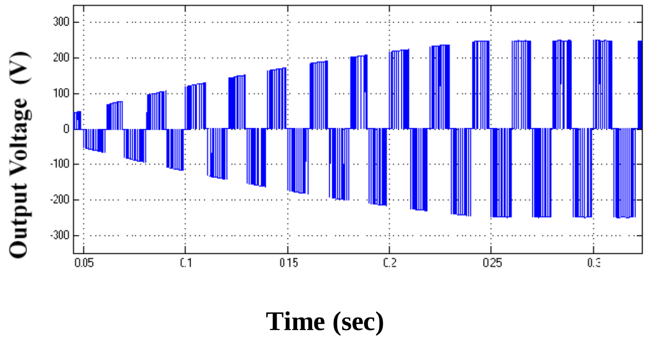

Fig.10. Inverter output voltage

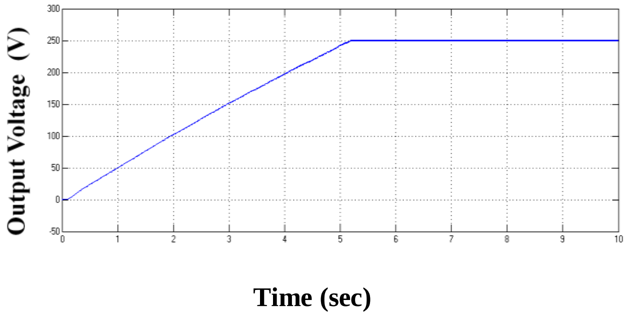

Fig11. Boost rectifier output *voltage*

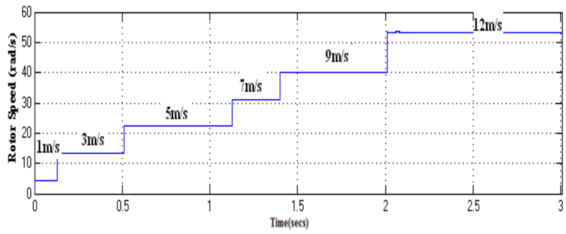

Fig.12. Generator speed

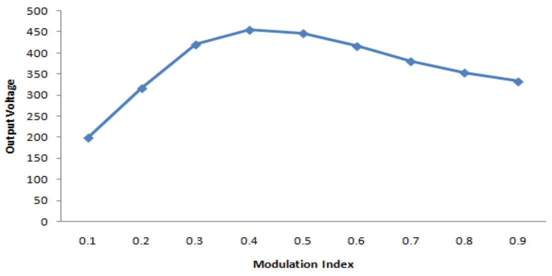

Fig.13. Inverter output voltage

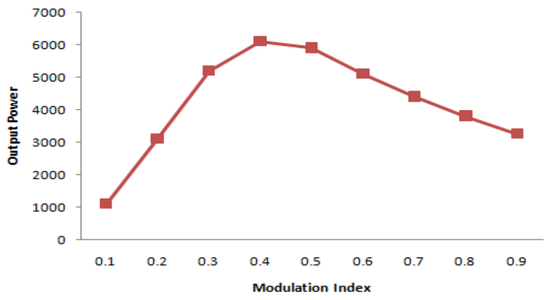

Fig.14. Inverter output power

S.No	Modulation Index	Voltage(V)	Power(W)
1.	0.1	198	1100
2.	0.2	316	3100
3.	0.3	420	5200
4.	**0.4**	**455**	**6100**
5.	0.5	447	5900
6.	0.6	416	5100
7.	0.7	380	4400
8.	0.8	353	3800
9.	0.9	332	3250

Table 3 .Variation of voltage and power for different MI

B. Simulation for closed loop

The SAWECS simulation is extended to closed loop condition in MATLAB/Simulink. The Proportional Integral (PI) controller is used to maintain constant output voltage. The reference voltage of 250 V is maintained constant for different load resistance varying from

R= 35Ω to 70Ω. In closed loop condition, two PWM strategies namely SPWM and ISCPWM are applied to inverter and its results are presented.

B.1.SPWM For SAWECS

For closed loop SAWECS, SPWM technique is applied for inverter and its corresponding output results are presented. The fig.15 shows the Simulink diagram for the SPWM based SAWECS. The SPWM pulse patterns are depicted in fig.16. For the set voltage of 250 V, resistive load of 35ohms the boost converter output voltage is maintained in the same value as shown in fig.17. Its AC form of inverter output voltage is shown in fig.18. The fig.19 portrays the output voltage spectrum having fundamental voltage of 242.8 V and THD of 53.11%**.**

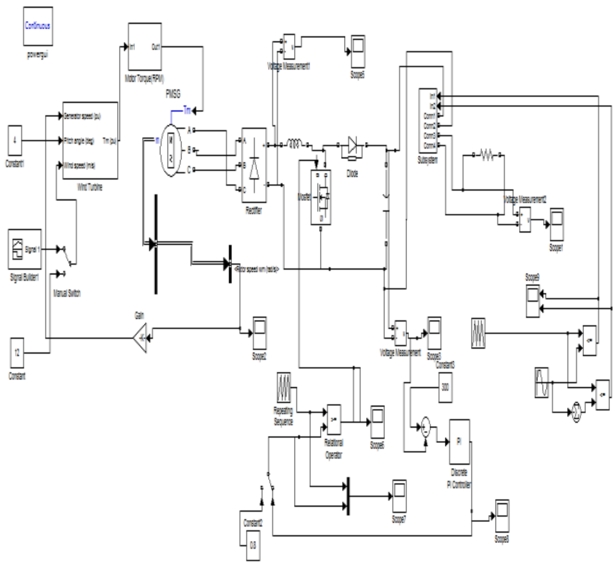

Fig 15. Simulink Diagram for Closed loop Circuit

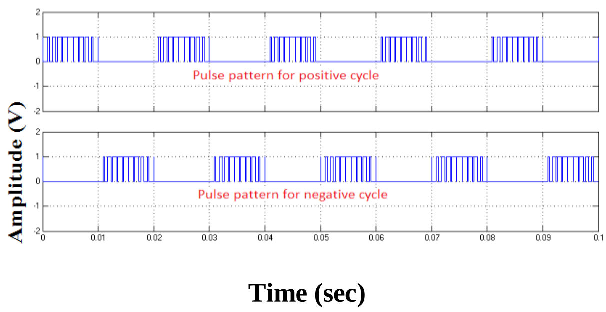

Fig.16. PWM Pattern

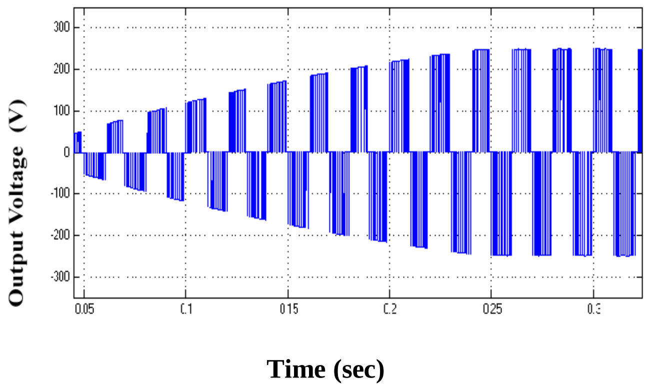

Fig.17. Inverter output voltage

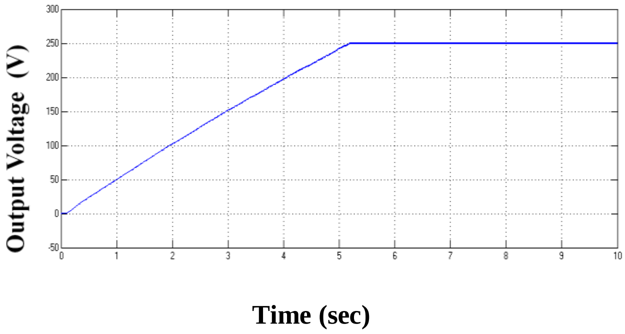

Fig.18. Boost rectifier output voltage

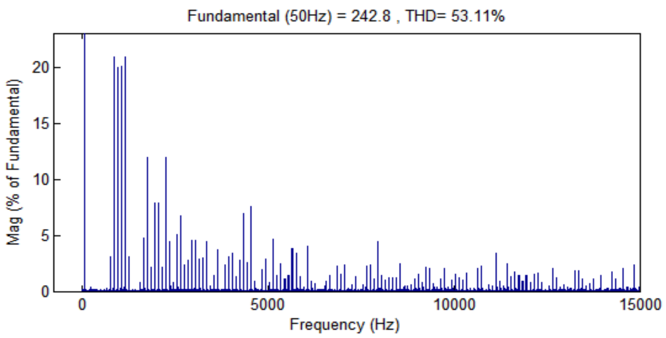

Fig.19.output voltage spectrum

B.2.INVERTED SINE CARRIER PWM (ISCPWM) FOR SAWECS

The fig.20 shows the Simulink diagram for the ISCPWM based SAWECS. The proposed ISCPWM pulses are generated by comparing sine and inverted sine as shown in fig.21. For the same set voltage of 250 V and resistive load of 35ohms, the boost converter voltage and inverter output voltage are shown in fig.22 and fig.23.The output voltage spectrum in fig.24. depicts the increased fundamental voltage of 266 V and reduced THD of 51.38%. The simulation is done for different set voltage and comparison is made between SPWM and ISCPWM. The table.4 illustrates the fundamental voltage and THD for SPWM and ISCPWM strategies by setting the reference voltage. Their graphical representations are shown in fig.25 and fig.26 respectively.

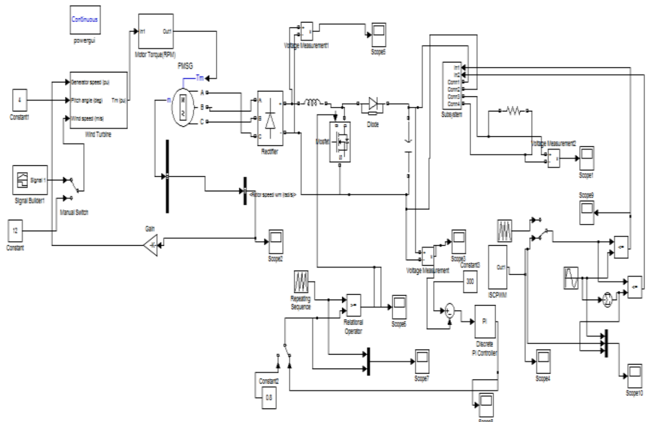

Fig 20.Simulink Diagram for Closed loop Circuit

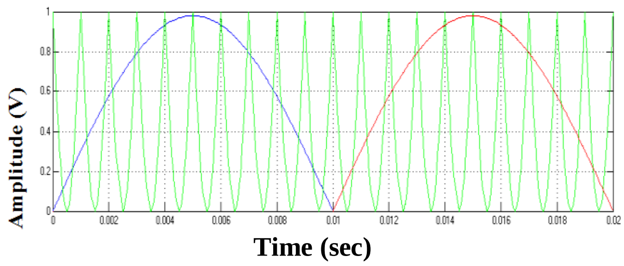

Fig.21. Reference and carrier signal generation

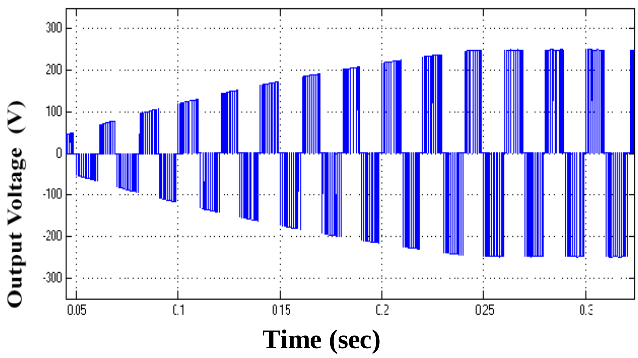

Fig.22.Inverter output voltage

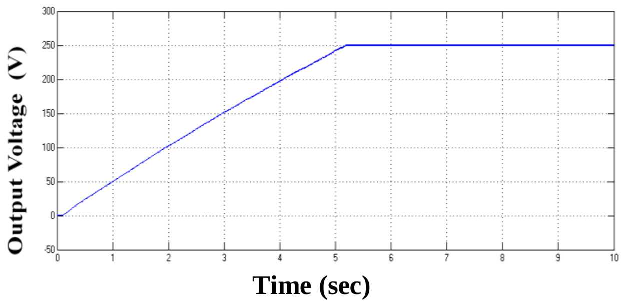

Fig.23. Boost rectifier output voltage

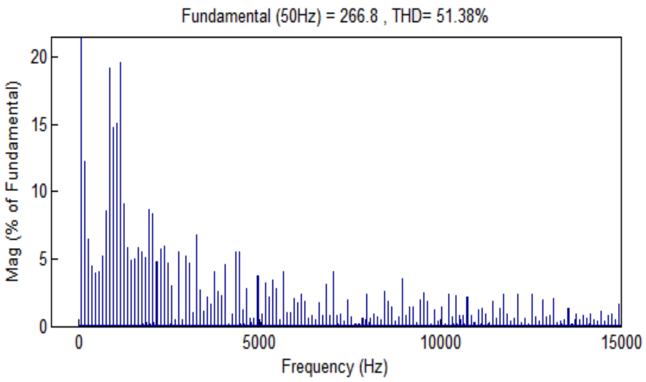

Fig.24. output voltage Spectrum

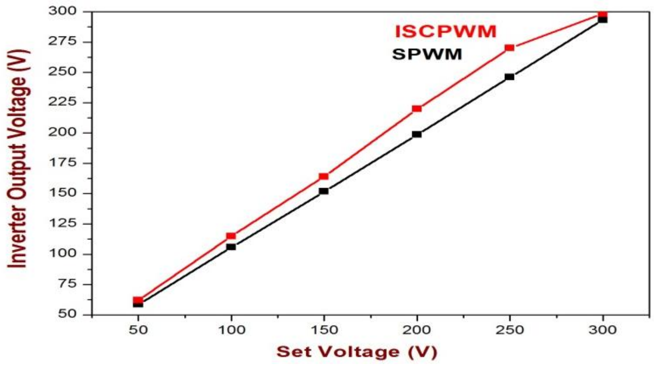

Fig.25 Inverter Output Voltage Vs Set Voltage

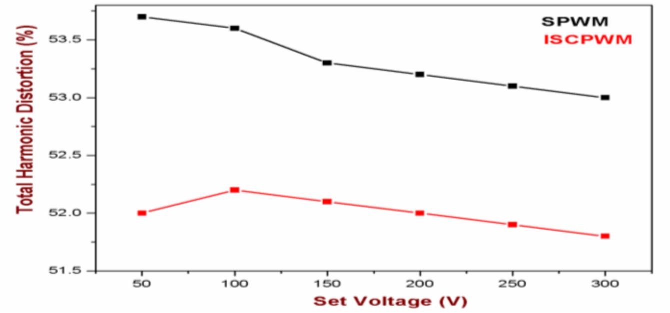

Fig.26. Total Harmonic Distortion Vs Set Voltage

Table 4 .Fundamental output voltage and THD for SPWM and ISCPWM

Set Voltage (volts)	Inverter output voltage (volts)		Total harmonic distortion (THD) (%)	
	SPWM	ISCPWM	SPWM	ISCPWM
50	58.6	62.1	53.7	52
100	105.8	114.9	53.6	52.2
150	151.7	164.1	53.1	52.1
200	198.6	219.7	53.5	52
250	246.1	270	53.6	51.2
300	293.3	298.8	53.7	51.1

VI. CONCLUSION

The paper reviews the developments in wind energy systems and the advances in power electronics, which have enabled efficient wind energy capture and analyses the closed loop system for the load variation. The model of WECS is developed in Matlab/ Simulink and simulation is carried out in both in open loop and closed loop system. The model includes the Wind turbine, PMSG, Rectifier, Inverter and an isolated load. This model is first simulated in open loop condition and performance of the WECS is examined. Then PI controller is designed and the output voltage of the boost converter is maintained stable for the given reference voltage by varying the load. Two control strategies namely SPWM and ISCPWM are applied to inverter and its fundamental voltage and THD are studied. It concludes from the two schemes that ISCPWM generates more fundamental voltage and very much lesser THD compared to SPWM based inverter.

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