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Characteristics Study of Impedance Source Inverter for PMSG Based Variable-Speed Wind Energy Systems

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***Abstract*— This paper deals with a robust and consistent grid power interface system for permanent-magnet synchronous generator (PMSG) based wind power generation system. The proposed system consists of a generator-side buck-type rectifier and a grid-side impedance source inverter, which is employed as a bridge between the generator and the grid. The proposed system components like PMSG, DC Link, impedance network, inverters are modeled by using MATLAB/SIMULINK. The control strategy for the proposed topology is developed from space-vector modulation and Z-source network operation principles. The unity-power-factor control method is suggested and to establish an optimized control scheme for the generator-side three-switch buck-type rectifier. To extract the maximum power from the wind turbine generator and the power is transferred to the grid system is achieved by adjusting the shoot-through duty cycles of the Z-source network. The performances of the PMSG based WECS has been analyzed and the results are verified.**

***Index Terms*— Permanent Magnet Synchronous Generator (PMSG), Wind Energy Conversion Systems (WECS), Impedance Source Inverter (ZSI), Space Vector Modulation Technique (SVM), Pulse Width Modulation (PWM), MATLAB, SIMULINK.**

I. INTRODUCTION

Wind energy is one of the important sources of renewable energy systems. The potential of wind energy is very large compared to the other non conventional sources. It is non-polluting, safe and the quality of life. The range power output from the wind driven PMSG is mainly depending on the wind velocity flections and load conditions. The increasing infiltration level of wind energy can have a significant impact on the grid, especially under abnormal grid voltage conditions. Thus, wind generation stations can no longer be considered as a simple energy source.

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Nowadays, they should provide an operational ability similar to that of conventional power plants. A demanding requirement for wind farms is the fault ride-through capability. According to this demand, the wind turbine is required to survive during grid faults. The ability of a wind turbine to survive for a short duration of voltage dip without tripping is often referred to as the low voltage ride through capability of a turbine. On the other hand, power fluctuation from a turbine due to wind speed variations incurs a deviation of the system frequency from the rated value. Variable-speed wind turbines using a PMSG equipped with full-scale back-to-back converters are very promising and suitable for application in large wind farms. Due to their full-scale power converter, they can deliver a larger amount of reactive power to the grid than a DFIG wind turbine under abnormal grid conditions. Due to the fact that a multiple pole design can be easily realized in the synchronous generator, it is the only type that provides a realistic opportunity to implement gearless operation, and hence, the features of lightweight and low maintenance can be obtained in this type of wind generation system.

In conventional, the PMSG is connected to the grid by means of a fully controlled frequency converter, which consists of a pulse width modulation (PWM) rectifier, an intermediate dc stage, and a PWM inverter. With this configuration, the generator-side converter can completely regulate the generator in terms of speed, power factor, and electromagnetic torque. This configuration requires more fully controlled switches, which make the system more expensive, particularly for megawatt level applications. Recently, research on three-switch buck-type rectifiers has focused on grid-side current quality improvement and with parallel operation. On the other hand, current research on Z-source inverters has focused on modeling and control of an application and performance improvement. The proposed configuration is to overcome the aforementioned drawbacks of existing configurations, and provides high reliability, low capital cost, and harmonic-free characteristics in both generator and grid sides.

II. BLOCK DIAGRAM OF THE PROPOSED SYSTEM

The block diagram of the proposed system is shown in Fig. 1. The PMSG-based generation system is a recent trend in the development of wind generation systems.

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Traditionally, there are two types of inverters that are being used, commonly known as voltage-source inverter (VSI) and current-source inverter (CSI). Both of these inverters have a limited operating range, even though both are widely used in DG applications.

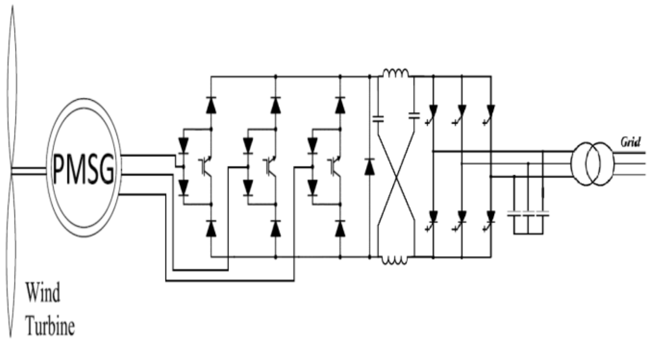

Fig. 1. Block diagram of the PMSG based WECS

To overcome the limited operating range, these inverters need to be connected with a separate dc–dc converter stage in the front end. This enables them to operate in both buck and boost modes. In traditional inverters, the upper and lower switches of each phase cannot be switched on simultaneously either by EMI noise. The output voltage of the ZSI is limited to either greater or lesser then the given input voltage. The variable output voltage from the induction generator is rectified and then inverted by using the proposed inverter. The ZSI can produce an output voltage greater than the input voltage by controlling the shoot through time T_o. This proposed scheme is used to improve the power factor and reduce harmonic current.

I. CONTROL TECHNIQUE

The control strategy for the generator-side converter (the three-switch buck-type rectifier) is discussed based on the equivalent circuit and phasor diagram of the PMSG as shown. The machine terminal voltage serves as the input voltage to the rectifier, termed as Vin, which is equal to the machine back EMF Es minus the voltage drop in the machine impedance ($Rs + jXs$). From the equivalent circuit, the steady state equation of the PMSG can be expressed as,

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} R_s & -p\omega_r L_{sq} \\ p\omega_r L_{sq} & R_s \end{bmatrix} \cdot \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ p\omega_r \lambda_{\text{pm}} \end{bmatrix} \quad \text{(A)}$$

Where,

R_s, L_{sd}, and L_{sq} are the PMSG stator resistance and the direct- and quadrature-axis inductances, respectively.

ω_r is the generator speed, p is the PMSG pole pairs, and

$\lambda_{\text{pm}} = L_{\text{pm}} I_{\text{pm}}$ is the permanent magnetic flux.

II. UNITY POWER FACTOR CONTROL

The angle ϕi between the PMSG terminal voltage and the generator stator current is equal to the input power-factor angle of the three-switch buck rectifier, assuming small capacitance of the filter.

The unity-power-factor control of the rectifier can be implemented by making the stator current vector follow the measured terminal voltage vector. That means that the angle ϕi is kept at zero, meaning that the rectifier can be treated as an equivalent ―resistance‖ load of the PMSG. Thereby, the generator current harmonics can be reduced, and the generator efficiency can be improved compared to the conventional diode–rectifier topology, where the sinusoidal generator current cannot be achieved. With unity-power-factor control, the overall volt–ampere of the front-end rectifier would contribute to the active power transfer and thereby reduce the power rating of the proposed configuration. This would lead to a smaller size and hence reduce the cost of the power circuit, which is one of the significant considerations for megawatt-level wind turbine design.

III. SPACE VECTOR MODULATION (SVPWM)

Active state vectors to from a hexagon, and two [$\mathbf{U}_0$ (000) and $\mathbf{U}_7$ (111)] are zero state vectors that lie at the origin, that is noted by the command voltage vector $\mathbf{U_c}$ in sector 1. The operation in under-modulation range is determined by the modulation index M, which is defined as the ratio between the magnitude of the command or reference voltage vector and the peak value of the fundamental component of the square-wave voltage. The modulation index (M) varies between 0 and 1. In the under-modulation region ($0 \le M < 0.907$) shown in Fig. 2.a, the reference voltage vector remains within the hexagon. The over-modulation region is subdivided into two modes: mode I [$0.907 \le M < 0.952$) and mode II [$0.952 \le M \le 1.00$].

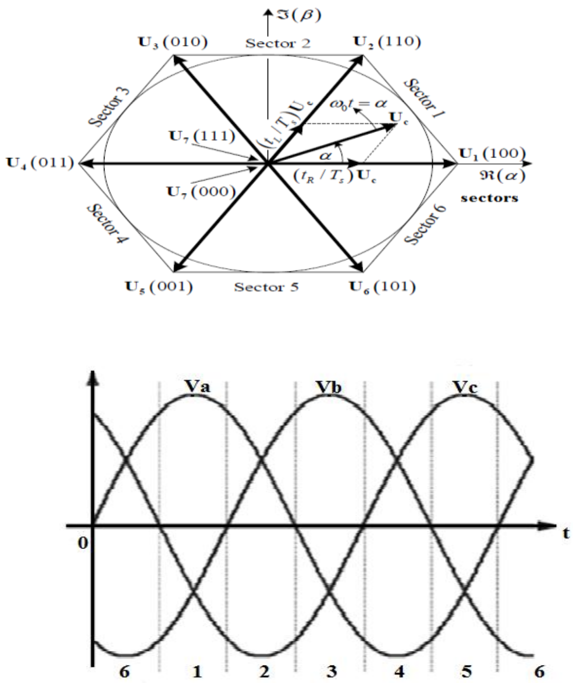

Fig 2.a Voltage and switching states of the inverter

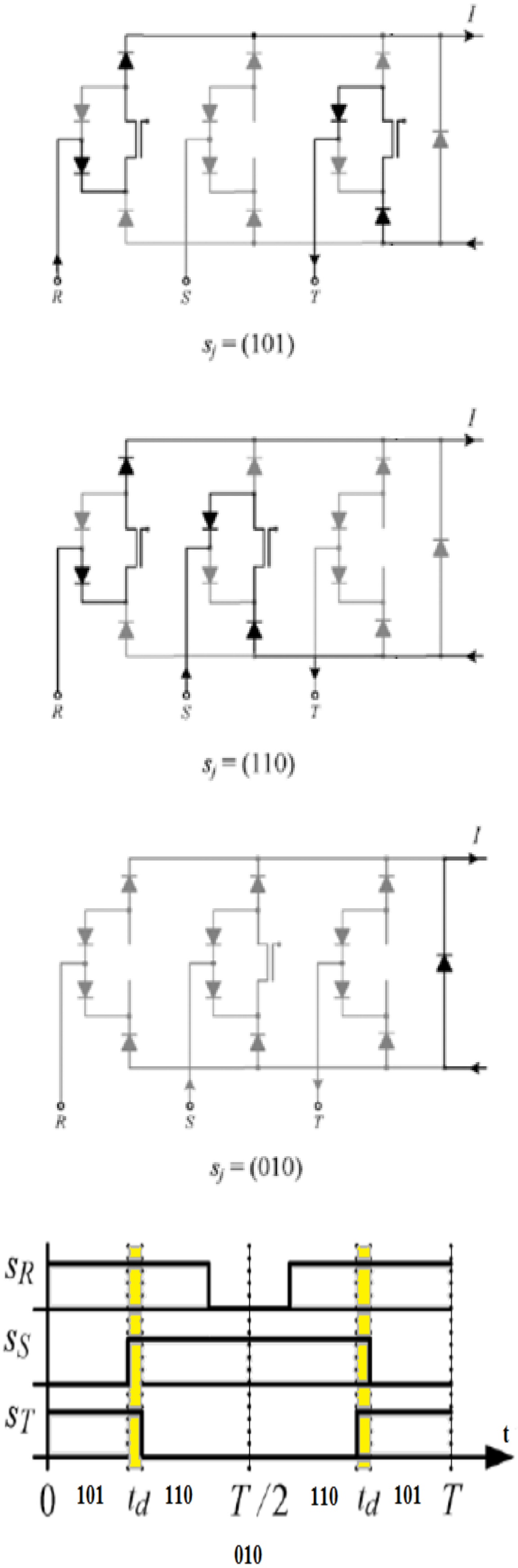

Fig 2.b Switching states and circuits of buck rectifier

$$\mathbf{U_c} = \mathbf{U_R} + \mathbf{U_L} = \mathbf{U}_i \frac{t_R}{T_s} + \mathbf{U}_{i+1} \frac{t_L}{T_s}$$

(1)

$$t_R = \frac{\sqrt{3}T_s}{U_{dc}} \left[U_{c\alpha} \sin\left(\frac{\pi}{3}N\right) - U_{c\beta} \cos\left(\frac{\pi}{3}N\right) \right]$$

$$t_L = \frac{\sqrt{3}T_s}{U_{dc}} \left[-U_{c\alpha} \sin\left(\frac{\pi}{3}(N-1)\right) + U_{c\beta} \cos\left(\frac{\pi}{3}(N-1)\right) \right]$$

$$t_0 = t_7 = \left(T_s - t_R - t_L\right)/2$$

(2)

Where,

t_R, t_L, t_0 – effective time for the right, left and zero switching vectors, respectively,

$T_s = 1/f_s$ – sampling time (f_s – switching frequency),

$U_{c\alpha}$, $U_{c\beta}$ – $\alpha\beta$ Components of the reference voltage vector $\mathbf{U_c}$,

U_{dc} – DC bus voltage.

Can be written as:

$$t_R = \frac{2\sqrt{3}}{\pi} M T_s \sin\left(\frac{\pi}{3}N - \alpha\right)$$

$$t_L = \frac{2\sqrt{3}}{\pi} M T_s \sin\left(\alpha - \frac{\pi}{3}(N-1)\right)$$

$$t_0 = t_7 = \left(T_s - t_R - t_L\right)/2$$

(3)

Where,

α is angle of $\mathbf{U_c}$

M is a modulation index:

$$M = \frac{U_c}{U_{1(six-step)}} = \frac{U_c}{\frac{2}{\pi}U_{dc}}$$

(4)

Where,

$U_c = \sqrt{U_{c\alpha}^2 + U_{c\beta}^2}$ – phase peak value,

$U_{1(six-step)}$ – Fundamental peak value of the square-phase voltage wave.

The modulation index M varies from 0 to 1 at the square-wave output[15]. The length of the $\mathbf{U_c}$ vector, in the whole range of α is equal to $U_{dc}/\sqrt{3}$. This is a radius of the circle inscribed in the hexagon in Fig. (b). At this condition the modulation index is:

$$M = \frac{U_{dc}/\sqrt{3}}{2 * U_{dc}/\pi} = 0.907$$

(5)

This means that 90.7% of the fundamental voltage at the square wave can be obtained.

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IV. RESULTS AND DISCUSSION

In the proposed method instead of the PWM, SVPWM is used and for rectifier three switch buck rectifier is used. The space vector model is done separately by calculating the vector states of the switches for both the rectifier and inverter with the help of the space vector calculation in the report and also from the reference papers. With the above references the model is simulated and the simulation results are given below. As the project is intended to the new modal in WECS the harmonics are not considered here. The output voltage of the wind driven PMSG can be evaluated at the wind velocity of 3 – 16 m/s. The PMSG rating is taken as 8 Nm, 300 V_{dc}, 2000 RPM and the torque is given as input to PMSG from the wind turbine. The leakage flux of wind generator along with the LC filter, used at PMSG output side to protect harmonics injected into the generating system.

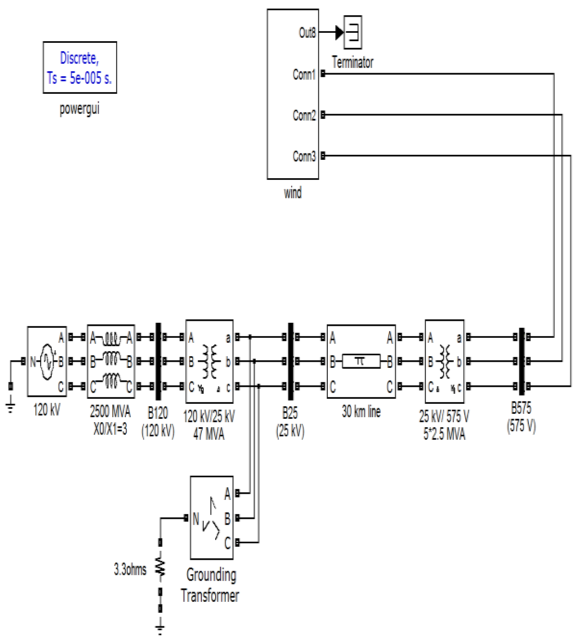

Fig 3. Simulink model of proposed system

PMSG RATING: 8 Nm, 300 Vdc, 2000 RPM, Torque as input.	
CUT IN WIND SPEED: 3 m/s	**CUT OUT WIND SPEED:** 16 m/s
GRID NOMINAL LINE VOLTAGE: 575 V	

SL. NO.	WIND SPEED	PMSG V_{ph}	GRID V_{ph}	GRID V_L (o/p)
1	16 m/s	270 V	490 V	1 p.u.
2	12 m/s	150 V	490 V	1 p.u.
3	8 m/s	100 V	490 V	1 p.u.
4	3 m/s	170 V	490 V	1 p.u.

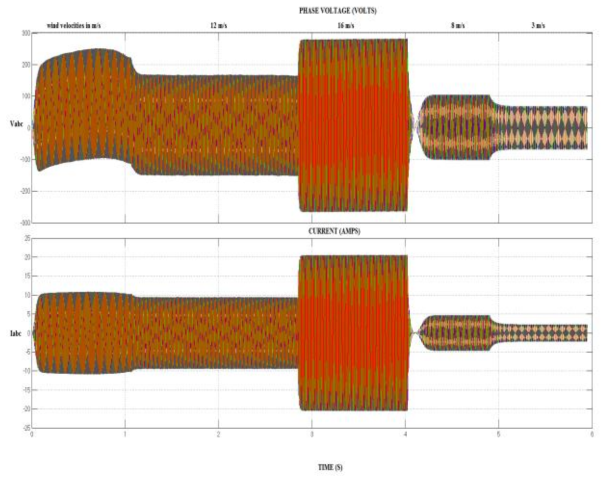

Fig 4. PMSG output voltage

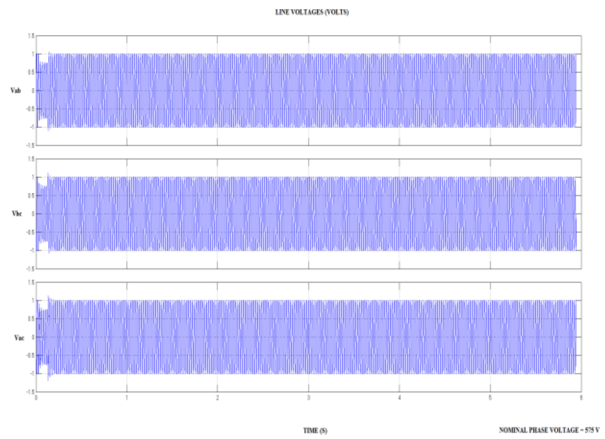

Fig 5. Line voltages of the inverter/grid connection

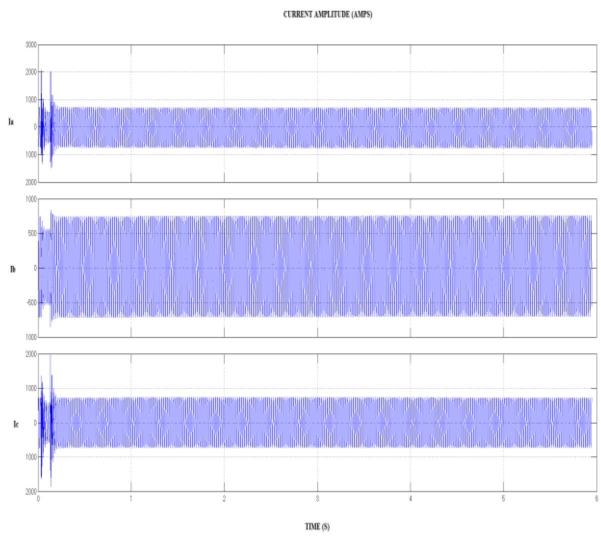

Fig 6. Current waveforms of the inverter

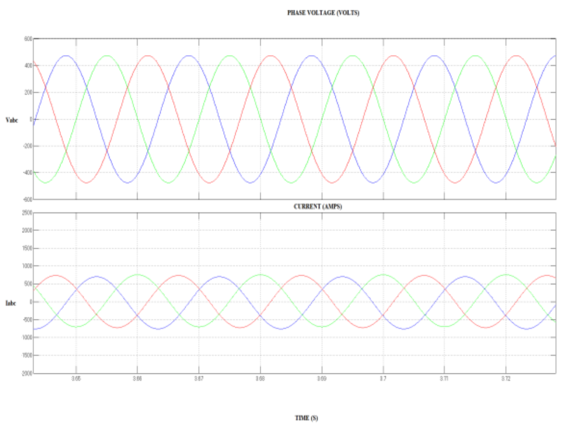

Fig 7. Phase voltage and current of the inverter

For a WECS connected to the grid, needs a constant grid voltage but the current may vary according to the grid load. From the above waveforms it is known that:

• For the varying wind velocity the amplitude of the PMSG varies which is shown in the Fig 4 where the velocity is indicated above the waveforms for a particular time period which will be convenient for viewing the changes.

• But the converter bridge between the systems maintains the constant output grid voltage across the ZSI capacitor.

V. CONCLUSION

The simulation results of a buck-type rectifier on the generator side and grid-side Z-source-inverter-based wind generation system have been discussed. The control algorithms of the proposed system have been developed from Z-source network and SVM principles. The proposed control stagey approach has been optimized from the fundamentals of the $I_d = 0$ control and unity-power-factor method. In these proposed system, Z-source inverter to decouple the active- and reactive-power control while extracting the maximum wind power by adjusting the shoot through duration of the Z-source network. Instead of only synchronization of SVM, if we took the output compared with the buck rectifier and inverter, the efficiency and effective output may increase.

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