Harmonic Reduction in Grid Integrated IPMSG with Multi Level Inverter Power Conditioner System

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Abstract: In this study, high efficient power conditioner system for grid integrated variable-speed wind turbine using an Interior Permanent-Magnet Synchronous Generator (IPMSG) is developed. The grid integrated Power Conditioner System (PCS) consists of phase-shifting transformer which powers series-type 12-pulse uncontrolled diode rectifier which is cascaded to a Pulse Width Modulated (PWM) diode clamped multilevel inverter. The active current of the grid-side PWM multi level inverter is controlled to follow the optimal active current reference. In proposed system the passive filter together with a series-type 12-pulse rectifier suppresses the distortions presented in the IPMSG voltages and currents and increases the efficiency by compensating the power factor angle of the IPMSG. Simulation results proves that the proposed reduces the harmonics and it is high efficient.

Key words: Permanent Magnet Synchronous Generator (IPMSG), phase shifting transformer, power conditioner system, Pulse Width Modulation (PWM), wind turbine

INTRODUCTION

Optimum speed operation of wind turbine, in response to wind velocity minimizes fluctuations of output power and its effects on the grid. Conventional wind turbines, needs many improvements in performance and consistent of the system in order to achieve higher economic efficiency (Heier, 1998; Tazil *et al.*, 2010; Ribrant and Bertling, 2007). Large-scale wind turbines with pitch control, variable-speed control and a permanent-magnet synchronous generator are feasible. Earlier researches concluded that the combination of a permanent-magnet synchronous generator and an inverter/converter leads to reduction in voltage deviation and variation in output power of wind-turbine. Further, when the generator is integrated with grid system, rush current is zero (Cutululis *et al.*, 2006; Pena *et al.*, 1996; Morimoto *et al.*, 2003). Using Maximum Power Point Tracking (MPPT) control, generator efficiency can be easily kept at the maximum value but this system is costly (Nishida *et al.*, 2006; Ahmed *et al.*, 2006; Chan *et al.*, 2010; Grzesiak *et al.*, 1999). While using synchronous generator, the generator-side converter is replaced by a three-phase diode rectifier and a chopper (Tan and Islam, 2004; Jiao *et al.*, 2001; Song *et al.*, 2003; Higuchi *et al.*, 2000; Hoffmann and Mutschler, 2000). Which is low cost when compared with the full-power converter. Voltage at dc side

of the diode rectifier changes with change in generator speed. A step-up chopper is used to adapt the rectifier voltage to the dc-link voltage of the inverter (Grzesiak *et al.*, 1999). The step-up chopper used as a rectifier utilize a high switching frequency, implying that the bandwidth of these components is much higher than the bandwidth of the generator. The machine torque can be controlled by controlling the inductance current in the step-up chopper. In a buck-boost converter is proposed for a dc-dc chopper, voltage stress in the chopper switch is higher than that of the boost converter (Higuchi *et al.*, 2000).

In Power Conditioner System (PCS) consisting of a series-type 12-pulse rectifier and a three-phase voltage-fed PWM inverter with grid Integration of the Interior Permanent-Magnet Synchronous Generator (IPMSG) is developed (Mademlis and Margaris, 2002).

In this study, grid integrated Power Conditioner System (PCS) consisting of phase-shifting transformer which powers series-type 12-pulse uncontrolled diode rectifier which is cascaded to a Pulse Width Modulated (PWM) diode clamped multilevel inverter. In this method, passive filter design at the generator terminals effectively reduces the losses in the system and the grid-side PWM inverter supplies sinusoidal currents to the grid within a wide range of the system operating speed. The power factor of the grid-side PWM diode clamped inverter can be adjusted by controlling its reactive current control.

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SYSTEM DESCRIPTION

In Fig. 1, conventional Power Conditioner System (PCS) consisting of a series-type 12-pulse rectifier and a three-phase voltage-fed PWM inverter for grid integration of the IPMSG is shown. In the proposed system grid side PWM voltage source inverter is replaced by a diode clamped multilevel inverter. The weight of the phase changing transformer on the generator-side 12-pulse diode rectifier is heavy due to the low-frequency operation of the generator output power.

Compared with the conventional system, the proposed system has advantages in terms of low cost and high reliability and reduction in harmonics.

Figure 1 shows conventional series-type 12-pulse rectifier and a three-phase voltage-fed PWM inverter for grid integration.

High-efficient operation of the generator can be achieved by connecting a simple passive filter at the generator terminal. Design of the passive LC filter for optimum parameters should compensate the power factor angle of the generator. In addition, employing series-type 12-pulse rectifier, the dc-link voltage can be easily kept at a high value enough to operate the latter grid-connected inverter even in a low-speed area.

Passive filter design: The passive filters, set at the generator terminals are designed not only to decrease harmonics in voltages and currents but also it improves the generator efficiency. To decrease the total losses in the stator windings and iron core of the generator, the desired weakening exciting stator current (i^*_{gd}) of the permanent-magnet flux with an indefinite q-axis stator current (I^*_{gq}) is given by Mademlis and Margaris (2002):
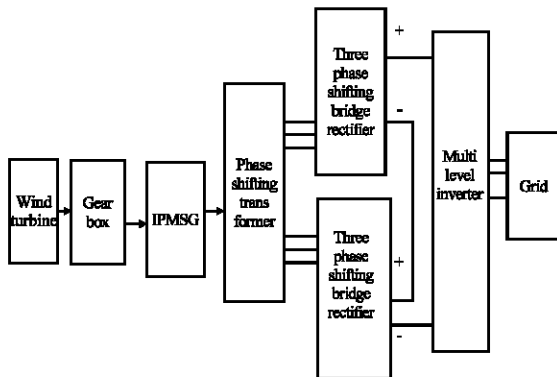

Fig. 1: Conventional series-type 12-pulse rectifier and a three-phase voltage-fed PWM inverter for grid integration

$$i^*_{gd} = \frac{\sqrt{1.5\phi_a}}{2(L_q-L_d)} \frac{R_a+b.(2-\gamma)}{R_a+b}$$
$$\overline{\quad - \sqrt{\frac{1.5\phi_a^2}{4(L_q-L_d)}\left(\frac{R_a+b.\gamma}{R_a+b}\right)^2 + i^{*2}_{gq}\frac{R_a+b.\gamma^2}{R_a+b}}\quad} \qquad (1)$$

Where:
$b = (\omega L_d)^2/R_c$
$\gamma = L_q/L_d$

Then, the desired current phase θ^* on the d-q frame, the angle between the back-induced emf and the current i_g of the IPMSG for achieving the high-efficiency operation of the generator through decreasing the copper and iron losses is set by:

$$\theta^* = \tan^{-1}\left(\frac{-i^*_{gd}}{i^*_{gq}}\right) \qquad (2)$$

Figure 2 and 3 shows the simplified equivalent circuit of the proposed system and its vector diagram, respectively, to obtain the angle θ. In Fig. 2, the passive filter is represented by Ls and Cs and the 12-pulse rectifier is modeled by a resistance R_{12P} which is inversely proportional to the generator frequency. The angle θ can be determined by the following which is based on Fig. 3:

$$\theta = \phi + \delta \qquad (3)$$
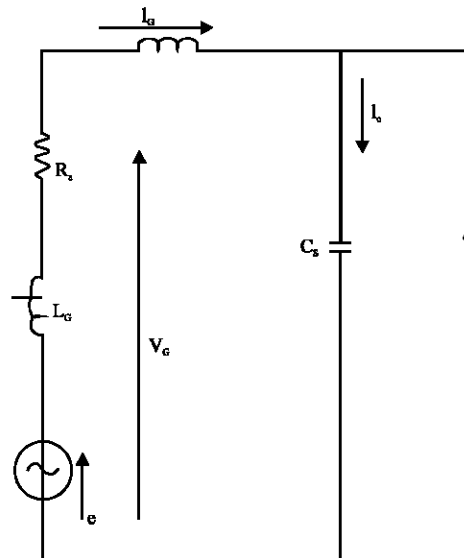
$$\text{Iron loss} = \frac{v_m^2}{R_e}$$

Fig. 2: Equivalent circuit of IPMSG with filter and rectifier

$$\phi = \tan^{-1}\left(\frac{2\pi f L_s + (2\pi f)^3 L_s.C_S^2.R_{12P}^2 - 2\pi f C_S.R_{12P}^2}{R_{12P}} \right)$$

$$(4)$$

$$P_G = \frac{e.v_g}{2\pi f L_q}.\sin\delta - \frac{v_g^2\left(L_q - L_d\right)\sin\delta}{2.2\,\pi f.L_q L_d} +$$

$$v_g\,R_a\,i_g\left\{ \frac{\cos\delta.\sin(\phi+\delta)}{2\,\pi f\,L_q} - \frac{\cos(\phi+\delta).\sin\delta}{2\pi f\,L_q} \right\}$$

$$(5)$$

where, P_G the generator power output.

Calculation example: $f = 70$ Hz, desired $P_G = 560$ W, $Ls = 8$ mH, $Cs = 3\,\mu F = 118$ V.

Experimental result: $R_{12P}\,P \cong v_g^2/P_G = 24.9\,\Omega$, $\varphi = 9.2°$, $i_g = 4.81$ A, $\delta = 10.8°$.

Estimation of the generator frequency: The three-phase voltage-fed PWM inverter is connected to the power grid through three-phase transformers, as shown in Fig. 4.

Figure 5 shows the experimental results of the dc-link voltage of the series-type 12-pulse rectifier under the conditions of dc load and speed variations.

The results indicate that the relation between the dc-link voltage and current is linear and is given experimentally as follows:

$$V_{dc0} = V_{dc} + k.I_{dc}$$

$$(6)$$

Where:

V_{dc} = The measured dc-link voltage of the series-type 12-pulse rectifier

V_{dc0} = The dc-link voltage at the no-load condition

I_{dc} = The dc-link current

$k\ (k = 8.0V/A)$ = A constant

Based on the experimental results represented by Eq. 6 the dc-link voltage V_{dc0} which is required to determine the generator frequency f is estimated using both the measured dc-link voltage V dc and the dc-link current I_{dc}.

By making the power balance between the dc-link power and the power supplied to the grid with neglecting the power losses in the grid-side PWM inverter, the dc-link current I_{dc} can be calculated as:
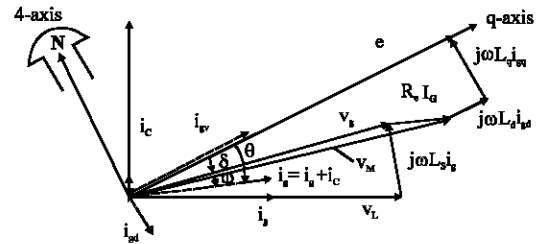

Fig. 3: Vector diagram of IPMSG in steady state where, v_g = Terminal voltage; $v_{\bar{1}}$ = 12 pulse rectifier transformer primary voltage; e = Electromotive force; θ = Phase difference between and e; δ = Load angle of SG; ω = Power factor angle of SG
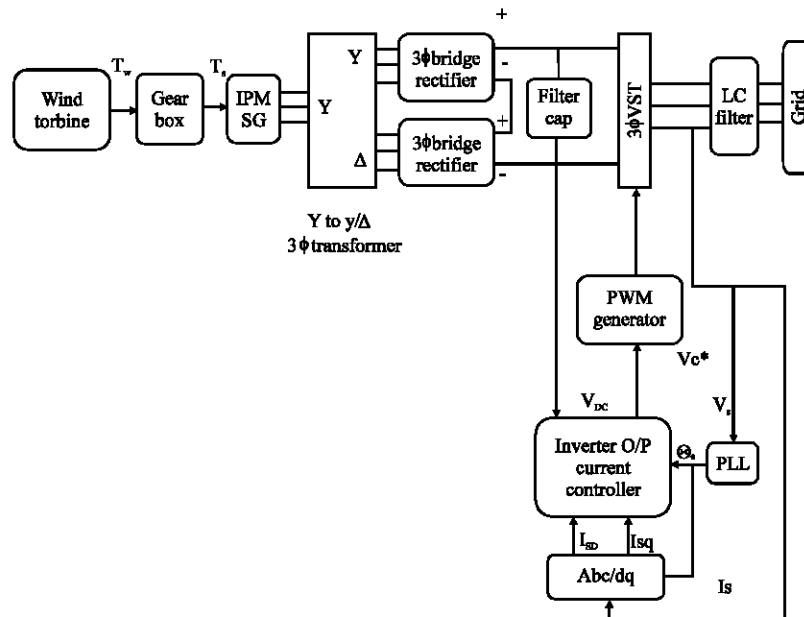

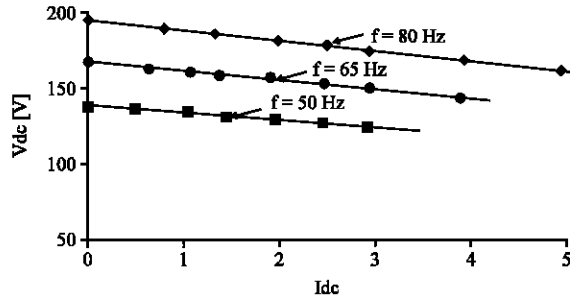Fig. 4: Control diagram for grid side PWM diode clamped multi level inverter

Fig. 5: Linear characteristics of IPMSG in steady state

$$I_{dc} = \frac{V_s}{V_{dc}} i_{sd} \qquad (7)$$

Therefore, V_{dc} can be redefined by substituting Eq. 7 and 8 in as follows:

$$V_{dc0} = \frac{V_{dc} + k.V_s i_{sd}}{V_{dc}} \qquad (8)$$

Where:
i_{sd} = The measured active current of the inverter
V_s = The rms value of line voltage (= 50 V)

On the other hand, V_{dc} can be also calculated from the steady-state characteristic equation of the IPMSG as follows. The maximum value of the generator phase voltaje EM is given by:

$$E_M = 2\pi f.\theta_a \qquad (9)$$

While the maximum value of the secondary line-to-line voltage of the transformer V_{2M} is defined by:

$$V_{2M} = E_M \times \frac{1}{n} \times \sqrt{3} \qquad (10)$$

Where:
φ_a = The maximum flux linkage due to the permanent magnet per phase (φ_a = 0.235 Wb)
n = The turn ratio of the transformer

As the rectifier is a series 12-pulse type with deviation angle of 30°, V_{dc0} can be also calculated from:

$$V_{dc0} = | V_{2M} + V_{2M}^{e^{j6}} |= V_{2M}.2.\cos 15°$$
$$= 2\pi f \, \phi_a \times \frac{1}{n} \times \sqrt{3} \times 2 \times \cos 15° \qquad (11)$$
$$= 2.47 \times f$$

Finally, the generator frequency is defined by using Eq. 8 and 11 as follows:

$$f = \frac{\dfrac{V_{dc} + k.V_s.i_{sd}}{V_{dc}}}{2.47} \qquad (12)$$

Diode clamped multi level inverter: The elementary concept of a multi level inverter is to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries and renewable energy voltage sources can be used as the multiple dc voltage sources. The commutation of the power switches aggregate these, multiple dc sources in order to achieve high voltage at the output; however, the rated voltages of the power semiconductor switches depends only upon the rating of the dc voltage of the capacitor to which it is connected.

Multi level converters not only can generate the output voltages with very low distortion but also can reduce the dv/dt stresses, therefore Electromagnetic Compatibility (EMC) problems can be reduced. Multi level converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency. Diode clamped multi level inverter is used to reduce the harmonic distortion in the output voltage and change in grid power.

EXPERIMENTAL RESULTS

Figure 6 shows the functions of designed passive filter and investigate significant advantages of proposed diode clamped multi level inverter which has been applied and tested for 1.5-KW IPMSG System. System parameters used in simulation are listed in Table 1.

Effect of the designed passive filter of different generator frequencies with grid side multi level inverter:
- CH1: IPMSG terminal voltage v_{ab} =100V/di, T.H.D = 2.47%
- CH4: Grid side voltage v_{out}= 50 V/div, T.H.D = 0.7%
- CH5: Grid side current i_{out}= 2 A/div, T.H.D = 1.08%

The harmonic distortion at the generator voltage of normal PWM based voltage source inverter 6.5% with 40.0 Hz. Whereas, the harmonic distortion contents at the generator voltage with grid side diode clamped multi level inverter are reduced to 4.5% with 40.0 Hz:

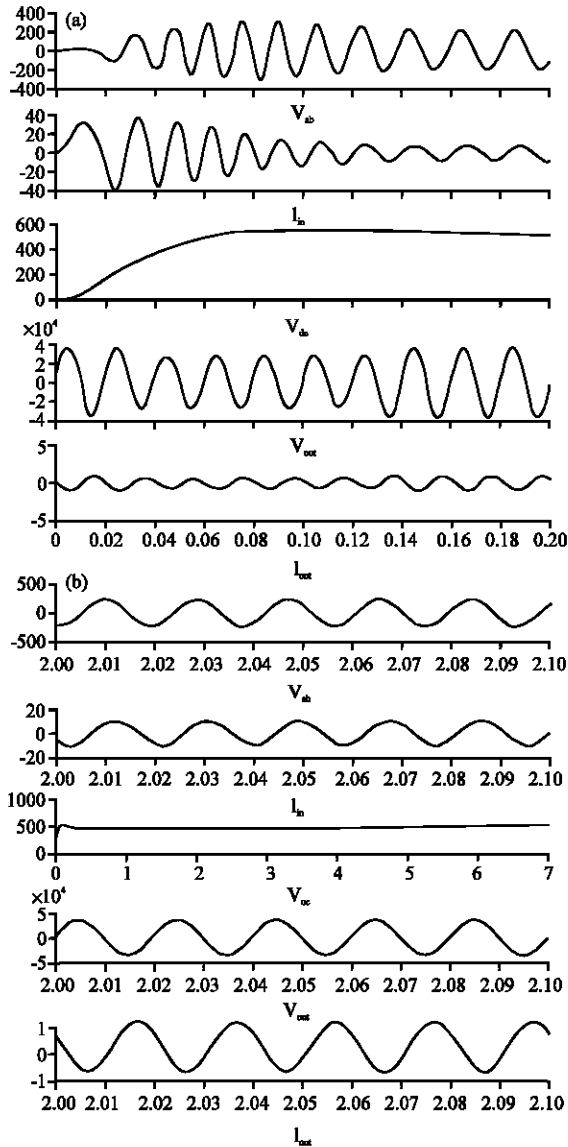- CH1: IPMSG terminal voltage v_{ab} = 100V/div, T.H.D = 2.67%

Fig. 6: Operating waveforms of IPMSG of different output frequencies with grid side multilevel inverter; a) Generator f = 40.0 Hz; b) Generator frequency f = 80.3 Hz

Table 1: System specifications

Symbols	Quantity	Number
ϕ_a	Magnet flux-linkage	0.235 Wb
P	Number of pole pairs	3
L_q	q-axis inductance	11.96 mH
L_d	d-axis inductance	8.90 mH
R_a	Armature resistance	0.774 Ω
I_{am}	Maximum current	6.3A
R_c	Iron loss resistance	444.6 Ω

- CH4: Grid side voltage v_{out} = 50 V/div, T.H.D = 1.02%
- CH5: Grid side current i_{out} = 2 A/div, T.H.D = 1.05%

The harmonic distortion at the generator voltage of normal PWM based voltage source inverter 6.5% with 80.3 Hz. Whereas, the harmonic distortion contents at the generator voltage with grid side diode clamped multi level inverter are reduced to 4.5% with 80.3 Hz.

CONCLUSION

In this study, grid-side PWM diode clamped Multi level inverter cascaded in series with a series-type 12-pulse rectifier for a variable-speed, Grid Integrated IPMSG System has been proposed. From the rectified output voltage of the IPMSG generator speed can be measured and the output power is supplied to the grid. The power factor of the grid-side multi level inverter can be kept at unity. Moreover, the designed passive filter connected at the terminal of the IPMSG reduces the harmonic distortion observed in the line current and the terminal voltage of the generator. The function of the passive filter is not only the harmonic elimination but also the reduction of the total losses of the generator.

Simulation results of the the implemented system with ac-dc-ac power conversion circuit employed with the grid side multi level inverter indicates that the proposed system has advantages including high reliability, harmonic reduction in grid voltage, minimizing output power loss and a wide speed range for variable-speed wind-turbine controllers.

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