Reactive Power Control of Permanent-Magnet Synchronous Wind Generator using Matrix Converter for Grid and Standalone Applications

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Abstract: ***In this paper, the reactive power control of a variable speed permanent-magnet synchronous wind generator with a matrix converter at the grid side is improved. A generalized modulation technique based on singular value decomposition of the modulation matrix is used to model different modulation techniques and investigate their corresponding input reactive power capability. Based on this modulation technique, a new control method is proposed for the matrix converter which uses active and reactive parts of the generator current to increase the control capability of the grid-side reactive current compared to conventional modulation methods. A new control structure is also proposed which can control the matrix converter and generator reactive current to improve the grid-side maximum achievable reactive power for all wind speeds and power conditions. Simulation results prove the performance of the proposed system for different generator output powers.***

Keywords: Matrix converter, Permanent-magnet synchronous generator (PMSG), Reactive power control, Singular value decomposition (SVD) modulation, Variable-speed wind generator.

1. Introduction

A matrix converter is a direct ac/ac frequency converter which does not require any energy storage element. Lack of bulky reactive components in the structure of this all silicon-made converter results in reduced size and improved reliability compared to conventional multistage ac/dc/ac frequency converters. Fabrication of low-cost and high-power switches and a variety of high-speed and high-performance digital signal processors (DSPs) have almost solved some of the matrix converter drawbacks, such as complicated modulation, four-step switching process of bidirectional switches, and the use of a large number of switches [1]. Therefore, its superior benefits, such as sinusoidal output voltage and input current, controllable input power factor, high reliability, as well as a small and packed structure make it a suitable alternative to back-to–back converters. One of the recent applications of matrix converters is the grid connection of variable-speed wind generators [2]–[14]. Variable-speed permanent-magnet synchronous (PMS) wind generators are used in low-power applications. The use of a matrix converter with a multiple PMSG leads to a gearless, compact, and reliable structure with little maintenance which is superior for low-power microgrids, home, and local applications [13], [15]–[17]. The wind generator frequency converter should control the generator-side quantities, such as generator torque and speed, to achieve maximum power from the wind turbine, and the grid-side quantities such as grid-side reactive power and voltage to improve the system stability and power quality (PQ) [17]–[19]. Unlike conventional back-to–back converters in which a huge dc-link capacitor makes the control of the generator and grid-side converters nearly independent [20], a matrix converter controls the generator and grid-side quantities simultaneously. Therefore, the grid-side reactive power of a matrix converter is limited by the converter voltage gain and the generator-side active or reactive power [21]. One necessary feature for all generators and distributed generators (DGs) connecting to a grid or a microgrid is the reactive power control capability. The generator reactive power can be used to control the grid or microgrid voltage or compensate local loads reactive power in either a grid-connected or an islanded mode of operation [19], [20].

In this paper, the grid-side reactive power capability and control of a PMS wind generator with a matrix converter is improved. To increase the matrix converter reactive current gain, the SVD modulation technique is used such that both active and reactive parts of the generator-side current can contribute to the grid-side reactive current. It is shown in Section IV that the generator free reactive power capacity can be used to increase the grid-side reactive power. A new control structure is also proposed which can control the generator and matrix converter reactive power to increase the controllability of the grid-side reactive power at any

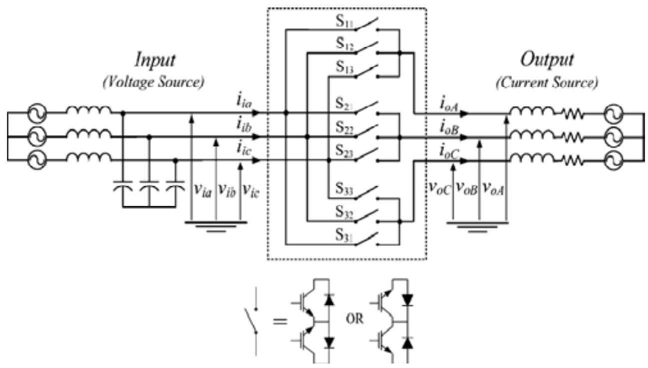


Figure 1: Typical three-phase matrix converter schematic

wind speed and power. The proposed control structure is simulated with a simple adaptive controller (SAC) on a gearless multiple variable-speed PMS wind generator, and the results are presented to verify its performance under different operating conditions. The simulations are performed using Matlab/Simulink software.

2. Matrix Converter

Fig. 1 shows a typical three-phase matrix converter. In a matrix converter, the input and output phases are related to each other by a matrix of bidirectional switches such that it is possible to connect any phase at the input to any phase at the output. Therefore, the controllable output voltage is synthesized from discontinuous parts of the input voltage source, and the input current is synthesized from discontinuous parts of the output current source or

$$
\begin{aligned}
&V_{o,ABC} = \mathbf{S} V_{i,abc} \\
&I_{i,abc} = \mathbf{S}^T I_{o,ABC} \\
&\mathbf{S} = \begin{pmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{pmatrix} \\
&\begin{cases} s_{kj} \in \{0,1\} \\ s_{k1} + s_{k2} + s_{k3} = 1 \end{cases} \quad k,\ j = 1,2,3 \\
&V_{i,abc} = \begin{pmatrix} v_{ia} \\ v_{ib} \\ v_{ic} \end{pmatrix}, \quad I_{i,abc} = \begin{pmatrix} i_{ia} \\ i_{ib} \\ i_{ic} \end{pmatrix} \\
&V_{o,ABC} = \begin{pmatrix} v_{oA} \\ v_{oB} \\ v_{oC} \end{pmatrix}, \quad I_{o,ABC} = \begin{pmatrix} i_{oA} \\ i_{oB} \\ i_{oC} \end{pmatrix}
\end{aligned} \tag{1}
$$

Where v_{oj} and i_{oj} (j=A,B,C) are the output phase voltages and currents, respectively; v_{ij} and i_{ij} (j=a,b,c) are the input phase voltages and currents; and s_{kj} is the switching function of switch kj. Lack of an energy storage component in the structure of a matrix converter leads to an equality between the input–output active power, i.e.,

$$p_i = V_{i,abc}^T \cdot I_{i,abc} = V_{o,ABC}^T \cdot I_{o,ABC} = p_o.$$

(2)

3. Matrix Converter Reactive Power Control

Several control strategies based on different modulation techniques can be used to control the input reactive current and power of a matrix converter. All modulation techniques can be modeled by the SVD modulation method. Therefore, this method can be used to study the reactive power capability and control of a matrix converter. According to Fig. 3, the input reactive power of a matrix converter can be written in a general form as [26]

$$
\begin{aligned}
Q_i &= \Im\mathfrak{m}\{S_i\} = V_{iq} I_{id} - V_{id} I_{iq} \\
&= q_d V_{iq} I_{od} - q_q V_{id} I_{oq} \\
&= Q_{id} + Q_{iq}
\end{aligned} \tag{3}
$$

Where S_i is the input complex power, Q_{id} is the part of the input reactive power made from I_{od} and Q_{id} is the part of the input reactive power made from I_{oq} . Therefore, the following three different strategies of synthesizing the input reactive power of a matrix converter can be investigated:

- Strategy 1: synthesizing from the reactive part of the output current (i.e., Q_{iq});
- Strategy 2: synthesizing from the active part of the output current (i.e.,Q_{id});
- Strategy 3: Synthesizing from the active and reactive parts of the output current (i.e.,$Q_{id}+Q_{iq}$).

3.1 Synthesizing From the Reactive Part of the Output Current

If in the SVD modulation technique, θ_i is set to the input voltage phase angle as shown in Fig. 5, the output voltages will also be aligned with the d–axis of the output synchronous reference frame which is defined by θ_o, and the generalized modulation technique will be the same as the Alesina and Venturini modulation technique with a more relaxed limitation on q_d and q_q [24].

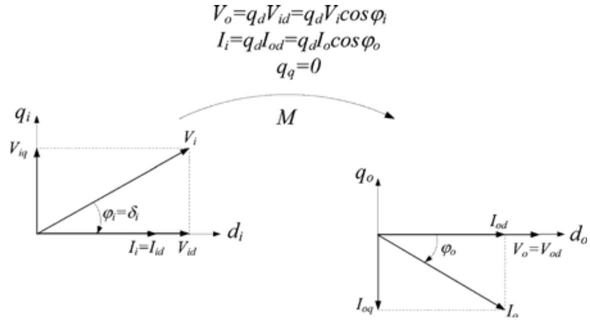


Figure 2: Modeling the SVM modulation method by the SVD modulation technique.

In this case, q_d controls the voltage gain and q_q controls the reactive current gain of the matrix converter. Therefore, the input reactive power is limited by the voltage gain and the output reactive power as given by
(4)

$$
\begin{cases} V_o = V_{od} = q_d V_{id} = q_d V_i \\ I_{id} = q_d I_{od} \\ I_{iq} = q_q I_{oq} \end{cases} \Rightarrow \begin{cases} Q_i = Q_{iq} = \frac{q_q}{q_d} Q_o \\ q_d = G_v = \frac{V_o}{V_i} \end{cases}
$$

$$(10) \Rightarrow |Q_i| \le \frac{1-q_d}{q_d}|Q_o| = \frac{1-G_v}{G_v}|Q_o| \tag{4}$$

Where $G_v=V_o/V_i$ is the voltage gain of the matrix converter and is the output reactive power.

3.2 Synthesizing From the Active Part of the Output Current

If q_q is set to zero, as shown in Fig. 6, the output voltage will be aligned with the d–axis of the output reference frame and the input current will be aligned with the d–axis of the input reference frame. Therefore, the SVD modulation technique will be the same as the SVM modulation technique [24]. In this case, q_d controls the voltage gain and $_{\phi ic}$ controls the input reactive current of the matrix converter. Therefore, the input reactive power is limited by the voltage gain and the output active power as given by

$$\begin{cases} V_o = q_d V_{id} = q_d V_i \cos\phi_i \\ I_i = q_d I_{od} = q_d I_o \cos\phi_o \end{cases} \Longrightarrow$$

$$\left.\begin{aligned} &Q_i = Q_{id} = V_i I_i \sin\phi_i = P_i \tan\phi_i = P_o \tan\phi_i \\ &G_v = q_d \cos\phi_i \le \tfrac{\sqrt{3}}{2}\cos\phi_i \Rightarrow \tan\phi_i \le \tfrac{\sqrt{\frac{3}{4}-G_v^2}}{G_v} \end{aligned}\right\} \Rightarrow |Q_i| \le \frac{\sqrt{\frac{3}{4}-G_v^2}}{G_v}|P_o| \quad (5)$$

Where P_o is the output active power.

3.3 Synthesizing From Both the Active and Reactive Parts of the Output Current

The two previous strategies do not yield the full capability of a matrix converter. To achieve maximum possible input reactive power, both active and reactive parts of the output current can be used to synthesize the input reactive current. To increase the maximum achievable input reactive current in a matrix converter for a specific output power, its input current should be maximized. Since M^T transforms I_o from the output space onto the input space, to maximize $|I_i|$, the free parameter θ_i must be chosen such that I_o is located as close as possible to the direction over which the M^T gain is maximum, i.e.,

$$\max|I_i| = \max_{\mathrm{M}}\{|\mathrm{M}^T I_o|\}$$

$$\text{subject to:} \begin{cases} V_o = \mathrm{M}V_i \\ |q_d|,\ |q_q| \le \frac{\sqrt{3}}{2} \\ G_v \le k = |q_d| + |q_q| \le 1 \end{cases} \quad (6)$$

where is a positive parameter which is used to vary the matrix converter constraint. can be changed from its minimum possible value (i.e., $k = G_v$) to its maximum possible value (i.e.,$k = 1$) to change the maximum current gain of the matrix converter (i.e.,$G_{c,max}$) and control its input reactive power. This optimization problem can be solved with different solvers. However, in this section, a closed form formulation is derived to simplify computations of the control system. It is proved in Appendix A that if q_d,q_q,δ_i, , and δ_o are chosen as given in (16), the input current gain of the matrix converter will be equal to its maximum achievable value for a given parameter k , voltage gain and output power factor

$$\begin{cases} q_d = \min\left\{k, \frac{\sqrt{3}}{2}, \frac{k+\sqrt{4G_v^2+k^2-4G_v k \sin|\phi_o|}}{2}\right\} \\ q_q = \mathrm{sign}(\phi_i)\mathrm{sign}(\phi_o)\min\left\{k-q_d, \frac{\sqrt{3}}{2}, \frac{q_d G_v \sin\phi_o}{\sqrt{q_d^2-G_v^2\cos^2\phi_o}}\right\} \\ \delta_i = -\mathrm{sign}(\phi_i)\tan^{-1}\sqrt{\frac{q_d^2-G_v^2}{G_v^2-q_q^2}} \\ \delta_o = \tan^{-1}\left\{\frac{q_q}{q_d}\tan\delta_i\right\}. \end{cases} \quad \text{...(7)}$$

Figs. 7 and 8 present the maximum current gain and input reactive power in a matrix converter which can be achieved by the three strategies described in this section. As depicted in these figures, the maximum current gain and input reactive power, which can be achieved by the proposed strategy (i.e., strategy 3), are more than that obtained by the other two.

4. PMS Wind Generator Reactive Power Control

The three methods of controlling the input reactive power of a matrix converter described in the previous section can be used to control the reactive power of a PMS wind generator. A gearless multiple PMS wind generator, which is connected to the output of a matrix converter, is simulated to compare the improvement in the matrix converter input or grid-side reactive power using the proposed strategy. The control block diagram of the system is shown in Fig. 9, and its parameters are listed in Table I. The simulations are performed using PSCAD/EMTDC software. To control the generator torque and speed, generator quantities are transferred onto the synchronous reference frame such that the rotor flux is aligned with the d–axis of the dq0 reference frame. Therefore, I_{gq} will become proportional to the generator torque, and I_{gd} can be varied to control the generator output reactive power. Usually, I_{gd} is set to zero to minimize the generator current and losses. However, in this section, the effect of I_{gd} on the input reactive power is also studied, and a new control structure is proposed which can control the generator reactive power to improve the reactive power capability of the system [27].

4.1 Fixed I_{gd}

If I_{gd} is set to zero, the generator output current and losses will be minimized. However, since the reactance of a syn

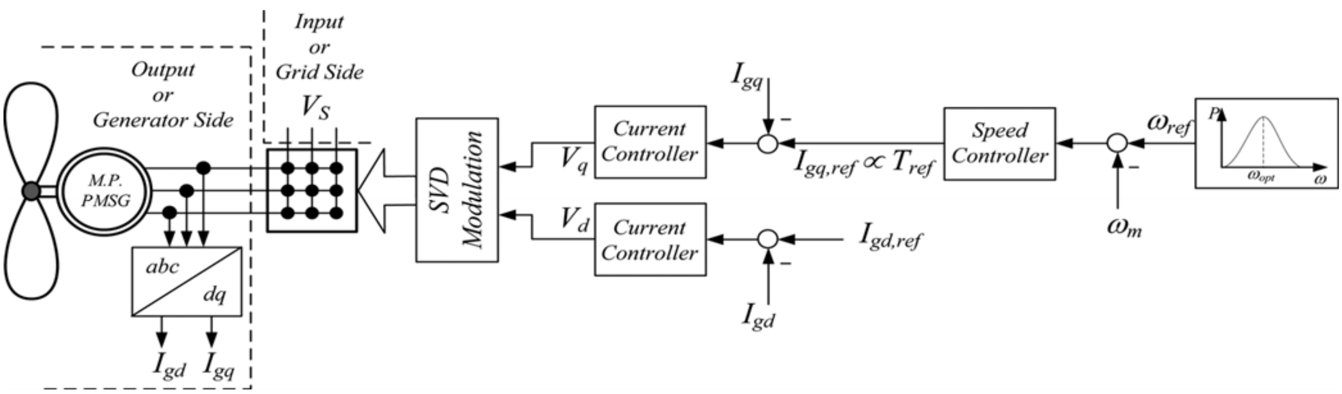
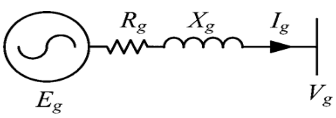


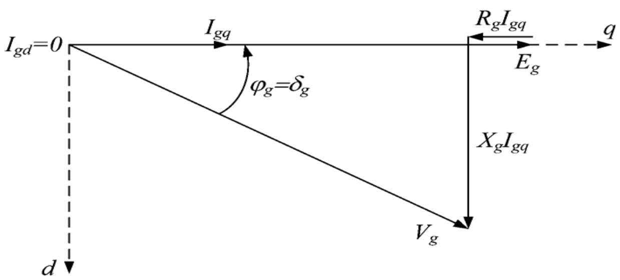
Figure 3: Simplified control block diagram of a PMSG

Table 1: Simulated System Parameters

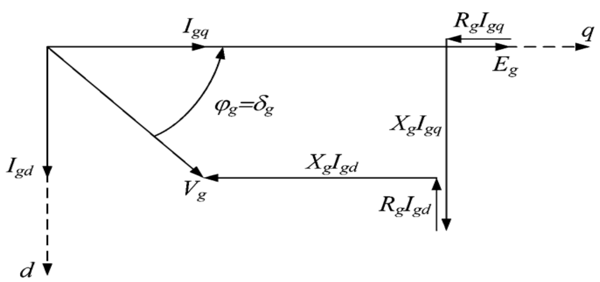
Source	V_S	530 V
	f_S	50 Hz
Matrix Converter	L_f	0.5 mH
	C_f	9 μf
	f_{SW}	10 kHz
Generator & Turbine	S_g	50 kVA
	E_g	380 V
	n_p	58
	f_g	50 Hz
	R_g	0.1 p.u.
	$L_{dg} \approx L_{qg}$	0.8 p.u.
	H_g	1 sec.
	$P_{W,opt}$	$K_{opt}\omega_m^3$
	K_{opt}	314



(a)



(b)



(c)

Figure 3: Phasor diagram of PMSG for different values of I_{gd} . (a) PMSG equivalent circuit. (b) I_{gd}=0. (c) I_{gd}>0 .

chronous generator is typically large, an increase in the wind speed and generator output power leads to an increase in the

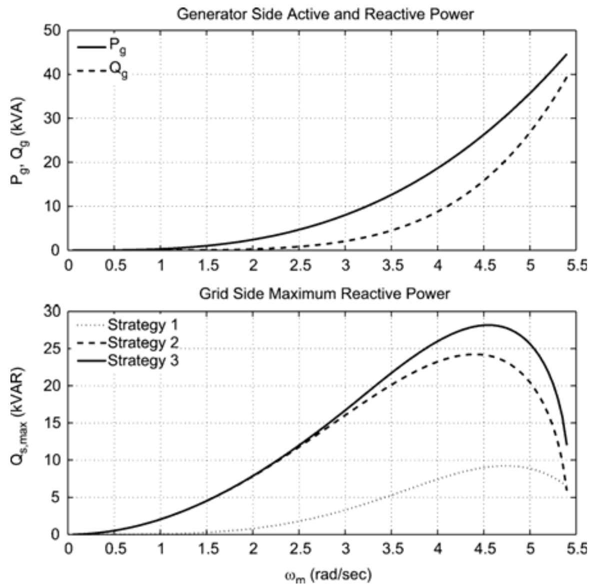


Figure 4: Generator-side active and reactive power and the maximum grid side reactive power versus generator shaft speed ω_m for different strategies.

generator output reactive power. Fig. 10(b) shows a typical phasor diagram of a generator for I_{gd}=0 . Fig. 11 shows the generator active and reactive powers and the maximum grid-side reactive power which can be achieved by the three strategies described in the previous section for different wind speeds and powers. Since an increase in the wind speed leads to an increase in the generator active and reactive powers, the maximum grid-side reactive power, which can be achieved by the proposed strategy, is higher than that obtained by the other two methods.

4.2 Controlled I_{gd}

Although the maximum achievable grid-side reactive power is improved by the proposed strategy, at low wind speed conditions, the system reactive power capability will be decreased severely which may decrease the system voltage quality and stability. Since, in the proposed strategy, the grid-side reactive current is made from both active and reactive parts of the generator- side current, control of the generator-side reactive power

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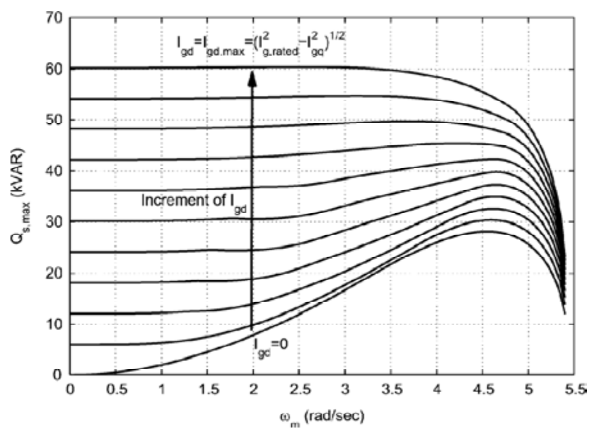

Figure 5: Grid-side maximum achievable reactive power for different values of I_{gd}

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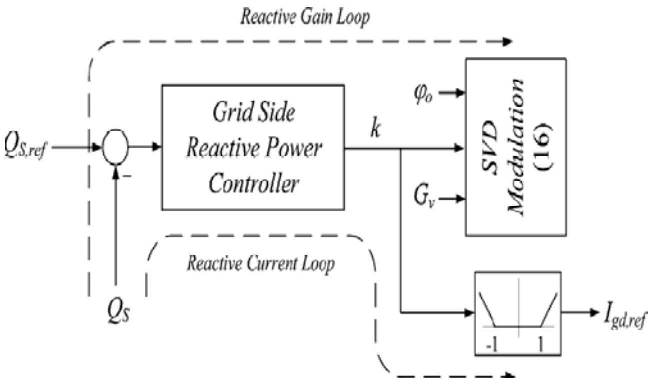

Figure 6: Proposed control structure which uses I_{gd} and matrix converter synchronously to control the grid-side reactive power. will be effective in increasing the grid-side reactive power at all wind speed conditions. As shown in Fig. 10(c), an increase of I_{gd} from zero will increase the generator current and decrease its terminal voltage while its effect on the output active power can be neglected. Decreasing the matrix converter voltage gain will increase the maximum current gain. Therefore, increasing I_{gd} will increase the grid-side reactive power and improve the system reactive power capability. Fig. 12 shows the maximum achievable grid-side reactive power if I_{gd} is set to a value different from its maximum-allowable value.

$$\left(I_{gd,max} = \sqrt{I_{g,rated}^2 - I_{gq}^2}\right)$$

It can be seen from this figure that if the generator free reactive power capacity is used, a nearly uniform maximum grid-side reactive power can be achieved at all wind speeds. Since increasing I_{gd} will increase the generator losses, a new control structure is also proposed in Fig. 13 which controls I_{gd} if and only if the maximum grid-side reactive power, which can be achieved for $I_{gd}=0$, is not sufficient. The proposed structure consists of two reactive gain and reactive current control loops which are controlled by a single reactive power controller. The reactive gain loop controls the matrix converter current gain or ϕ_i by changing the absolute value of parameter k defined in (16). The sign of k defines the sign of ϕ_i or the sign of the grid-side reactive power. When parameter k is lower than its maximum value (i.e.,k = 1), the reactive current loop, which controls $I_{gd,ref}$ is open by the dead zone element, and the reactive gain loop controls the matrix converter current gain. When k reaches its maximum value, the reactive gain loop will be opened due to the saturation of the matrix converter current gain, and the reactive current loop will be controlled by the same controller. The proposed structure defines $I_{gd,ref}$ in Fig. 9, and G_v and ϕ_o define the desired matrix converter output voltage required to control the generator. This required voltage is generated by the generator current controllers in Fig. 9. The controller used in these simulations for the grid-side reactive power control is a simple adaptive controller (SAC). It can be seen from these figures that the controller increases I_{gd} to track the desired grid-side reactive power, if the maximum achievable grid-side reactive power for $I_{gd} = 0$ is not sufficient. An increase in I_{gd} will decrease the generator terminal voltage and increase the generator losses.

5. Simulation Results

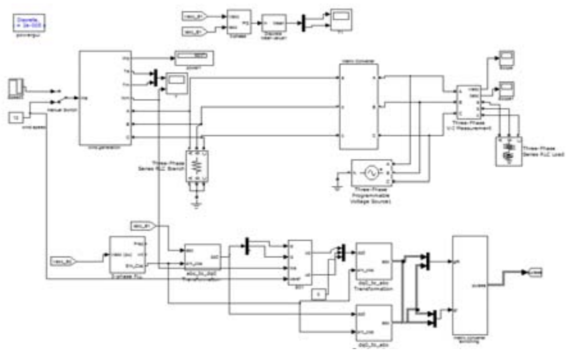

Figure 7: Simulation model of permanent magnet synchronous wind generator with matrix converter with grid

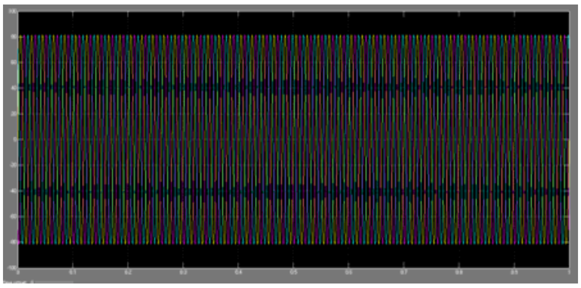

Figure 8: Grid voltage

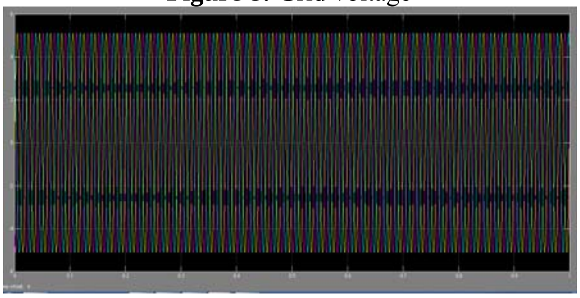

Figure 9: Grid current

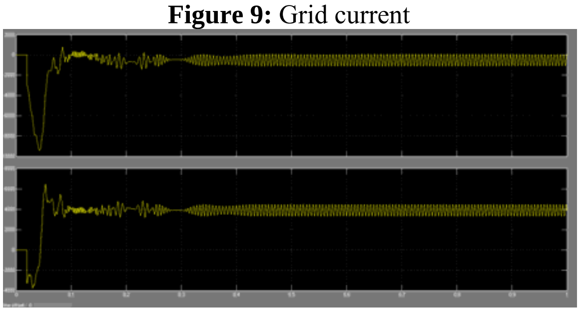

Figure 10: Active and reactive power

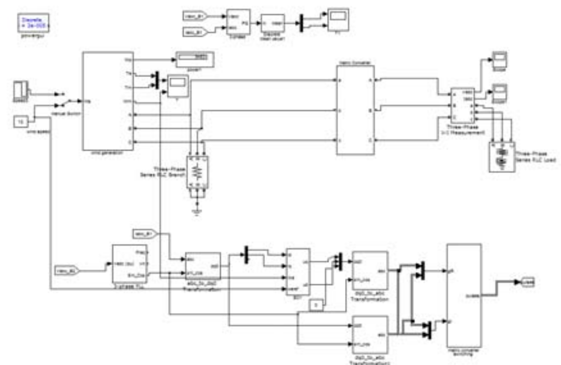

Figure 11: Simulation model of permanent magnet synchronous wind generator with matrix converter for standalone applications

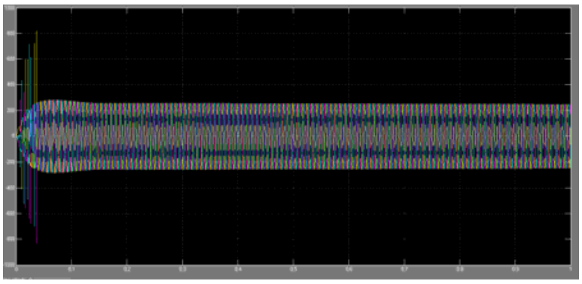

Figure 10: Grid voltage

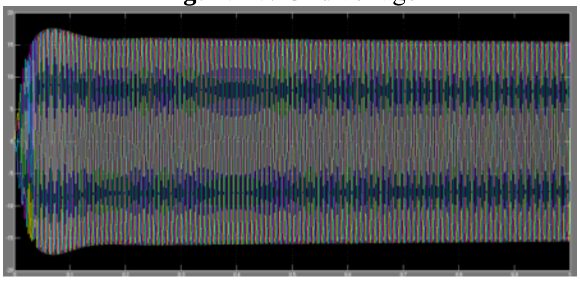

Figure 10: Grid current

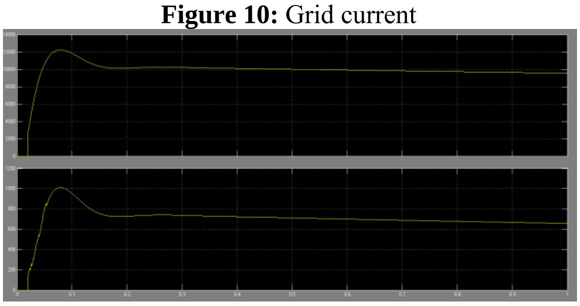

Figure 10: Active and reactive power

6. Conclusion

In this paper, a new control strategy is proposed to increase the maximum achievable grid-side reactive power of a matrix converter-fed PMS wind generator. Different methods for controlling a matrix converter input reactive power are investigated.

It is shown that in some modulation methods, the grid-side reactive current is made from the reactive part of the generator-side current. In other modulation techniques, the grid-side reactive current is made from the active part of the generator-side current. In the proposed method, which is based on a generalized SVD modulation method, the grid-side reactive current is made from both active and reactive parts of the generator-side current. In existing strategies, a decrease in the generator speed and output active and reactive power, will decrease the grid-side reactive power capability. A new control structure is proposed which uses the free capacity of the generator reactive power to increase the maximum achievable grid-side reactive power. Simulation results for a case study show an increase in the grid side reactive power at all wind speeds if the proposed method is employed.

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