Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 57(2), 396–404(2016)

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Multiphase Wind Energy Conversion Systems Based on Matrix Converter

DOI 10.7305/automatika.2016.10.1313
UDK [681.516.7-531.6:621.548]:621.313.332.025.4.045.56

Original scientific paper

This paper presents a new variable speed wind energy conversion systems (WECS). It is based on a six-phase asymmetrical squirrel cage induction generator (SCIG) and a matrix converter (MC) as power electronic interface between six-phase SCIG and electrical network. The analysis employs a rotor flux vector control algorithm and a scalar strategy modulated MC to control the generator. Characteristics of MC are used for maximizing the power tracking control when different wind speeds and delivering powers to the grid are simultaneously considered. The MC provides sinusoidal input and output voltages and a unity power factor, but causes an asymmetry in the generator. A current control strategy including the method of suppressing imbalance caused by this asymmetry is discussed. Some numerical simulations are carried out showing the effectiveness of the proposed WECS topology.

Key words: AC machines, matrix converters, vector control, wind energy conversion systems

Višefazni sustav za pretvorbu energije vjetra zasnovan na matričnom pretvaraču. U ovom radu prikazan je novi sustav za pretvorbu energije vjetra s promjenjivom brzinom. Zasnovan je na šestofaznom asimetričnom kaveznom generatoru i matričnom pretvaraču koji je sučelje između generatora i elektroenergetske mreže. U analizi se koristi vektorsko upravljanje tokom u rotoru i skalarna strategija moduliranog matričnog pretvarača za upravljanje generatorom. Karakteristike matričnog pretvarača koriste se za maksimiziranje slijeđenja snage u slučajevima kada se istovremeno promatraju različite brzine vjetra i snage koja se daje u mrežu. Matrični pretvarač daje sinusni ulazni i izlazni napon te jedinični faktor snage, ali uzrokuje asimetriju u generatoru. Razmotrena je strategija upravljanja strujom koja uključuje metodu za smanjivanje neravnoteže koju uzrokuje asimetrija. Provedene su numeričke simulacije koje pokazuju efektivnost predložene topologije sustava za pretvorbu energije vjetra.

Ključne riječi: asinkroni strojevi, matrični pretvarači, vektorsko upravljanje, sustavi za pretvorbu energije vjetra

1 INTRODUCTION

The solution for medium-voltage high-power variable-speed WECS is nowadays based on the multiphase machine. Compared with conventional three-phase machines, multiphase machines with sinusoidal spatial magnetomotive force distribution have lower space harmonics, greater fault tolerance, lower pulsating torque, and lower per phase power ratings for given power [1-4]. Multiphase generators have been studied much less than multiphase variable-speed drives and this remains to be an interesting topic, especially for WECS. In particular, multiphase machines with multiple three-phase windings are very convenient for WECS and several studies, employing six-phase and nine-phase generators, have been conducted recently [5,6]. Companies, as GAMESA Electric, also propose WECS, using eighteen-phase generator with six back-to-back three-phase converters [7]. The modularity of three-phase windings in multiple three-phase winding machines can take advantage of the well established three-phase technology, allowing the use of off-the-shelf three-phase converters.

Several studies on six-phase generators for wind applications have been reported earlier, such as a six-phase permanent magnet generator with back-to-back converters [8], a six-phase induction generator for stand-alone generation and for offshore-wind energy conversion system [9]. The direct MC can be used as an alternative to the DC-link voltage-sourced converter for WECS [10]. It features no energy storage components (DC electrolytic capacitors or inductors), has bidirectional power flow capability and controllable input power-factor [11]. Also, the MC provides a smooth transition of the generator speed through its synchronous speed. To evaluate performance and design controls of a grid-connected wind turbine utilizing the MC topology, it is necessary to develop a dynamic model of the MC. As to the grid-connected wind turbines applica-

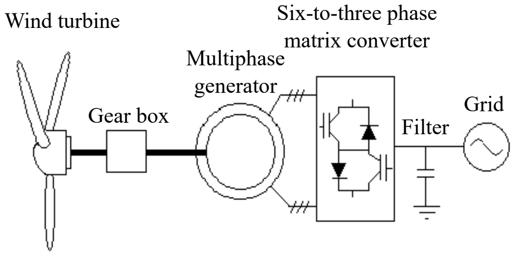


Fig. 1. Proposed topology of multiphase (six-phase) wind generation systems

tion, the MC model should be developed in a *d-q* reference frame to be consistent with the grid and generator models. In literature, those MC models for multiphase drive applications are usually customized for specific objectives, such as vector control of motors, direct torque/power control, but cannot be generalized for wind power system studies [12].

The paper is organized as follows. Section 2 describes general description of the system, including the six-to-three phase matrix converter model and the machine model. In section 3 indirect rotor flux oriented control IR-FOC, power delivery and MPPT control system are explained. Finally, simulation results and conclusions are presented in section 4 and section 5, respectively, to verify the performance and value of the proposed system.

2 GENERAL DESCRIPTION OF THE SYSTEM

2.1 System overview

The generator used in Fig. 1 is an asymmetrical six-phase squirrel cage induction machine, i.e. its two three-phase windings are mutually shifted in space by 30°. The neutral points of the two windings are isolated. As shown in Fig. 1, the generator is controlled using the six-to-three phase matrix converter.

2.2 Six-to-three phase matrix converter model

The schematic diagram of the six-to-three phase matrix converter is presented in Fig. 2. Its inputs are the phase voltages *va1, vb1, vc1, va2, vb2, vc2*, and its outputs are the voltages *vo1, vo2, vo3*. The MC components (*S111, S112,…, S233*) represent eighteen bi-directional switches which are capable to stop the voltage in either directions and to switch between them without any delays [13-15]. The MC connects the six-phase of the generator, with amplitude V_s and frequency $f_s = \omega_s/2\pi$, through the eighteen switches to the output terminal in accordance with calculated switching angles.

The use of MC for variable-speed WECS as proposed in this contribution presents some drawbacks of MC consist of the switching problems resulting from the absence

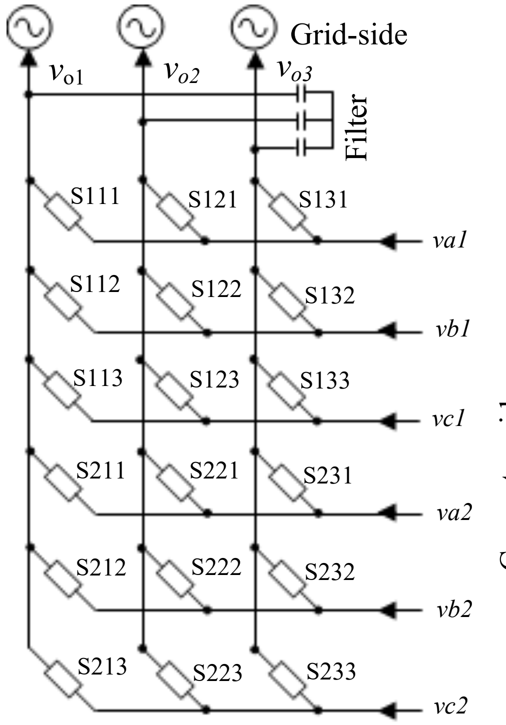


Fig. 2. Basic scheme of a six-to-three phase matrix converter for high power WECS

of static free-wheeling paths, the comparatively complex control algorithms for the frequency conversion and of the reduced output-input voltage ratio which is at most 0.866 (sinusoidal output voltage and input current modulation).

Nevertheless, it offers very interesting advantages, notably:

1. The power converter requires no bulky and costly energy storage components, like those in dc-link converter,

2. The control scheme required by a direct AC-AC conversion scheme is simpler than that used by a two-stage power conversion.

The input six-phase voltages of the MC are described by:

$$\begin{bmatrix} v_{a1} \\ v_{b1} \\ v_{c1} \\ v_{a2} \\ v_{b2} \\ v_{c2} \end{bmatrix} = V_s \begin{bmatrix} \cos(w_s t) \\ \cos(w_s t - 2\pi/3) \\ \cos(w_s t - 4\pi/3) \\ \cos(w_s t - \pi/6) \\ \cos(w_s t - 5\pi/6) \\ \cos(w_s t - 3\pi/2) \end{bmatrix} \quad (1)$$

The three-phase output voltages obtained have controllable amplitudes V_o and frequency $f_o = \omega_o/2pi$ [15].

The required first harmonic of the output phase voltages of the MC are [15]:

$$\begin{bmatrix} v_{o1} \\ v_{o2} \\ v_{o3} \end{bmatrix} = V_o \begin{bmatrix} \cos(w_o t) \\ \cos(w_o t - 2\pi/3) \\ \cos(w_o t - 4\pi/3) \end{bmatrix} \tag{2}$$

The problem may be defined as follows: with input voltages as in (1), the MC switching angles equations will be formulated so that the first harmonic of the output voltages will be as in (2). The switching angles of the eighteen bidirectional switches S_{xyz} (where *x=1,2* represents the index of the number of winding (double star)*; y=1,2,3* represents the index of the output voltage and *z=1,2,3* represents the index of the input voltage) which will be calculated, must comply with the following rules [13]:

1. At every instant t, only one switch S_{xyz} (*x=1,2* and *z=1,2,3*) will be in 'ON' state. This assures that no short circuit will occur at the generator-side.
2. At every instant t, at least two of the switches S_{xyz}(*x=1,2* and *y=1,2,3*) will be in 'ON' state. This condition guarantees a closed-loop path for the load current (usually this is an inductive current).
3. The switching frequency is f_s and its angular frequency ($\omega_s = 2\pi f_s$), in other words the switching frequency is much higher ($f_s = 20.\max(f_i, f_o)$) than the input and output frequencies) [13].

During the k^{th} switching cycle $T_s(T_s = 1/f_s)$, the first phase output voltage is given by:

$$v_{o1}=\begin{cases} v_{a1} & 0 \le t-(k-1)\,T_s < m_{111}^k T_s \\ v_{b1} & m_{111}^k T_s \le t-(k-1)\,T_s < \left(m_{111}^k + m_{112}^k\right) T_s \\ v_{c1} & \left(m_{111}^k + m_{112}^k\right) T_s \le t-(k-1)\,Ts < T_s \\ v_{a2} & 0 \le t-(k-1)\,T_s < m_{211}^k T_s \\ v_{b2} & m_{211}^k T_s \le t-(k-1)\,T_s < \left(m_{211}^k + m_{212}^k\right) T_s \\ v_{c2} & \left(m_{211}^k + m_{212}^k\right) T_s \le t-(k-1)\,Ts < T_s \end{cases} \tag{3}$$

In (3), m_{xyz}^k are defined by :

$$m_{xyz}^k = \frac{t_{xyz}^k}{T_s} \tag{4}$$

Where t_{xyz}^k is the time interval when S_{xyz} is in 'ON' state, during the k^{th} cycle, and k the switching cycle sequence number. The duty cycle m is [13]:

$$\begin{array}{l} \sum_{z=1}^{3} m_{11z}^k = 1 \quad ; \quad \sum_{z=1}^{3} m_{21z}^k = 1 \\ 0 < m_{xyz}^k < 1 \end{array} \tag{5}$$

2.3 Six-phase Induction Machine Model

Using vector space decomposition method [4], the machine model can be decoupled into three orthogonal subspaces, which are denoted as $\alpha-\beta$, $x-y$, and zero sequence subspaces. For machines with distributed windings, only $\alpha-\beta$ components contribute to the useful electromechanical energy conversion, whereas $x-y$ and zero-sequence components only produce losses. A power invariant decoupling transformation is used to convert the phase variables of the stator (*a1,b1,c1,a2,b2,c2*) and rotor windings into $\alpha-\beta$ and $x-y$ variables [4].

$$[T] = \sqrt{\frac{2}{6}} \times [T^{'}] \tag{6}$$

$$[T^{'}]= \begin{array}{c} \alpha \\ \beta \\ x \\ y \end{array} \begin{bmatrix} 1 & -1/2 & -1/2 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & -1/2 & -1/2 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 & 1/2 & 1/2 & -1 \end{bmatrix}$$

Transformation (6) is the Clark's matrix for an asymmetrical six-phase system ($\alpha = \pi/6\ rad$). Zero-sequence components are omitted from the consideration and are therefore not included in (6), since the machine has two isolated neutral points. Two pairs of real variables that result after application of (6) onto phase quantities ($\alpha-\beta$and $x-y$) can be combined into corresponding space vectors [4].

A rotational transformation is applied next to transform the $\alpha-\beta$ variables into a synchronously rotating reference frame ($d-q$), which is suitable for vector control.

$$[D] = \begin{array}{c} d \\ q \\ x \\ y \end{array} \begin{bmatrix} \cos\theta_s & \sin\theta_s & & \\ -\sin\theta_s & \cos\theta_s & & \\ & & 1 & \\ & & & 1 \end{bmatrix} \tag{7}$$

The transformation of $d-q$ variables in (7) is identical as for a three-phase system [4]. The second pair of variables ($x-y$) is not rotationally transformed since the equations for these variables do not contain stator-to-rotor coupling. In (7), θ_s is the angle of the rotational transformation for stator. Assuming that the electrical angular speed of the machine is ω_r and the reference frame is rotating at an arbitrary speed ω_s (so that $\theta_s = \int \omega_s dt$), the model of the induction machine can be described using the following voltage and flux equations in the ($d-q$) plane (generating convention is used):

$$\begin{cases} v_{ds} = -R_s i_{ds} + d\phi_{ds}/dt - \omega_s \phi_{qs} \\ v_{qs} = -R_s i_{qs} + d\phi_{qs}/dt + \omega_s \phi_{ds} \\ 0 = R_r i_{dr} + d\phi_{dr}/dt - (\omega_s - \omega_r)\phi_{qr} \\ 0 = R_r i_{qr} + d\phi_{qr}/dt + (\omega_s - \omega_r)\phi_{dr} \end{cases} \tag{8}$$

$$\begin{cases} \phi_{ds} = (L_{ls} + L_m)i_{ds} + L_m i_{dr} \\ \phi_{qs} = (L_{ls} + L_m)i_{qs} + L_m i_{qr} \\ \phi_{dr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds} \\ \phi_{qr} = (L_{lr} + L_m)i_{qr} + L_m i_{qs} \end{cases} \tag{9}$$

Where R_s and R_r are the stator and rotor resistances, respectively; whereas L_{ls}, L_{lr} and L_m are the stator and rotor leakage inductances and the magnetizing inductance, respectively. Additional stator equations, which describe the machine in the (*x*−*y*) plane, are:

$$\begin{cases} v_{xs} = -R_s i_{xs} + d\phi_{xs}/dt \\ v_{ys} = -R_s i_{ys} + d\phi_{ys}/dt \end{cases} \tag{10}$$

$$\begin{cases} \phi_{xs} = L_{ls} i_{xs} \\ \phi_{ys} = L_{ls} i_{ys} \end{cases} \tag{11}$$

For a machine with p pole pairs, the electromagnetic torque solely depends on the *d*−*q* components and is given with:

$$T_e = pL_m(i_{dr}i_{qs} - i_{ds}i_{qr}) \tag{12}$$

Finally, the equation of rotor motion is:

$$T_m - T_e = J\frac{d\omega_m}{dt} \tag{13}$$

Where ω_m is the rotor mechanical speed, J is inertia, and T_m is the mechanical torque.

2.4 Compensation of asymmetries

One important consideration when operating six-phase generator is the suppression of *x-y* currents. Ideally, if the two windings are supplied with two sets of balanced sinusoidal three-phase voltages, which are symmetrical and phase-shifted by 30°, two sets of balanced three-phase currents of the same amplitude would flow in each winding. In this case, there will be no current flowing in the *x-y* plane (except for the switching harmonics related ripple current). However, if there are some phase and/or magnitude deviations from this ideal condition, *x-y* currents will flow, and the machine is considered to have asymmetries. The asymmetries due to the type of control strategy of the voltage source converter can be minimised by choosing suitable modulation technique. However, the compensation of asymmetries due to machine and/or supply is not so straightforward. Conventional control method that utilises only one pair of *d-q* current controllers is incapable to suppress the *x-y* currents requiring additional current controllers.

A rotational transformation matrix (14) was introduced to rotate the (*x*−*y*) plane in the counter-synchronous direction [1]:

$$\left[D'\right] = \begin{matrix} d \\ q \\ x_{dq} \\ y_{dq} \end{matrix} \begin{bmatrix} \cos\theta_s & \sin\theta_s & & \\ -\sin\theta_s & \cos\theta_s & & \\ & & \cos\theta_s & -\sin\theta_s \\ & & \sin\theta_s & \cos\theta_s \end{bmatrix} \tag{14}$$

3 CONTROL SYSTEM

The structure of the control system is shown in Fig. 3. The control system is composed of two parts, the Indirect Rotor Flux Oriented Control (IRFOC) and the Maximum Power Point Tracking (MPPT).

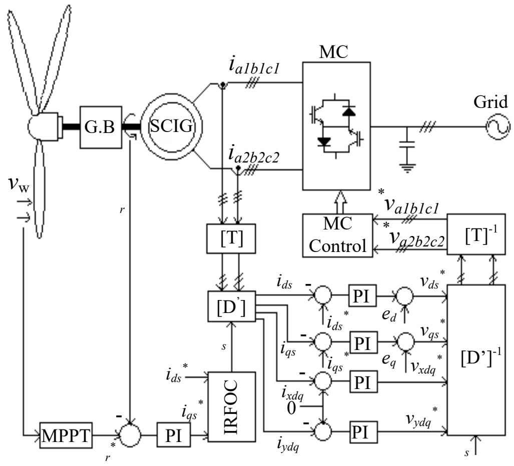


Fig. 3. Block diagram of control for WECS using six-phase SCIG and six-to-three phase MC

3.1 Indirect rotor flux oriented control

With the voltage space decomposition model, the six-phase SCIG can be controlled using indirect rotor flux oriented control method in a similar manner as a three-phase SCIG [4]. The rotor flux angle, which is required for the rotational transformation (14), is calculated from the estimated slip speed and the measured rotor position.

$$\theta_s = \int (p\omega_m + \omega_{sl}^*)dt \tag{15}$$

$$\omega_{sl}^* = \frac{1}{T_r}\frac{i_{qs}^*}{i_{ds}^*} \tag{16}$$

PI controllers are used to composite the asymmetries. The references for x−y current controllers are set to zero to eliminate the asymmetries. Structure of the current control scheme, based on (14), is shown in Fig. 3, where e_d, e_q are the feed-forward terms for indirect rotor flux oriented control.

3.2 Maximum power point tracking

The steady-state wind turbine model at various wind speeds is given by the power-speed characteristics shown in Fig. 4(a). The 1.5 kW are produced by a three-blade horizontal axis wind turbine with diameter of 2 m. At a given wind speed, the operating point of the wind turbine is determined by the intersection of the turbine characteristics and the load characteristics.

From Fig. 4(a), it is noted that the shaft power of the wind turbine is related to its wind speed v and rotor speed N. In practice, characteristics of a wind turbine can also be represented in a simplified form of power performance coefficient and tip ratio ($C_p - \lambda$) as shown in Fig. 4(b).

Following the Abel Betz's theory [16], we know that extracted power from the air by a wind turbine is given by:

$$P_m = \rho A C_p v_{wind}^3 / 2 \tag{17}$$

Where v_{wind} is the wind speed in m/s, ρ is the air density in kg/m3, A is the exposed area in m2 and C_p is the power coefficient. The power coefficient depends on the pitch angle β, which is the angle at which the rotor blades can rotate along its long axis. We can thus define the tip-speed ratio λ defined by [16]:

$$\lambda = \frac{\omega_r R}{v_{wind}} \tag{18}$$

Where ω_r is the rotor speed in rad/s and R is the blade radius of turbine in m. As it can be seen in Fig. 4(b), the power coefficient C_p is a function of λ and its maximum value is yield at the particular tip-speed ratio λ_{nom}, determined from the blade design. Considering (17), the mechanical power is proportional to C_p and hence the maximum output power of wind turbine is obtained at $C_{p\max}$.

$$P_{\max} = \rho A C_{p\max} v_{wind}^3 / 2 \tag{19}$$

Then, the optimum speed of generator is determined as:

$$\omega_r^* = \frac{\lambda_{nom}}{R} v_{wind} \tag{20}$$

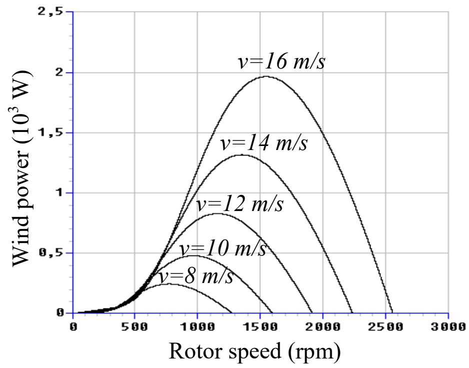
This optimum speed is used as reference speed for speed controller of WECS.

4 SIMULATION RESULTS

To verify the performance of the proposed WECS, several simulation tests are performed. These simulations were performed using methods mentioned in section 3.

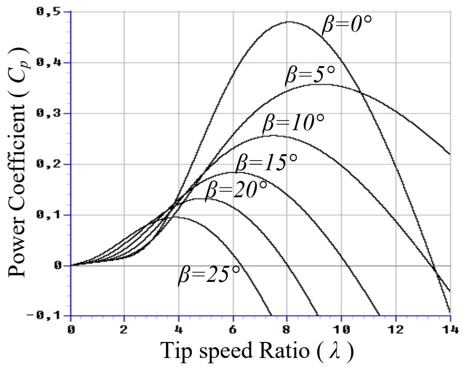
Per-phase equivalent circuit parameters of the 50 Hz six-phase induction machine are given in the Appendix.

a)



(a) Characteristics power speed of wind turbine

b)



(b) Power coefficient tip speed ratio of wind turbine

Fig. 4. Characteristics power-speed (a) and power coefficient-tip speed ratio (b) of wind turbine

Because the grid frequency is different from the output frequency, variable frequency operation mode is selected. Initially, the system is simulated with just *d-q* current controllers and constant wind speed, to visualise the operation of the WECS under ideal operating conditions. In the second simulation, variable wind speed is selected with asymmetries in the generator due to the control strategy of MC. In the last simulation, the *x-y* current controllers are activated to suppress the asymmetries.

4.1 Operation of constant wind speed

The first simulation examines the ideal operation (constant wind speed $v = 16$ m/s) of the system. With the use of MPPT controller, the generator's speed reference is constant ($N* = 1520$ rpm). This reference speed and the actual speed are shown in Fig. 5. Once, the generator's speed converges to the reference. Figure 6 shows the *d-q* currents of the generator. The torque producing *q-axis* current is limited to take only negative values, to ensure the machine from operating in the generating mode. The flux-controlling *d-axis* current is well regulated at its rated value, giving rise to a constant rotor flux in the machine, as depicted in Fig. 7. The *x*-*y* currents and stator current (phase *a*1) of the generator are shown in Fig. 8 and Fig. 9, respectively.

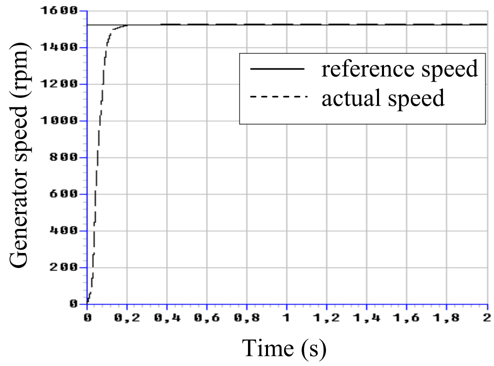


Fig. 5. Speed reference and actual speed

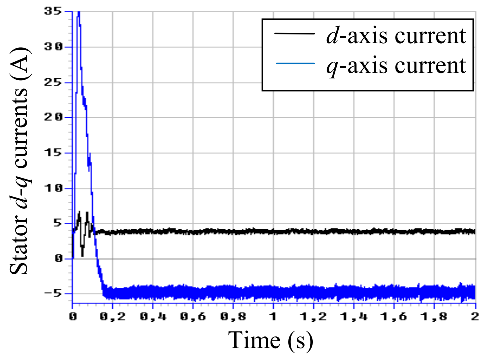


Fig. 6. Stator d-q currents of the generator

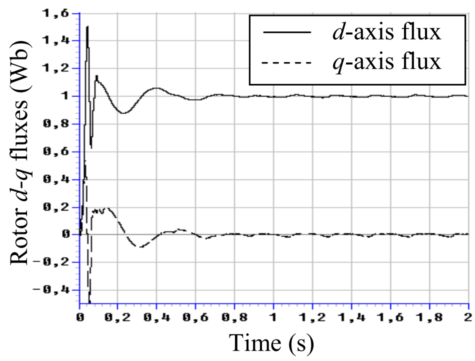


Fig. 7. Rotor d-q fluxes of the generator

4.2 Operation of variable wind speed

To verify dynamic of the proposed system, the wind speed has been varied. The next simulation was repeated

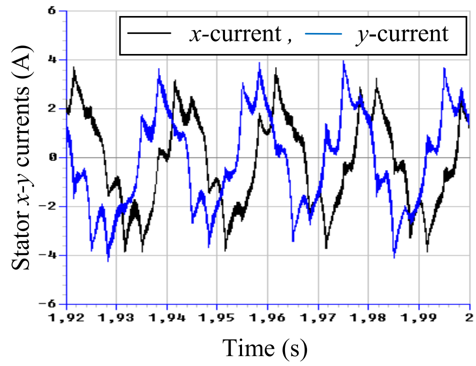


Fig. 8. Stator x-y currents of the generator

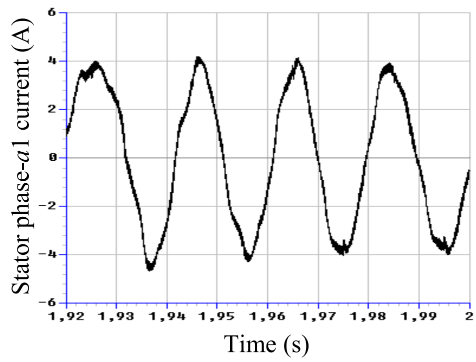


Fig. 9. Stator phase-a1 current in the generator

in operation of variable wind speed. With the use of MPPT controller, the generator's speed reference is varied accordingly, to allow optimal power generation.

Variation of the generator's speed reference and the actual speed are shown in Fig. 10. Once the generator's speed converges to the reference, the operation is considered to be at the maximum power point and the speed does not change until the next change in the reference. Figure 11 shows the *d*-*q* currents of the generator. The *d*-*q* rotor fluxes are depicted by Fig. 12 and the *x*-*y* stator currents producing losses are shown in Fig. 13. Stator phase-*a* current delivered by the generator is illustrated by Fig. 14.

4.3 Compensation of asymmetries

Since the simulation goal is to illustrate the effect of asymmetry compensation, the generator is operated under rated conditions and the fundamental frequency of the stator currents is 50 Hz. Initially, the system is simulated with just *d*-*q* controllers (*x*-*y* voltage references are set to zero). Figure 15 shows the *x*-*y* currents in the generator, before compensation ($t < 1.96$ s) and after compensation ($t > 1.96$ s). It can be seen in Fig. 16, that after the *x*-*y* controllers have been activated ($t > 1.96$ s), the current

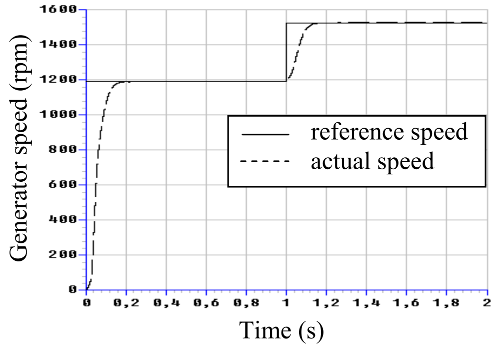


Fig. 10. Speed reference and actual speed

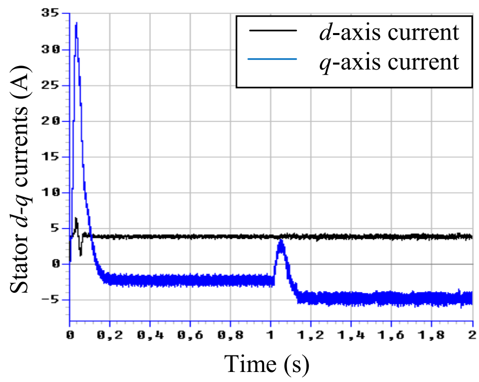


Fig. 11. Stator d-q currents of the generator

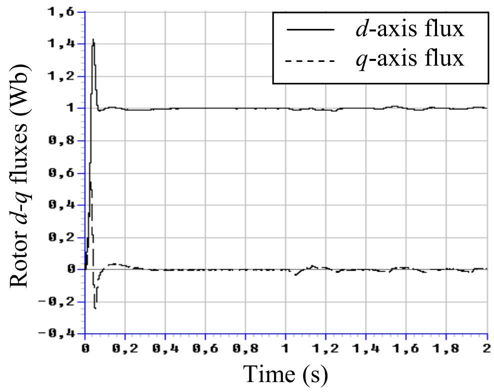


Fig. 12. Rotor d-q fluxes of the generator

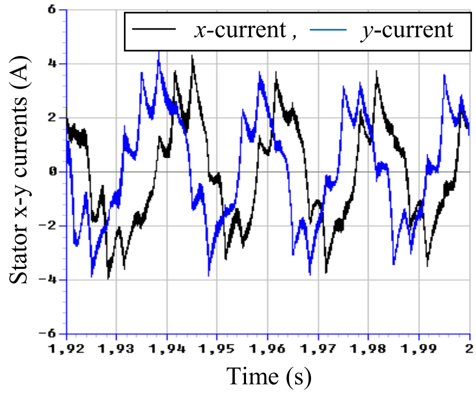


Fig. 13. Stator x-y currents of the generator

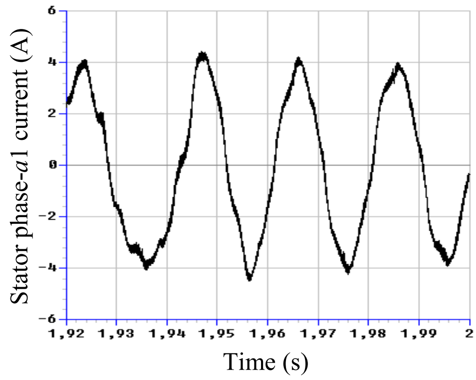


Fig. 14. Stator phase-a1 current in the generator

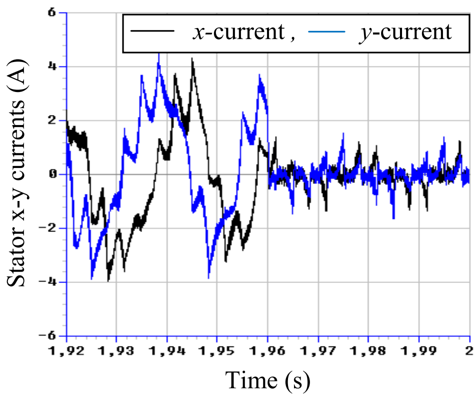


Fig. 15. Stator x-y currents of the generator

amplitude is reduced. After compensation, the *x-y* stator currents are suppressed.

5 CONCLUSION

The paper presents a novel application for grid-connected multiphase wind energy conversion system, employing an asymmetrical six-phase induction machine and a six-phase input to three-phase output matrix converter. The input to the matrix converter is six-phase generator voltages and the output is three-phase variable voltage and variable frequency (grid side). The proposed topology and the concept are equally applicable for variable-speed drive

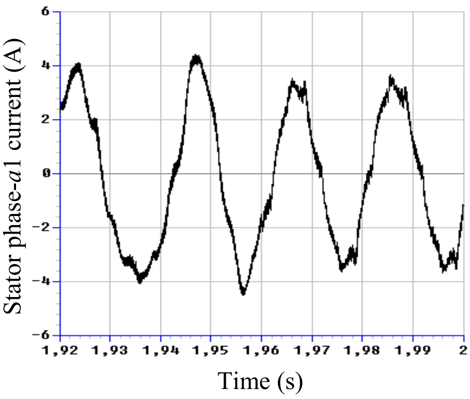


Fig. 16. Stator phase-a1 current in the generator

and for generation applications.

The system is believed to be well suited to remote offshore wind farms with no HVDC-link connection. However, there is a potential problem with the additional degrees of freedom provided by the generator *x-y* currents due to the matrix converter modulation, which the generator is considered to be operating with asymmetry. This paper overcomes this limitation by using *PI* controllers in a synchronous frame; to compensate the asymmetry and making this novel topology simple and easy for implementation.

APPENDIX A DATA OF THE TESTED DRIVE

Table 1. Parameters of the six-phase machine

Parameter	value	Parameter	value
$V(RMS)$	220 V	R_r	3.8 Ω
$I(RMS)$	3.6 A	L_{ls}	0.04 H
P_n	1.5 kW	L_{lr}	0.04 H
p	2	L_m	0.26 H
R_s	4.8 Ω	J	0.03 Kgm^2

REFERENCES

[1] H. S. CHE, E. Levi, M. Jones, M. J. Duran, W. P. Hew, N. Abdrahim, "Operation of six-phase induction machine using series-connected machine-side converters," *IEEE Transaction on Industrial Electronics*, vol. 61, no. 1, pp. 164–176, Jan. 2014. [Online]. Available: http://dx.doi.org/10.1109/TIE.2013.2248338.

[2] H. Abu-Rub, J. Holtz, J. Rodriguez, G. Baoming, "Medium-voltage multilevel converters – state of the art, challenges and requirements in industrial applications," *IEEE Transaction on Industrial Electronics*, vol. 57, no. 8, pp. 2581–2596, Aug. 2010. [Online]. Available: http://dx.doi.org/10.1109/TIE.2010.2043039.

[3] S. Kouro, J. Rodriguez, B. Wu, S. Bernet, M. Perez, "Powering the future of industry: high-power adjustable speed drive topologies," IEEE Ind. Appl. Mag., vol. 18, no. 4, pp. 26–39, Jul/Aug. 2012. [Online]. Available: http://dx.doi.org/10.1109/MIAS.2012.2192231.

[4] E. Levi, R. Bojoi, F. Profumo, H. A. Tolyat, S. Williamson, "Multiphase induction motor drives – A technology status review," *IET Elect. Power Appl.,* vol. 1, no. 4, pp. 489–516, Jul. 2007. [Online]. Available: http://dx.doi.org/10.1049/iet-epa:20060342.

[5] G. K. Singh, A. Senthil kumar, R. P. Saini, "Selection of capacitance for self-excited six-phase induction generator for stand-alone renewable energy generation," *Energy,* vol. 35, no. 8, pp. 3273–3283, Aug. 2010. [Online]. Available: http://dx.doi.org/10.1016/j.energy.2010.04.012.

[6] D. Vizircanu, S. Brisset, P. Brochet, "Design and optimization of a 9-phase Axial-flux PM synchronous generator with concentrated winding for direct-drive wind turbine," *IEEE Ind. Appl. Conf.,* 41st IAS Annual Meeting. Conference Record of the 2006, vol. 4, pp. 1912–1918, 2006. [Online]. Available: http://dx.doi.org/10.1109/IAS.2006.256797.

[7] B. Andresen, J. Birk, "A high power density converter system for the Gamesa G10x 4.5 MW wind turbine," *European Conf. On Power Electronics and Applications EPE*, Aalborg, Denmark, CD-ROM, 2007.

[8] M. J. Duran, S. Kourou, B. Wu, E. Levi, F. Barrero, S. Alepuz, "six-phase PMSG wind energy conversion system based on medium-voltage multilevel converter," *European Conf. On Power Electronics and Applications EPE*, Birmingham, UK, CD-ROM, 2011.

[9] M. J. Duran, F. Barrero, S. Toral, M. Arahol, R. Gregor, R. Marfil, "Multiphase generators viability for offshore wind farms with HVDC transmission," *Int. Conf. On Renewable Energies and Power Quality ICREPQ*, Valencia, Spain, CD-ROM, 2011.

[10] E. Reyes, R. Pena, R. Cardenas, P. Wheeler, J. Clare, R. Blasco-Gimenez, "Application of indirect matrix converters to variable speed doubly fed induction generators," *Power Electronics Specialists Conference, Record-IEEE Annual PESC,* Rhodes*,* pp. 2698-2703, 2008. [Online]. Available: http://dx.doi.org/10.1109/PESC.2008.4592351.

[11] P. W. Wheeler, J. Rodriguez, J. C. Clare, L. Empringham, A. Weinstein, "Matrix converters: A technology review," *IEEE Transaction on Industrial Electronics*, vol. 49, pp. 276–288, Apr. 2002. [Online]. Available: http://dx.doi.org/10.1109/41.993260.

[12] H. Nikkhajoei, A. Tabesh, R. Iravani, "Dynamic model of a matrix converter for controller design and system studies," *IEEE Transaction on Power Delivery*, vol. 21, pp. 744–754, Apr. 2006. [Online]. Available: http://dx.doi.org/10.1109/TPWRD.2005.859301.

[13] A. Djahbar, B. Mazari, M. Latroch, "Control strategy of three-phase matrix converter fed induction motor drive system," Pulsed Power Symposium, UK, pp. 11/1-11/6, 2005. [Online]. Available: http://dx.doi.org/10.1049/ic:20050038.

[14] A. Djahbar, B. Mazari, N. Mansour, "High performance motor drive using three-phase matrix converter," *International Conference On Computational Intelligence for Modelling, Control and Automation,* Vienna, pp. 810-814, 2005. [Online]. Available:http://doi.ieeecomputersociety.org/10.1109/CIMCA.2005.1631364.

[15] A. Djahbar, B. Benziane, A. Zegaoui, "A novel modulation method for multilevel matrix converter," *Energy Procedia Journal,* vol. 50, pp. 988-998, 2014. [Online]. Available: http://dx.doi.org/10.1016/j.egypro.2014.06.118.

[16] Y. Chen, Y. Yang, L. Wang, Z. Jia, W. Wu, "Grid-connected and control of MPPT for wind power generation systems based on the SCIG," 2nd International Asia Conference on Informatics in Control Automation and Robotics, pp. 51-54, 2010. [Online]. Available: http://dx.doi.org/10.1109/CAR.2010.5456726.

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Received: 2015-05-09
Accepted: 2016-03-12