Optimal Controlled Matrix Converter Interfaced WECS for Increased Disturbance Rejection Capability

Vinod Kumar, Virendra Choudhary, Rahul Garg, and R. R. Joshi

Abstract**—**This paper investigates the optimal controlled matrix converter (MC) for wind energy conversion system (WECS). In this paper, development of adaptive fuzzy control algorithm cooperated with space vector pulse width modulation for MC is proposed to enhance disturbance rejection capabilities. The control system is implemented on a dSPACE DS1104 real time board. Feasibility of the proposed system has been experimentally verified using a laboratory 1.2 kW prototype of WECS under varying load conditions.

Keywords**—**Wind turbine emulator, wind energy conversion system (WECS), matrix converter.

I. Introduction

As the wind turbines begin to displace conventional generation, there is an increasing requirement that they remain connected to the power system during disturbances. Due to this requirement, system operators in many countries have recently established transmission and distribution system grid codes that specify the range of voltage conditions for which WTG must remain connected to the power system. These are commonly referred to as the disturbance or fault ride-through specifications.

Achieving this requirement is a significant technical issue on which turbine manufacturers are working [1]. Considering that there are various commercially available WTG designs, including squirrel- cage induction machine based, doubly-fed induction generator based, and full rated series converter-based designs, there are various problems that must be overcome in achieving the fault ride-through requirements and some solutions have been proposed. Optimizing the parameters of the current control loops in the rotor-side converter is proposed in [3].

The use of the crowbar is evaluated in [4] and a non-linear controller is designed in [5].The inherent difficulty of ride-through control during a symmetrical grid fault is explained in [6]. In [7], wind-turbine voltage ride-through capabilities were investigated for the squirrel-cage design using different reactive compensation techniques such as fixed capacitor and an SVC, which primarily addresses the support of network voltage during a fault.

But, recently matrix converter have got lot of attention by the researchers, because of their robustness and reliability, it is a suitable solution to meet new regulations to ride through real grid conditions in wind energy applications as compared to back-to back voltage source converter (VSC). Although the MCs have numerous applications, this paper discusses the use of this approach in the wind energy conversion system (WECS). MCs have many advantages, which are well documented in the literature [8]. MCs provide bidirectional power flow, sinusoidal input/output currents, and controllable input power factor [9]–[14]. When compared with conventional back-to-back converters, the MC has some significant advantages. For instance, due to the absence of components with significant wear-out characteristics (such as electrolytic capacitors), the MC can potentially be very robust and reliable. The amount of space saved by an MC, when compared with a conventional back-to-back converter, has been estimated as a factor of three [15], [16]. Therefore, due to its small size, in some applications, the MC can be embedded in the machine itself [16]. Furthermore, there is not an intrinsic limitation to the power of an MC. An MC of 150 kVA [15] has already been fabricated and tested for military applications. MCs in the megawatt range have not been fabricated yet, but the devices required for building them are commercially available.

Based on above merits of matrix converter, this work presents experimental investigation of the developed laboratory 1.2 kW prototype of MC based wind energy conversion system. An adaptive fuzzy logic control along with SVPWM switching have been used to enhance disturbance rejection capabilities under different conditions like varying load. Here, the paper proposes a control strategy that blocks the converters for a time interval. In this way, the over-currents are limited and the voltage recovers quickly. Novelty of this work is that reversed matrix converter in voltage-boosted capability with lesser no. of switches incorporated with adaptive fuzzy control as compare to traditional matrix converter is experimentally investigated and validated for WECS. To the author's best knowledge, such configuration for

Vinod Kumar is with Department of Electrical Engineering, College of Technology and Engineering, Udaipur, India(E-mail: vinodcte@yahoo.co.in).

Virendra Choudhary is with Department of Electronics &Communication Engineering, Govt. Engineering College, Bikaner, India(E-mail: virendrachoudhary@yahoo.com)

Rahul Garg is with Department of Electrical Engineering, Govt. Mahila Engg. College, Ajmer, India(E-mail: rahulgarg78@yahoo.co.in).

R. R. Joshi is with Department of Electrical Engineering, College of Technology and Engineering, Udaipur, India(E-mail: rrjoshiiitd@yahoo.com)

WECS applications have been neither addressed nor investigated before for disturbance rejection capabilities

II. PROPOSED WECS

Fig. 1 shows the block diagram of the proposed unidirectional indirect matrix converter (MC) and PMSG based wind energy conversion system. The main advantages of the proposed WECS when compared to traditional WECs are low harmonic content, can accommodate large terminal voltage excursions at either side of the MC, any input to output frequency ratio, large frequency variations at either side of the MC, and unbalanced grid conditions.

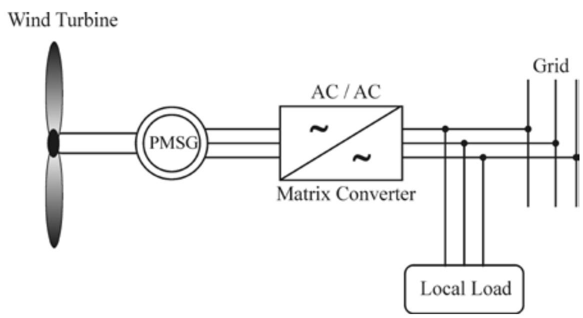


Fig. 1. Schematic diagram of proposed WECS.

Total harmonic distortion (THD) of output voltages and currents are in consent with the permissible limits of IEEE-519 standard, which severely restricts line harmonic injection.

A. Wind Turbine Model

In this paper, a wind turbine emulator which drives the PMSG is developed for laboratory tests. Fig. 2 presents the structure of the wind emulator. The wind speed changes and load switching conditions are performed using the wind turbine emulator, which consist of 4-quadrant controlled chopper dc drive, whose control is implemented using dSPACE DS1104 real time board. It obtains the wind speed values and, by using the turbine characteristics and dc motor speed, calculates the torque command of the wind turbine. In this way, it is able to reproduce the steady and dynamic behavior of a real wind turbine to the energy conversion system.

The aerodynamic torque (T_m) and power captured (P_0) by a wind turbine is given by [16]

$$T_m = \frac{1}{2}\pi\rho C_p(\lambda) R_\omega^3 V_w^2 \tag{1}$$

$$P_0 = \frac{1}{2}\rho C_p A_r V_w^3 \tag{2}$$

where P_0 is the power, ρ the air density, C_p a dimensionless factor called power coefficient, A_r the turbine rotor area, and V_w wind speed.

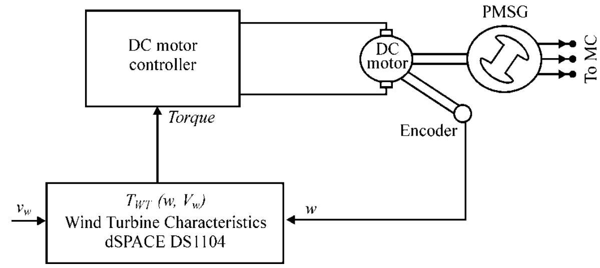


Fig. 2. Wind turbine emulator system.

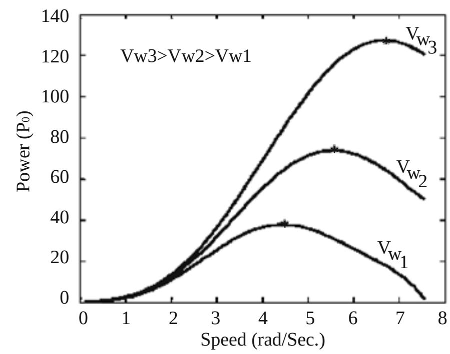


Fig. 3. Power-speed characteristics of a wind turbine.

Fig. 3 illustrates the steady-state power-speed characteristics and the maximum power point attained at each wind speed (marked). The power coefficient is related to the tip speed ratio λ and rotor blade pitch angle θ according to equation (3) [16], as shown in Fig. 4.

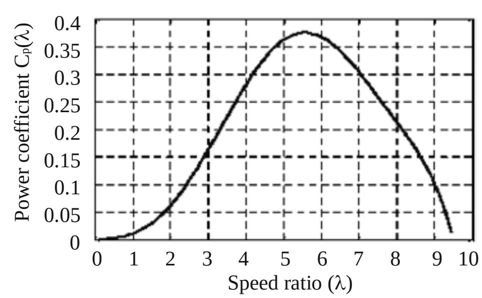


Fig. 4. $C_P - \lambda$ characteristics of wind turbine

$$C_p(\lambda,\theta) = 0.73\left(\frac{151}{\lambda_i} - 0.58\theta - 0.002\theta^{2.14} - 13.2\right)e^{-18.4/\lambda_i} \tag{3}$$

where

$$\lambda_i = \frac{1}{\frac{1}{\lambda - 0.02\theta} - \frac{0.003}{\theta^3+1}} \tag{4}$$

and
$$\lambda = \frac{\omega_m R_r}{V_\omega} \tag{5}$$

In (5) ω_m is the angular speed of the turbine shaft. By substituting V_ω from equation (5) into (2), we get

$$P_0 = \frac{1}{2}\rho C_P A_r\left(\frac{\omega_m R_r}{\lambda}\right)^3 \tag{6}$$

At any given wind velocity, maximum power can be captured from the wind, if the shaft speed is adjusted at the value corresponding to the peak power. The novel idea in this paper is to change the angular frequency of PM synchronous generator through SVPWM control of voltage-boosted matrix converter to track the shaft speed corresponding to the maximum turbine power at all times.

B. Configuration of Reversed Matrix Converter

Fig. 5 shows the schematic diagram of the unidirectional voltage-boosted indirect MC with twelve switches. As shown, six switches with anti-parallel diodes are arranged as front end voltage source rectifier (VSR), whereas other six switches with series diodes as rare end current source inverter (CSI). It has its power flow from VSR to CSI terminals, which is the reverse direction of traditional matrix converter. This reversal is important with aspect to wind generation system as these require voltage boosting of its source with power flowing to grid or local loads.

At any instant, two switches each from upper and lower group of conducts. An active state is formed when two conducting switches are from different phase legs, whereas idle state is formed when conducting switches are from same phase legs, and thus forming total three idle and six active states.

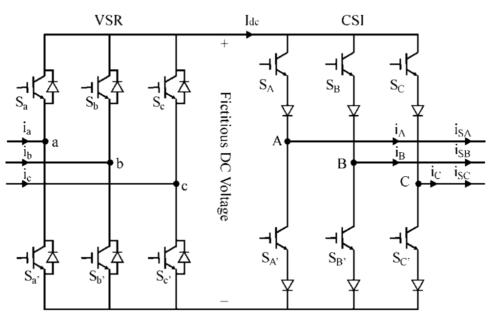


Fig. 5. Schematic diagram of the reversed MC topology.

During active state, power is transferred to load, whereas during idle state circulating current flow within the MC due to shorting of fictitious dc voltage to zero. The detailed modulation algorithm has been explained in detail by [11], [13], and [17-20].

C. Adaptive Fuzzy Control System

Fig. 6 shows the schematic of the developed laboratory prototype of the proposed system. The system has fuzzy logic controllers for angular frequency and ac voltage regulation, which through the MC manages to yield maximum wind power according to the current wind speed by regulating the angular frequency of the PMSG. The Disturbance Detection Control System (DDCS) is designed in order to detect all the types of disturbances at the grid. It estimates the severity of each disturbance and takes the appropriate action, according to its severity level. Its action stages are described below.

(i) Disturbance Detection:

When any disturbance occurs, fictitious dc link voltage suddenly increases, and this deviation of voltage from its previous value is monitored by the fuzzy control, which detects the disturbance.

Fig. 6. Schematic of the laboratory setup of the developed prototype.

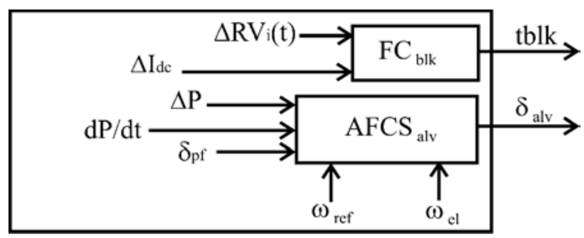


Fig. 7. Proposed Disturbance detection control system.

(ii)Disturbance Severity Estimation

When the disturbance is detected, control system blocks the firing of MC for a short time interval, in order to avoid the over-currents at the converter. The proposed control system uses a variable blocking period, according to the severity of the disturbance. The blocking period, tblk is derived from a fuzzy controller as shown in Fig. 7. Its inputs are the deviations of the dc voltage and the dc current from their previous values, $\Delta RV_i(t)$ and ΔI_{dc}, respectively. Its output is the duration of the blocking period, tblk.

(iii) Mitigation of the Disturbance Impacts

After the de-blocking of the MC firing pulses, the mitigation period starts. During the mitigation period, the role of the signal “δ” is not to achieve maximum power from the wind, but to eliminate the fluctuations in the electrical system.

(iv) Disturbance Ride-Through Enhancement Strategy

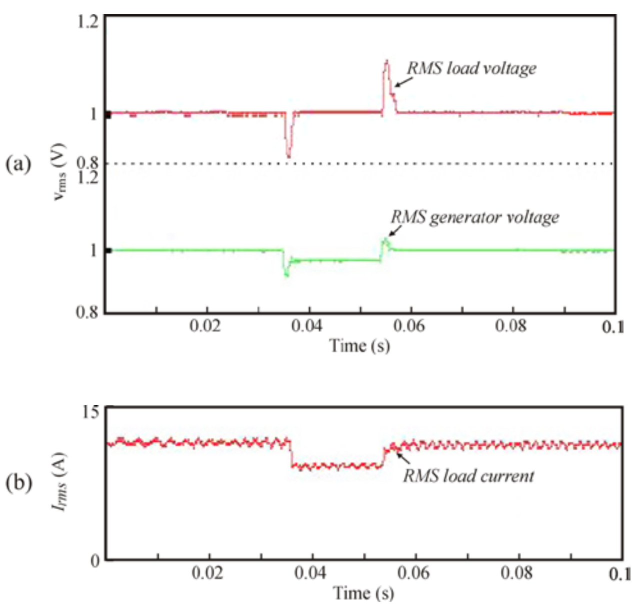
In this work, a fuzzy logic-based supervisor is proposed to control the flywheel sub-system in association with the generator. At the occurrence of the fault at the ac grid, an appropriate signal generated from the d-SPACE 1104 will activate the flywheel sub-system to deliver the requisite energy for a priori fixed time interval (blocking period tblk) reckoned through DDCS control system to render the enhanced ride-through operation.

The control strategy leads the wind generation system to capture the maximum power from the wind and make the machine work with higher efficiency by changing the flux in the air-gap. It also controls the terminal voltage. All the control objectives are achieved through improved SVPWM based reversed matrix converter. Control algorithm has been developed in MATLAB/Simulink programming environment using dSPACE DS1104 kit, which is very flexible and powerful system featuring both high computational and comprehensive I/O periphery.

III. Experimental Results And Discussion

Fig. 6 shows the laboratory 1.2 kW prototype of reversed MC based wind energy conversion system built, using the MATLAB/Simulink and dSPACE DS1104, in order to allow real time control, experimental evaluation of system under different conditions. The LC filter between the MC and the grid consists of inductance of $1.5mH$ and a capacitor of $12.5\mu F$. The laboratory prototype is investigated under different input/output conditions like abrupt change in wind speed, disconnection from grid, misfire in the converter, sudden out of one phase, varying load, wind; and fault conditions etc. Selected experimental results are discussed below for varying load conditions.

Experimental response of the reversed voltage boosted MC based WECS under varying load is illustrated in Fig. 8, where the load is changed from full load to half load and then from half load to full load to simulate the transient load changing. The experimental waveforms of RMS load voltage, generator voltage, RMS load current, frequency, fictitious dc link voltage, modulation index, MC current and instantaneous three phase load voltage are illustrated in Fig. 8.



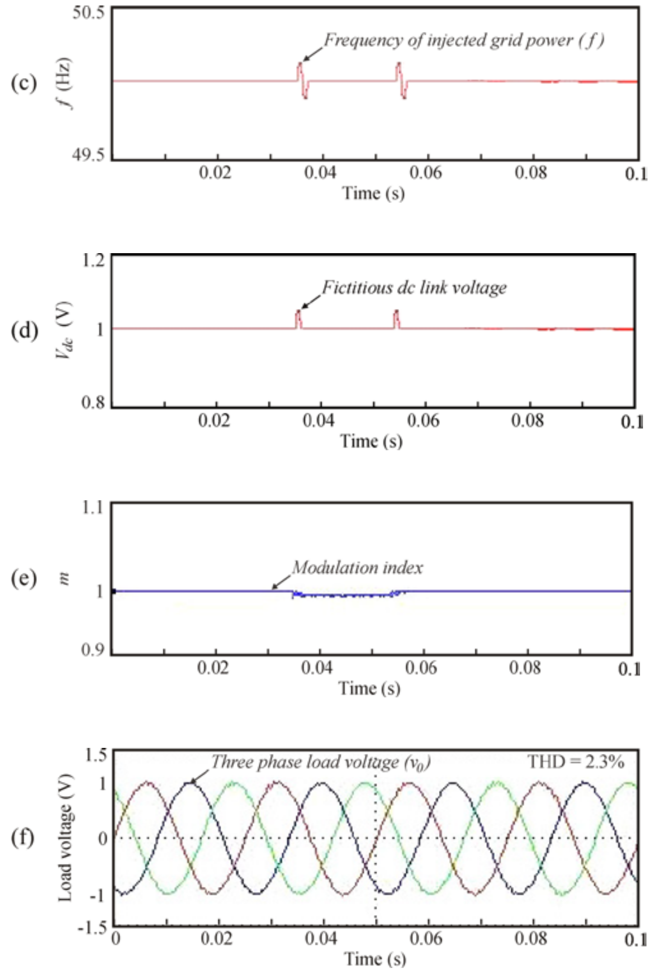


Fig. 8: Experimental waveform during varying load condition: (a) RMS load voltage, and RMS generator voltage; (b) RMS load current; (c) frequency; (d) fictitious dc link voltage; (e) modulation index; and (f) Instantaneous three phase grid voltage response when the load changes from full load to half load and from half load to full load.

Examining the experimental waveforms of load current and load voltage in Fig. 8, it is verified that when the load is changed to smaller value, the load current is increased and so closed loop control commands the necessary control action to maintain the constant voltage magnitude. On the other hand, when load is change to larger value, load current is decreased and controller keeps the load voltage constant, as expected.

Also, it can be examined from the experimental waveforms of RMS load voltage in Fig. 8 (a) that a voltage rise occurs load is decreased suddenly and voltage dip occurs when the load is increased suddenly. During these actions, the proposed controller adjusts dynamically the reference output current of the matrix converter to regulate the load voltage at desired value as shown in Fig. 8(g). The experimental results indicate that the generation system is able to stabilize load voltage under varying load changing by regulating the modulation index of MC, and thus evaluates and explores the disturbance rejection capability of the proposed system under varying load conditions.

IV. CONCLUSION

In this paper, an optimal adaptive fuzzy control system for the MC based WECS is proposed, in order to enhance the disturbance ride-through capability. In the proposed system, a control system that deals with varying load with a corresponding action is proposed. The novelty of the proposed system is that it makes no assumptions on the input and output frequencies of the MC and so applicable under unbalanced input and/or output conditions. The experimental results illustrates that the controller works very well and shows excellent steady-state and dynamic response with low harmonic characteristics.

REFERENCES

[1] P. Gardiner, H. Snodin, A. Higgins, and S. M. Goldrick, "The Impacts of increased levels of wind penetration on the electricity systems of the Republic of Ireland and Northern Ireland," Garrad Hassan and Partners Limited, Glasgow, U.K., Tech. Rep. 3096/GR/04, 2003.

[2] O. Anaya-Lara and N. Jenkins, "Fault current contribution of DFIG wind turbines," presented at the IEE Conf. Reliability of Transmission and Distribution Networks, London, Feb. 2005.

[3] A. Petersson, L. Harnefors, and T. Thiringer, "Evaluation of current control methods for wind turbines using doubly-fed induction machines," *IEEE Trans. Power Electron.*, vol. 20, no. 1, pp. 227–235, Jan. 2005.

[4] G. Pannell, D. Atkinson, R. Kemsley, L. Holdsworth, P. Taylor, and O. Moja, "DFIG control performance under fault conditions for offshore wind applications," presented at the CIRED Conf., Turin, Italy, Jun. 2005.

[5] A. Mullane, G. Lightbody, and R. Yacamini, "Wind -turbine fault ride-through enhancement," *IEEE Trans. Power Systems*, vol. 20, no. 4, pp. 1929–1937, Nov. 2005.

[6] D. Xiang, L. Ran, P. J. Tavner, and J. R. Bumby, "Control of a doubly fed induction generator to ride through a grid fault," presented at the Int. Conf. Electric Machines (ICEM), Cracow, Poland, Sep. 2004.

[7] C. Chompoo-inwai, C. Yingvivatanapong, K. Methaprayoon, and W.J. Lee, "Reactive compensation techniques to improve the ride-through capability of wind turbine during disturbance," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 666–672, May/Jun. 2005.

[8] P. W. Wheeler, J. Rodriguez, J. C. Clare, L. Empringham, and A.Weinstein, "Matrix converters: A technology review," *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 276–288, Apr. 2002.

[9] A. Alesina and M. G. B. Venturini, "Analysis and design of optimum amplitude nine-switch direct AC–AC converters," *IEEE Trans. Power Electron.*, vol. 4, no. 1, pp. 101–112, Jan. 1989.

[10] D. Casadei, G. Serra, A. Tani, and L. Zarri, "Matrix converter modulation strategies: A new general approach based on space-vector representation of the switch state," *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 370– 381, Apr. 2002.

[11] T. Kume, K. Yamada, T. Higuchi, E. Yamamoto, H. Hara, T. Sawa, and M. Swamy, "Integrated filters and their combined effects in matrix converters," *IEEE Trans. Ind. Appl.*, vol. 43, no. 2, pp. 571–581, Mar./Apr. 2007.

[12] V. Kumar, R. C. Bansal, and R. R. Joshi, "Experimental Realization of Matrix Converter Based Induction Motor Drive under various Abnormal Voltage Conditions", *Int. Journal of Control, Automation, and Systems*, vol. 6, no. 5, pp. 670-676, Oct. 2008.

[13] R. Cardenas, R. Pena, P. Wheeler, J. Clare, and G. Asher, "Control of the reactive power supplied by a WECS based on an induction generator fed by a matrix converter," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 429–438, Feb. 2009.

[14] F. Bradaschia, M. C. Cavalcanti, F. A. S. Neves, and H. E. P. de Souza, "A modulation technique to reduce switching losses in matrix converters," *IEEE Trans. Ind. Electron.*, vol. 56, no. 4, pp. 1186–195, Apr. 2009.

[15] T. F. Podlesak, D. C. Katsis, P. W. Wheeler, J. C. Clare, L. Empringham, and M. Bland, "A 150-kVA vector-controlled matrix converter induction motor drive," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 841–847, Jun. 2005.

[16] P. Wheeler, J. Clare, D. Lampard, S. Pickering, K. Bradley, and L. Empringham, "An integrated 30 kW matrix converter based induction motor drive," in *Proc. IEEE Power Electron. Spec. Conf.*, 2005, pp. 2390–2395.

[17] V. Kumar**,** R. R. Joshi, and R. C. Bansal, "Optimal Control of Matrix Converter Based WECS for Performance Enhancement and Efficiency Optimization" *IEEE Trans. Energy Conversion*, vol. 24, No. 1, March 2009, pp. 264-273.

[18] S. M. Barakati, M. Kazerani and J. D. Aplevich, "Maximum Power Tracking Control for a Wind Turbine System Including a Matrix Converter", *IEEE Trans. Energy Conversion*, vol. 24, No. 3, Sept. 2009, pp. 705-713.

[19] X.Liu, P. C. Loh, P. Wang, F.Blaabjerg, Y. Tang, and E. A. Al-Ammar, "Distributed generation using indirect matrix converter in reverse power mode", IEEE Trans. on Power Electron., vol.28,no.3,pp.1072–1082, Mar. 2013.

[20] Vinod Kumar, R. R. Joshi, and R. C. Bansal, "Experimental evaluation of matrix converter for wind energy conversion system under various abnormal conditions," *Int. Journal of Renewable Energy Research*, vol. 4, no. 1, pp. 15-22, 2014.