Electric Power Systems Research 155 (2018) 144–152

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Proposed control policy for high power transfer capability DFIG

Nadia A. Elsonbaty, Mohamed A. Enany*, Ahmed M. Diab

Electrical Power & Machines Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt

ARTICLE INFO

Article history:
Received 1 May 2017
Received in revised form
18 September 2017
Accepted 12 October 2017
Available online 23 October 2017

Keywords:
Doubly-fed induction generator
Unity rotor power factor
Maximum power point tracking
High power transfer capability

ABSTRACT

This paper aims to extract maximum power from wind turbine at all permissible wind speed range while minimizing the total copper loss of the doubly fed induction generator (DFIG) simultaneously. A proposed steady state model is presented whereby unity rotor power factor (URPF) of the DFIG and wind-turbine MPPT variables are the state variables. The URPF proposed variable is the load angle (α) by which the generator performance characteristics can be controlled over the whole operating speed range. Comparison of URPF with conventional operation is given. This comparison illustrate and evaluate the generator performance characteristics at URPF operation up two twice synchronous speed. An analytical approach has been implemented to predict the optimal load angle and the speed dependent rotor voltage magnitude that insure MPPT at URPF. This speed dependent rotor voltage magnitude may be burnt into the EPROM of the digital reference generator provided by a rotor side converter in DSP system. Experimental results are given to strongly validate the proposed technique. Results have shown the DFIG as high power transfer capability (HPTC) transducer.

1. Introduction

Control strategies, for the doubly fed induction generator (DFIG) excited via a back-to-back converter which (rotor side converter (RSC) and grid side converter (GSC)) are in a great progress. Several designs and arrangements have been investigated by using predictive functional, internal mode controllers and adaptive control schemes for active and reactive power control. One of the most important issues related to wind energy conversion is the maximum wind power extraction at minimum losses. Basically the GSC is controlled for maintaining constant dc-link voltage and to regulate exchange of reactive power between grid and GSC. RSC is controlled for achieving MPPT and unity power factor operation at the stator terminals (USPF).

DFIG uses Rotor Position Computation Algorithm (RPCA) for the sensor-less control through rotor position estimation is presented by Ref. [1], where RSC control algorithm has been implemented for sensor-less and MPPT, while the control algorithm of GSC has been modified for feeding regulated power to the grid. A new Phase Locked Loop PLL based slip speed estimator using three phase rotor current is proposed for speed sensor-less vector control operation of RSC. It ensures decoupled control of stator active and reactive power while maximizing the power generation at stator unity power factor under varying wind speed [2,3]. Predictive current control for MPPT could easily be extended to minimize the stator and rotor reactive power with unity power factor operation as stated in Ref. [4]. Neural network and fuzzy logic controller have been introduced. In order to have an active power reference, reference power reactive is maintained zero (i.e. maintain a unity stator side) [5].

The stator unity power factor is compared to leading and lagging stator power factors. It has been shown, that stator unity power factor operation requires a higher power rating of RSC than lagging stator power factor but a lower RSC power rating for leading stator power factor [6].

The DFIG has been operated under five different operating modes, the maximum stator reactive power Q_s absorption mode, the rotor unity power factor mode URPF, the minimum DFIG loss mode, the stator unity power factor mode USPF, and the maximum Q_s generation mode [7]. The authors have specifically concluded that, with USPF mode, both Q_s and Q_r are higher than that at URPF mode, and so the rotor current. As given in Ref. [7], when it is desirable to deliver more reactive power to the grid under low voltage fault condition, the DFIG may be switched from maximum power tracking mode to de-rated output power mode such that direct axis rotor current I_{dr} and Q_s can be increased. However, the entire operating speed range obtained using the above used technique was limited by $-0.05 \leq S \leq 0.35$, Thus, the most variable speed generating mode lies at sub synchronous region. Ref. [8], has declared that constraining the stator power factor results in a small increase in

* Corresponding author.
E-mail addresses: m_enany79@yahoo.com, menany@zu.edu.eg (M.A. Enany).

https://doi.org/10.1016/j.epsr.2017.10.012

Nomenclature

R_s, R_r Stator and rotor resistances
X_s, X_r, X_m Stator, rotor and magnetizing reactances
P, S Pole pairs number and operating slip
V_s, V_r Stator and rotor voltages
I_s, I_r Stator and rotor voltages
Q_s, Q_r Stator and rotor reactive power
P_s, P_r Stator and rotor active power
P_{cus}, P_{cur} Stator and rotor copper losses
P_d, P_{do} Total and optimum developed power
P_{ind1}, P_{ind2} First and second induction power components
P_{syn} Synchronous power component
α, ω_s Rotor voltage angle and synchronous speed
P_m, P_{mopt} Operating and optimum wind turbine power
λ, λ_{opt} Operating and optimum tip speed ratio
ω_g, ω_t Generator and wind turbine mechanical speed
ω_{go}, ω_{to} Optimum generator and wind turbine speed
$\omega_{go_{\min}}$, $\omega_{go_{\max}}$ Min. and max. optimum generator speed
$\omega_{to_{\min}}$, $\omega_{to_{\max}}$ Min. and max. optimum wind turbine speed
$C_{P\max}$, R Maximum power coefficient and blade radius
K_{go}, K_{to} Optimum generator and turbine constant
A, V Wind swept area and wind speed
$V_{cut\,in}$, V_{rated} Cut in and rated wind speed
GR_o, ρ Optimum gear ratio and air density

the rotor supply voltage but a more significant increase in the rotor current. This additional current has to be provided by the rotor converter and is needed to inject reactive power into the rotor to ensure unity stator power factor. Simulated results were undertaken over a speed range from approximately 10% below synchronous speed to 40% below.

The magnitude and frequency control (MFC) method presented in Ref. [9] only controls the magnitude and frequency of the rotor voltage. In Ref. [10], the q-axis rotor current command I_{qr} was set to achieve maximum torque and real power and the d-axis rotor current command I_{dr} was set to be zero. To evaluate the maximum output power of a DFIG, Ref. [11] presented detailed expressions for stator power, rotor power, stator loss, rotor loss, and electrical power as functions of the generator speed and the magnitude and phase angle of the rotor excitation voltage. The effect of stator resistance on the magnitude and phase angle of the resultant optimal rotor excitation voltage, which gives maximum output power and minimum loss, is examined. The optimal rotor reactive current value was derived for minimal copper losses in Refs. [12–16]. These methods only consider copper loss minimization, but the reactive power from the stator is not zero, so the required power factor at the generator terminals is regulated by the GSC, which will cause loss on the converter. An optimal reactive power control strategy to minimize the loss of the whole DFIG based wind system when providing reactive power to the grid [17]. Zhou et al. [18] have concluded that although the compensation from the GSC significantly increases the power loss of the GSC itself, it will still have lower total loss dissipation of the whole DFIG system, as the compensation approach by the RSC will impose the DFIG loss as well as the RSC loss.

So the energy capture efficiency from wind can be improved by maximizing the extracted mechanical power from the wind turbine using MPPT control algorithm [19], and minimizing the copper losses of DFIG using rotor current control algorithm [20].

The main objective of this paper is to present a predictive systematic approach to the determination of optimal rotor excitation voltages for maximizing the extracted wind energy at extended stable operating range while obtaining an almost maximum efficiency at possible reduced cost. MPPT algorithm is based on URPF in which the rotor neither absorbs nor delivers reactive power. Furthermore, the proposed scheme meets various desirable requirements of a high power transfer capability, no requirement of flux estimation, no necessity of low frequency signal integration. Moreover, it can be successfully applied to small wind turbine generators as the stator resistance is included unlike previous works.

In this paper, the work is divided to two main goals each of which is done separately and after that they integrated together in a novel controller. The first goal was to minimize the copper losses through URPF operation and the second one was maximize the DFIG output power.

The authors present a novel approach for DFIG with HPTC using novel controller to compute the optimum load angle. Optimum load angle is quickly identified via an analytical approach for a new operating point as a function of the speed and stator voltage.

2. Steady state Model of DFIG

From the per phase T-model equivalent circuit for three phase induction machine, the steady state performance analysis of DFIG has been presented as given in Ref. [21], where stator and rotor voltage were derived as:

$$\begin{bmatrix} V_s\llcorner 0 \\ V_r\llcorner\alpha \end{bmatrix} = \begin{bmatrix} R_s + jX_s & jX_m \\ jX_m & R_r + jsX_r \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} \tag{1}$$

So the stator and rotor current can be derived as follows:

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \frac{1}{(R_r + jsX_r)(R_s + jX_s) - {X_m}^2} \begin{bmatrix} R_r + jsX_r & -jX_m \\ -jX_m & R_s + jX_s \end{bmatrix} \begin{bmatrix} V_s\llcorner 0 \\ V_r\llcorner\alpha \end{bmatrix} \tag{2}$$

The stator and rotor current can be rearranged as follows:

$$I_s = \frac{A + JB}{C + JD} = \frac{[(R_r + jsX_r)\,V_s\llcorner 0 - jX_m\,(V_r\llcorner\alpha)]}{\left\{\left[(R_rR_s) - S\left(X_sX_r - {X_m}^2\right)\right] + j\left[(sR_sX_r + R_rX_s)\right]\right\}} \tag{3}$$

$$I_r = \frac{E + JG}{C + JD} = \frac{[(R_s + jX_s)\,(V_r\llcorner\alpha) - jsX_m\,(V_s\llcorner 0)]}{\left\{\left[(R_rR_s) - s\left(X_sX_r - {X_m}^2\right)\right] + j\left[(sR_sX_r + R_rX_s)\right]\right\}} \tag{4}$$

Where;

$$A = R_rV_s + X_mV_r sin\,(\alpha) \tag{5}$$

$$B = SX_rV_s - X_mV_r cos\,(\alpha) \tag{6}$$

$$C = \left[(R_rR_s) - S\left(X_sX_r - X_m^2\right)\right] \tag{7}$$

$$D = SR_sX_r + R_rX_s \tag{8}$$

$$E = R_sV_r cos\,(\alpha) - X_sV_r sin\,(\alpha) \tag{9}$$

$$G = R_sV_r sin\,(\alpha) + X_sV_r cos\,(\alpha) - SX_mV_s \tag{10}$$

Then the stator and rotor active power (P_s, P_r) can thus be derived as follow [22];

$$P_s = \Re\,(V_s\llcorner 0.I_s{}^*) = 3V_s\frac{AC + BD}{C^2 + D^2} \tag{11}$$

$$P_r = R\,(V_r\llcorner\alpha.I_r{}^*) = 3V_r\frac{(EC + GD)\cos\ \alpha + (CG - ED)\sin\ \alpha}{C^2 + D^2} \tag{12}$$

There are the four possible combinations. The flow of stator power and developed power state that the machine operate in Generator or Motor mode, while the value of speed state the flow of rotor power in generator mode or the flow of rotor power state the value of speed in motor mode.

So the total developed power P_d can be calculated as follow;

$$P_d = P_s + P_r - (P_{cus} + P_{cur})$$

$$P_d = \frac{3P\,(1 - s)X_m^2}{C^2 + D^2}\left\{SR_rV_s^2 - R_sV_r^2 + \frac{-V_sV_r}{X_m}\,(C\sin\ \alpha - D\cos\ \alpha)\right\} \tag{13}$$

$$P_d = P_{ind1} + P_{ind2} + P_{syn}$$