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Optimal Efficiency Control of Induction Generators in Wind Energy Conversion Systems using Support Vector Regression

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ABSTRACT

In this paper, a novel loss minimization of an induction generator in wind energy generation systems is presented. The proposed algorithm is based on the flux level reduction, for which the generator d-axis current reference is estimated using support vector regression (SVR). Wind speed is employed as an input of the SVR and the samples of the generator d-axis current reference are used as output to train the SVR algorithm off-line. Data samples for wind speed and d-axis current are collected for the training process, which plots a relation of input and output. The predicted off-line function and the instantaneous wind speed are then used to determine the d-axis current reference. It is shown that the effect of loss minimization is more significant at low wind speed and the loss reduction is about to 40% at 4[m/s] wind speed. The validity of the proposed scheme has been verified by experimental results.

Keywords: Optimal efficiency, Induction generator, Wind power generation, SVR

1. Introduction

Wind power has proven to be a potential clean and renewable source for generation of electricity with minimal environmental impact. In recent years, there has been a widespread growth in the exploitation of wind energy, which required the development of larger and more robust wind systems [1]. It is preferable to run the wind energy generation system (WEGS) at a variable generator speed to maximize the captured wind power. Compared with constant speed operation, a variable speed operation of wind turbines can provide 10~15[%] higher output power, lower mechanical stress, and less power fluctuation [2].

Nowadays, the use of squirrel-cage induction generators for direct grid-connection of WEGS has been well established, due to the low cost in comparison with other types of electric machines. By using back-to-back PWM converters between the grid and generator and employing the vector control technique, the generator power and flux can be controlled, and therefore, optimizing a utilization of the machine [3]. The grid side converter is controlled in order to keep the DC-link voltage constant and unity power factor.

Recently, attention has been focused on improving induction machine efficiency and transient performance [4]. A machine is normally operated at the rated flux, in order

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to give the best transient response. However, at light loads, the rated flux operation gives excessive core loss, thus impairing machine efficiency. Since WEGSs operate at light load most of the time, optimum efficiency can be obtained by reducing the generator flux [5]. This is due to the fact that the electromagnetic losses in a machine are a direct function of the magnetic flux and by a proper adjustment of the flux, an appropriate balance between iron and copper losses can be achieved.

Several loss-minimization control schemes for induction machines using reduced flux level have been reported. The techniques for efficiency improvement can be classified into two categories. The first one is the so-called model-based approach [6], [7], which uses the machine model to compute the optimum flux level. The second one is the search-based approach, also known as online efficiency optimization control [5], [8], in which the flux is adjusted until the input power settles down to the minimum in the motor drive or the output power to the maximum in the generator for a given torque and speed.

In order to achieve the maximum power point tracking (MPPT) control, two typical methods have been studied [9], which are an optimal tip-speed ratio control (TSR) and a search-based or perturbation-based strategy including fuzzy-logic based control [1], [5], [10]. The optimal TSR method is used widely in practical wind turbine control. In this paper, the TSR control method is applied to extract the maximum power point.

In this paper a novel SVR-based scheme is proposed to minimize the loss of a vector controlled induction generator for a wind energy generation system. In this method, a continuous function that plots the fundamental relation between a given wind speed and its corresponding d-axis current reference based on the training data. This function then can be used to predict output for given input that is not included in the training set. This is similar to a neural network; however, the solution is based on empirical risk minimization. In contrast, SVR introduces structural risk minimization into the regression and thereby achieves a global optimization while a neural network can achieve only a local minimum [12]. The SVR algorithm is implemented to estimate the d-axis current reference to minimize generator loss. Experimental results are presented to validate the proposed induction generator control algorithm.

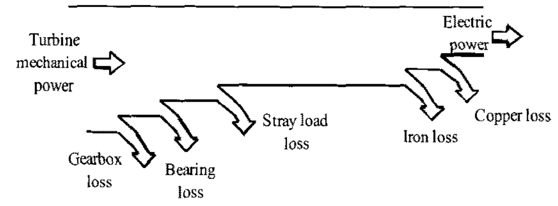

Fig. 1 Power flow in the wind power generation system

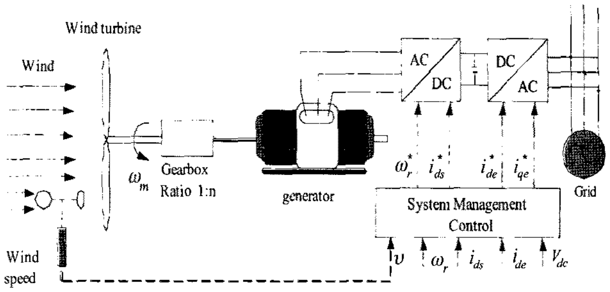

Fig. 2 Back-to-back PWM converter system for grid connection

2. Losses in Wind Energy Generation System

A general power flow diagram for a WEGS is shown in Fig. 1. The power losses consist of two major components; the mechanical losses and the electrical losses. The mechanical losses are the gearbox losses and the friction of the rotational part. For rated load conditions, the total gearbox losses are about 2.7%. The losses due to friction are about 1% for same conditions [13]. For light load conditions, the mechanical losses increase and system efficiency is deteriorated. Mechanical losses are difficult to estimate and to reduce.

The generator losses consist of copper loss and iron loss, which are dependent on the current and flux level. In light load conditions, the iron loss can be decreased by reducing the flux level.

The power converter losses are dependent on the current and switching frequency, which is a lower portion of the total loss and is difficult to control.

3. Wind Energy Generation System and Control

A wind energy generation system for a cage-type induction generator connected with back-to-back PWM converters to the utility gird is discussed in this paper and

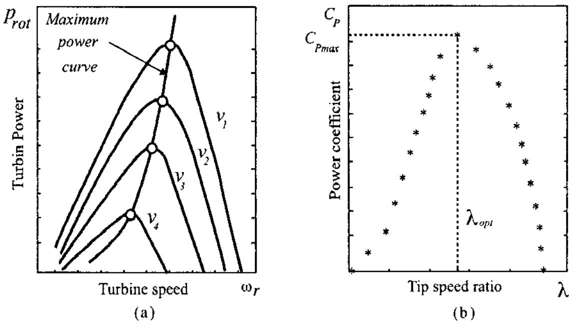

Fig. 3 Characteristic curves of wind blade
(a) Output power versus rotational speed
(b) Power conversion coefficient versus tip-speed

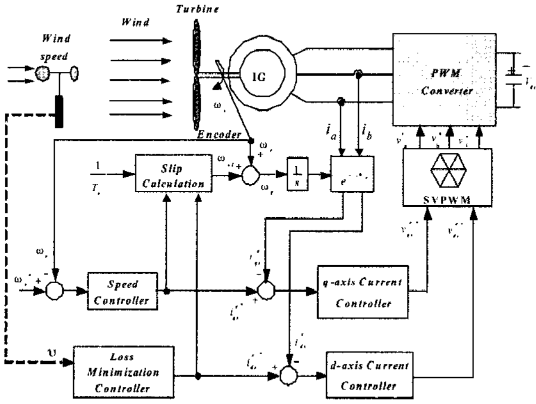

Fig. 4 Control block diagram of induction generator

it is shown in Fig. 2. The power captured by the wind turbine may be written as [16],

$$P_t = \frac{1}{2}\rho\pi R^2\upsilon^3 C_p(\lambda) \tag{1}$$

and the tip-speed ratio is defined as

$$\lambda = \frac{\omega_t R}{\upsilon} \tag{2}$$

where, ρ is the specific density of air, υ is the wind speed, R is the radius of the turbine blade, ω_t is the turbine speed, and C_p is the coefficient of power conversion.

Fig. 3(a) shows that the power captured in the turbine blade is a function of the rotational speed and is at a maximum for the particular rotational speed. Fig. 3(b) shows that the value of C_p is a function of λ and it is at a maximum at λ_{opt} . Hence, to fully utilize the wind energy, λ should be maintained at λ_{opt} , which is determined by the blade design. Then, from (1),

$$P_{\max} = 0.5\rho\pi R^2 C_{p\max}\upsilon^3 \tag{3}$$

For maximum output power, the speed of the turbine should be controlled at maximum C_p, which corresponds to the optimal tip-speed ratio. From (2), so, the turbine speed reference is given by

$$\omega_t^* = \frac{\lambda_{opt}}{R}\upsilon$$

Fig. 4 shows the control block diagram of the induction generator. There is a speed controller, a loss minimization controller, and d-q axis current controllers in the synchronous reference frame. The loss minimization control block produces the generator d-axis current reference. At light loads, the d-axis current reference is adjusted to the value which minimizes the generator total loss using SVR, which will be described in the next section. To maintain the DC-link voltage constant and to ensure the reactive power flowing into the grid at null, the grid-side converter currents are controlled using the d-q vector control approach. The DC-link voltage is controlled to the desired value by using a PI controller and the change in the DC-link voltage represents a change in the q-axis current. For unity power factor, the demand for the d-axis current is zero [19].

4. Support Vector Machines for Regression

A regression method is an algorithm that estimates an unknown mapping between a system's inputs and outputs, from the available data or training data. Once such a relation has been accurately estimated, it can be used for prediction of system outputs from the input values. The goal of regression is to select a function which approximates best the system's response [17].

The generic SVR estimating function takes the form [18]

$$f(x) = (w\cdot\Phi(x)) + b \tag{5}$$

where w is a weighting matrix, b is a bias term, Φ denotes a nonlinear transformation from n-dimensional space to a higher dimensional feature space, and the dot represents the inner vector product. The goal is to find the value of w and b such that values of x can be determined by minimizing the regression risk as

$$R_{reg}(f) = \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{n}\Gamma(f(x_i) - y_i) \tag{6}$$

subject to

$$\begin{aligned} & y_i - w.\Phi(x_i) - b \le \varepsilon + \xi_i^* \\ & w.\Phi(x_i) + b - y_i \le \varepsilon + \xi_i \\ & i = 1,2,\ldots\ldots\ldots\ldots n \quad \xi_i, \xi_i^* \ge 0 \end{aligned} \tag{7}$$

where $\Gamma(\cdot)$ is a cost function, ε is the permissible error and C is a constant determining the trade-off between minimizing training errors and minimizing the model complexity term $\|w\|^2$. If C becomes infinitely large, the SVR will not allow the occurrence of any errors and results in a complex model, whereas when C goes to zero, the result would tolerate a large amount of errors and the model would be less complex. Everything above ε is captured in slack variables ξ_i, ξ_i^*, which are introduced to accommodate errors in the input training set.

The optimization problem in (7) can be transformed into the dual problem, and its solution is given by

$$f(x) = (\sum_{i=1}^{n}(\alpha_i - \alpha_i^*).(\phi(x_i)\phi(x)) + b \tag{8}$$

subject to $0 \le \alpha_i \le C, 0 \le \alpha_i^* \le C$

In (8) the dot product can be replaced with the kernel function $k(x_i,x)$. Kernel functions enable dot product to be performed in high-dimensional feature space using low dimensional space data input without knowing the transformation Φ as shown in Fig. 5. Using a kernel function, the required decision function will be:

$$f(x) = \sum_{i=1}^{n}(\alpha_i - \alpha_i^*).K(x_i, x) + b \tag{9}$$

In this paper, the used kernel function is radial base function (RBF)

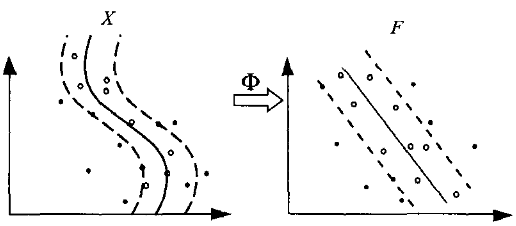

Fig. 5 A feature map from input to higher dimensional feature space

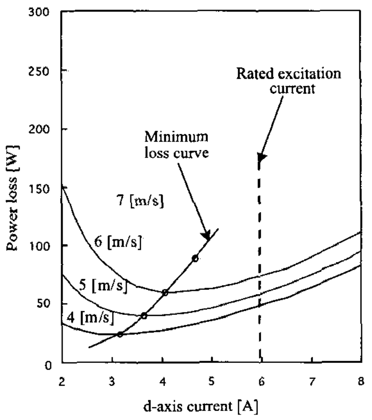

Fig. 6 D-axis current locus for minimum power loss

$$K(x_i, x) = \exp\{-\frac{|x_i - x|^2}{\sigma^2}\} \tag{10}$$

5. Loss Minimization Based on SVR

The power loss characteristics at different wind speed levels for an induction generator is shown in Fig. 6. For each speed, there is only one d-axis current value which gives a minimum power loss. Since most of the time the wind speed is lower than the rated value and the wind turbines operate at low speed and light load, the generator d-axis current can be reduced from the rated value to reduce the core loss and thereby system efficiency is increased.

Figure 7 shows the flowchart of the proposed method, which is described as

① An adequate set of training data (x_i,y_i), ε, C and a kernel function should be first specified.

② Compute kernel function for the training data $k(x_i,y_i)$.

③ Training of SVR involves the off-line adjustment of Lagrange multipliers and bias α_i and b.

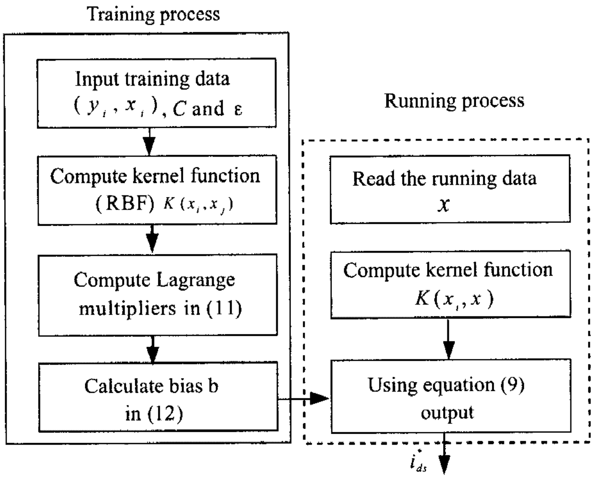

Fig. 7 Flowchart of loss minimization using SVR

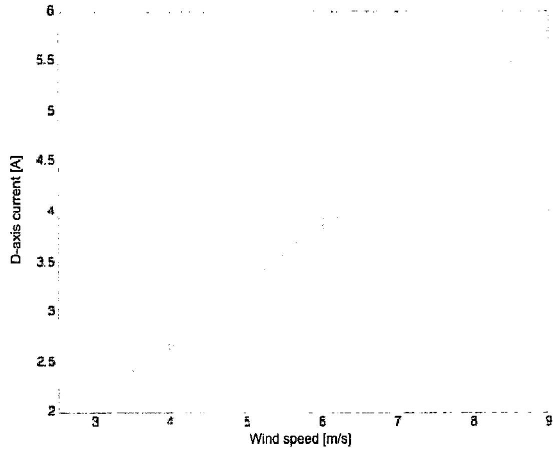

Fig. 8 Optimum d-axis current versus wind speed from training

$$W(\alpha_i,\alpha_i^*) = \frac{1}{2}\sum_{i,j=1}^{n}(\alpha_i-\alpha_i^*)(\alpha_j-\alpha_j^*)K(x_i,x_j) \tag{11}$$

$$-\sum_{i=1}^{n} y_i(\alpha_i-\alpha_i^*) + \frac{1}{2C}\sum_{i=1}^{n}(\alpha_i^2-\alpha_i^{*2})$$

subject to

$$\sum_{i=1}^{n}(\alpha_i-\alpha_i^*) = 0,\ \alpha_i,\alpha_i^* \in [0,C]$$

$$b = mean\left(\sum_{i=1}^{n}\left\{y_i-(\alpha_i-\alpha_i^*)K(x_i,x_j)\right\}\right) \tag{12}$$

All parameters in (9) are already off-line computed using (11) and (12).

④ Equation (9) is used online for any input wind speed x to compute the output d-axis current reference.

Only the non-zero values of the Lagrange multipliers α_i - α_i^* are useful in forecasting the regression line, which are known as support vectors. Parameters C and ε are usually selected by users based on a prior knowledge and/or user expertise. An RBF kernel function with parameter C = 5000 and ε = 0.01 and quadratic loss function are used.

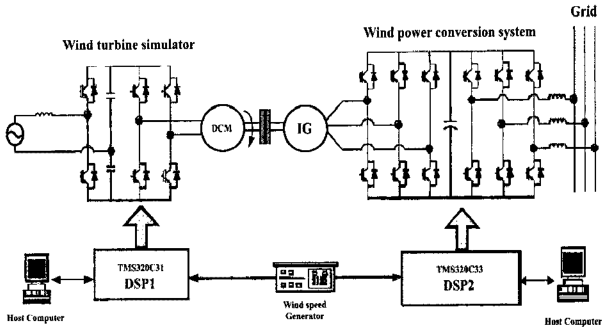

Fig. 9 Experimental setup

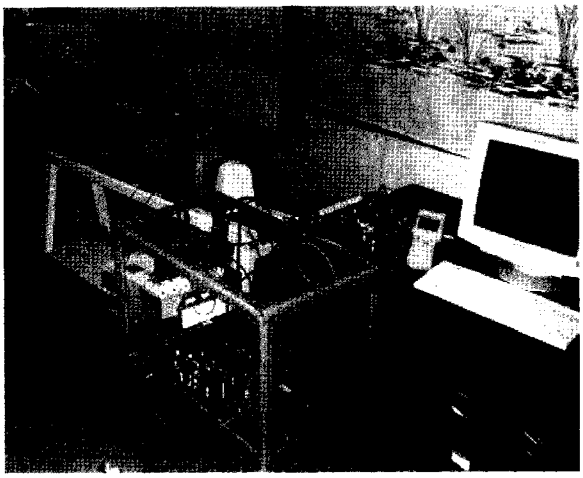

Fig. 10 Laboratory setup

Figure 8 shows the SVR training results for the reduced d-axis current estimation. In Fig. 8, the solid lines represent the learned function and the cross points are the training data points that do not support vectors. The circle points are the training data points that support vectors.

6. Experimental Results

The experimental setup has been built on a reduced-scale in the laboratory, of which configuration is shown in Figs. 9 and 10. A torque-controlled DC motor drive is used to emulate the characteristics of the wind turbine. The DC motor control is performed using a

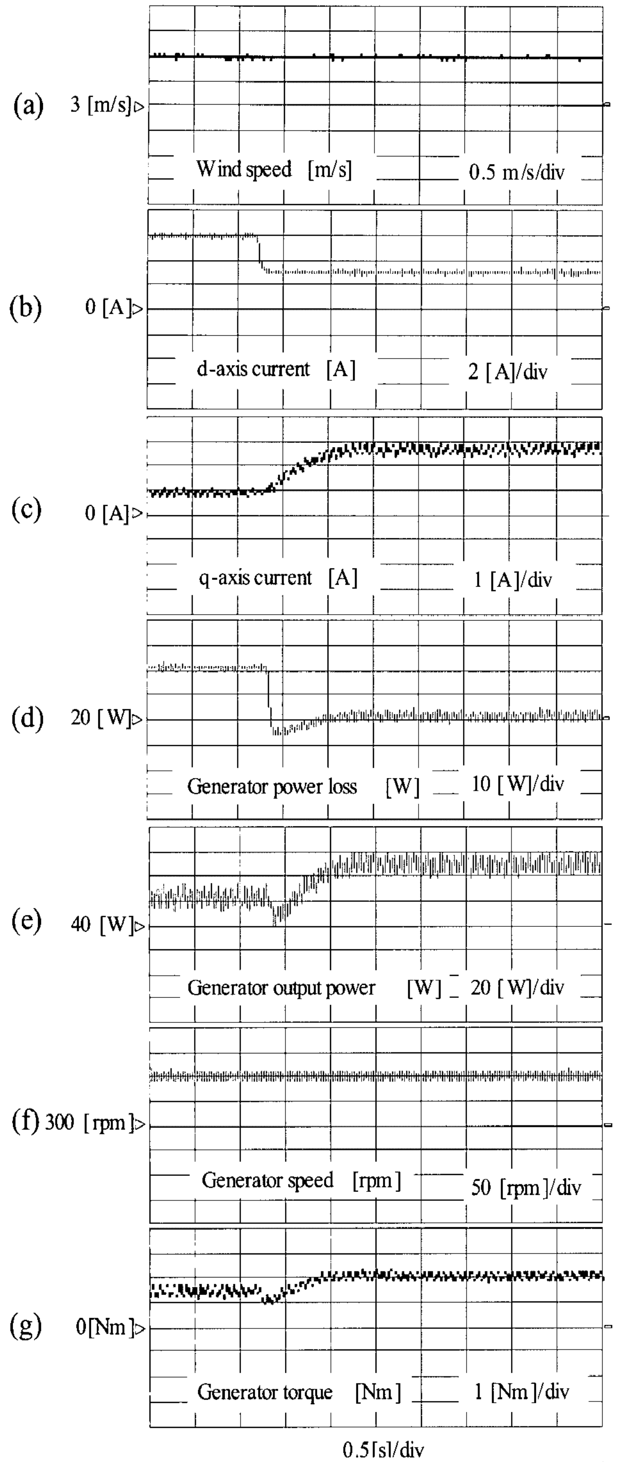

Fig. 11 Generator characteristics with loss minimization at 4[m/s]

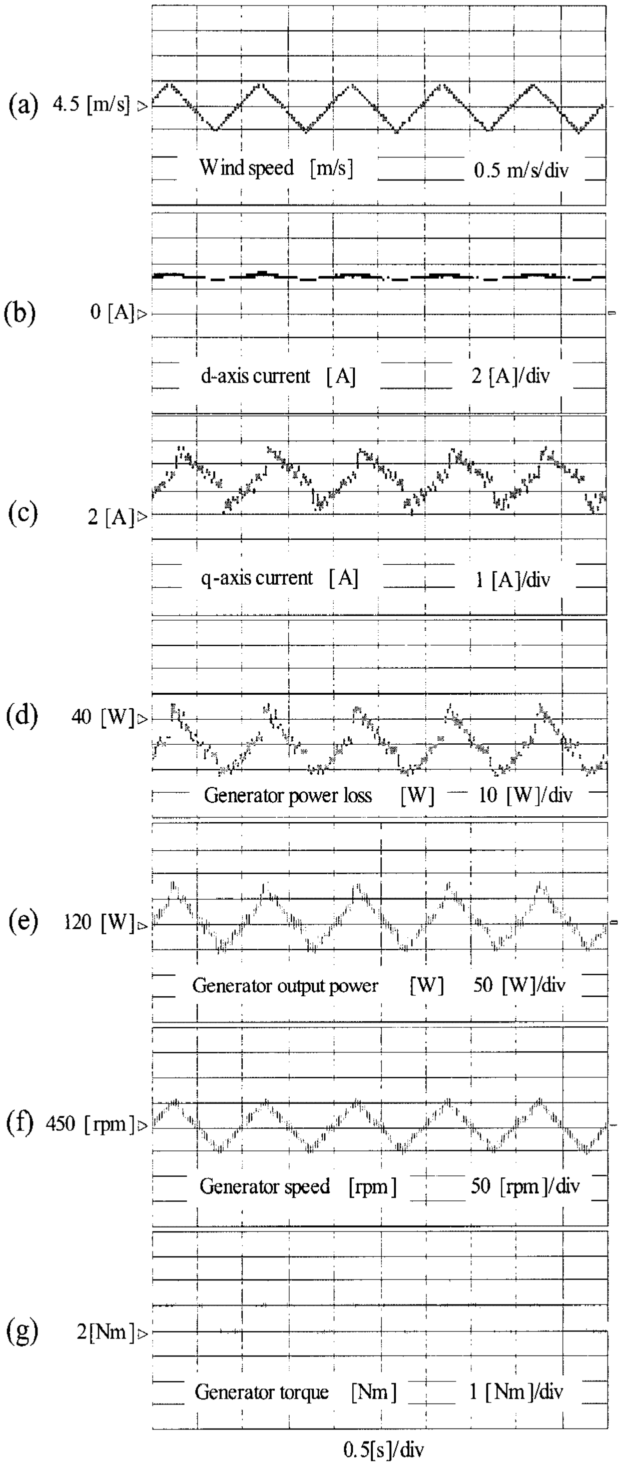

Fig. 12 Generator characteristics with loss minimization

TMS320C31 DSP. The output signal of the function generator is used as a wind speed simulator, which is read into the DSP through the D/A converters. A 3[kW] squirrel-cage induction generator is mechanically coupled to the DC motor without a gear box.

The generator output terminals are connected to the utility grid through back-to-back converters and a transformer. The converter control is performed using a TMS320C33 DSP. The ratings and parameters of the system are listed in the Appendix. The generator controller is based on a conventional field-oriented controller, whereby the d-axis current is maintained constant and equal to the rated value during the starting process. Then the d-axis current is determined to optimize the generator efficiency based on SVR theory. The q-axis current is regulated in order to extract the maximum power point.

Figure 11 shows the generator performance at 4m/s wind speed. The induction generator is started with the rated flux current, and then the loss minimization algorithm is activated to calculate the reference flux current and remain active to ensure optimum efficiency operation in case of speed or torque changes. In this figure, the d-axis current achieves its steady state reduced value, about 3.1[A], quickly to achieve minimum power loss. To maintain the constant torque and constant speed, instead, the q-axis current is increased as shown in Fig. 11(c). Power loss is decreased from 42[W] to 22[W], which means a power savings of about 45% is obtained, as shown in Fig. 11(d). At the same time the generator output power increases due to loss reduction. Since the generator speed is constant and the generator output power increases with flux reduction, the generator torque increases proportionally to the generator output power as shown in Fig. 11(g).

Although this is a well known basic principle, it confirms the proposed control algorithm is effective in reducing induction generator operating loss. Even though the q-axis current increases when the d-axis current decreases, which leads to an increase in copper losses, the optimization between the copper loss and iron loss leads to a minimization of total losses.

Figure 12 shows the induction generator control performance in the case of triangular wind speed variation between 4[m/s] and 5[m/s]. Figure 12(b) shows that the d-axis current decreased widely from the rated value and the power loss, as shown in Fig. 12(d), reduced widely compared with rated current value. It is also seen that, the generator output power and torque levels are increased due to the continuous production of optimum flux current.

Figure 13 shows the reduction of the generator power loss in low and medium speed ranges due to the d-axis current optimization for loss minimization. At high wind speed, the increment of the output power is negligible since the d-axis current increases up to the rated value for high torque so that there is no reduction of iron loss. It can be seen that improvement of generator efficiency is not possible using the flux current control at high wind speed.

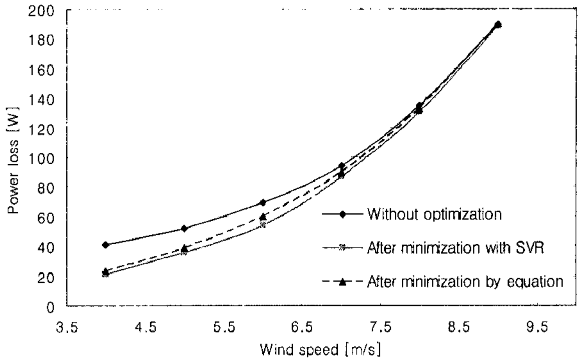

Fig. 13 Generator power loss at rated and reduced d-axis current

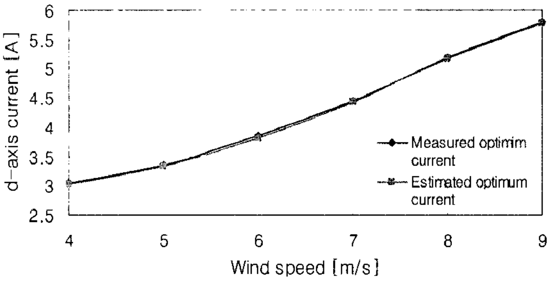

Fig. 14 Measured and estimated optimum flux currents

Figure 14 shows the accuracy of the proposed algorithm to estimate the optimum flux current with respect to the measured current. It is obvious that the SVR algorithm estimates the optimum flux current value which is almost equal to the measured optimum one.

7. Conclusions

In this paper, a loss minimization control scheme of induction generators for wind energy generation systems was proposed. The generator speed and d-axis current were regulated to extract the maximum wind power and to minimize the generator total losses, respectively. The generator reference speed was adjusted based on the optimum tip-speed ratio. A new support vector regression algorithm to estimate the optimum value for the generator d-axis, based on the training data, was presented. Wind speed was employed as the input of the SVR and the generator d-axis current reference samples were used as a target to train the SVR off-line. A fundamental interrelation between wind speed and generator d-axis current reference was predicted from the off-line training process. The predicted function and the instantaneous wind speed were then used on-line to determine the unknown d-axis current reference. The proposed algorithm proved validity in reducing generator loss up to 40%. The SVR algorithm featured excellent accuracy and robustness compared with the model based or search based controller. This method was based on the generator characteristics and independent of the generator parameters or turbine constants, it resulted in a fast estimation for optimum flux level. It is obvious that the SVR algorithm can be used for both induction motors and generators. It is important to mention that the SV regression model deserves to be used in control applications or for short-term prediction, where it can advantageously replace traditional techniques.

Table 1 Parameters of Induction Machine

Parameters	Value
Stator resistance	0.93 [Ω]
Rotor resistance	0.533 [Ω]
Iron loss resistance	190 [Ω]
Stator leakage inductance	0.003[H]
Rotor leakage inductance	0.003[H]
Mutual inductance	0.076[H]
Moment of inertia	0.0071 kgm^2

Table 2 Parameters of Turbine Blade Model

Parameters	Value
Blade radius	0.95 [m]
Max. power conv. coeff.	0.45
Optimal tip-speed ratio	5
Cut-in speed	3 [m/s]
Rated wind speed	12 [m/s]

Appendix

The specifications of the induction machine used for testing has three-phases, four poles, 230[V], 50[Hz], 3[kW], and 143 5[rpm], of which parameters are listed in Table 1. The parameters of the wind turbine used are shown in Table 2.

Acknowledgment

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References

[1] M.G. Simoes, B.K. Bose, R.J. Spiegel, “Fuzzy logic based intelligent control of a variable speed cage machine wind generation system”, *IEEE Trans. on Power Electron.*, Vol. 12. No. 1, pp. 87- 95, Jan. 1997.

[2] Q. Wang, L. Chang, ”An intelligent maximum power extraction algorithm for inverter-based variable speed wind turbine systems”, *IEEE Trans. on Power Electron.*, Vol. 19, No. 5, pp. 1242–1249, Sept. 2004.

[3] F. F. M. El-Sousy, M. Orabi, H. Godah, “Maximum power point tracking control scheme for grid connected variable speed wind driven self-excited induction generator”, *Journal of Power Electron.*, Vol. 6, No. 1, pp. 45–51, Jan. 2006.

[4] K. Matsuse, T. Yoshizumi, S. Katsuta, S. Taniguchi, “High-response flux control of direct-field-oriented induction motor with high efficiency taking core loss into account”, *IEEE Trans. on Ind. Appl.*, Vol. 35, No. 1, pp. 62–69, Jan./Feb. 1999.

[5] M.G. Simoes, B.K. Bose, R.J. Spiegel, “Design and performance evaluation of fuzzy-logic-based variable -speed wind generation system”, *IEEE Trans .on Ind. Appl.*, Vol. 33, No. 4, pp. 956– 964, 1997.

[6] R. Leidhold, G. Garcia, M. I. Valla, “Field-oriented controlled induction generator with loss minimization”, *IEEE Trans. on Ind. Electron.*, Vol. 49, No. 1, pp. 147–156, 2002.

[7] S.-M. Yang, F-C Lin, “Loss-minimization control of vector-controlled induction motor drives”, *IEEE PEDS Conf. proc.*, Vol. 1, pp. 182-187, Oct. 2001.

[8] G. C Sousa, B. K. Bose, J. G. Cleland, “Fuzzy logic based on-line efficiency optimization control of an indirect vector-controlled induction motor drive”, *IEEE Trans. on Ind. Electron.*, Vol. 42, No. 2, pp. 192–198, Apr. 1995.

[9] I. K. Buehring, L. L. Freris, “Control policies for wind energy conversion systems”, *IEE Proceeding*, Vol. 128, No. 5, pp. 253–261, Sept. 1981.

[10] R. Hilloowala, A. M. Sharaf, “A rule-based fuzzy logic controller for a PWM inverter in a stand alone wind energy conversion scheme”, *IEEE Trans. Ind. App.*, Vol. 32, No. 1, pp. 57–65, Jan. 1996.

[11] R. Datta, V. R. Ranganathan, “A method of tracking the peak power points for a variable speed wind energy conversion system”, *IEEE Trans. Energy Conv.*, Vol. 18, No. 1, pp. 163–168, March 2003.

[12] K.-R Nuller, A. J. Smola, G. Ratsch, B. Scholkopf, J. Kohlmorgen, V. Vapnik, “Predicting time series with support vector machine”, *ICANN’97 Proc.*, pp. 999–1004,

1997.
[13] A. Grauers, "Efficiency of three wind generation systems", *IEEE Trans. Energy Conv.*, Vol. 11, No. 3, pp. 650–657, Sept. 1996.
[14] A. Inoue, A. M. Hasan, R. Takahashi, T. Murata, J. Tamura, M. Kimura, M. Futami, M. Ichinose, Ide Kazumasa, "A calculation method of the total efficiency of wind generator", *IEEE PEDS Proc.*, Vol. 2, pp. 1595–1600, 2005.
[15] F. Abrahamsen, F. Blaabjerg, J. K. Pedersen, P. B. Thoegersen, "Efficiency-optimized control of medium-size induction motor drives", *IEEE Trans. Ind. Appl.*, Vol. 37. No. 6, pp. 1761–1767, Nov.-Dec. 2001.
[16] Z. Lubosny, "Wind turbine operation in electric power systems", Springer-Verlag, 2003.
[17] V. Cherkassky, F. Miller, Learning from data concepts, theory and methods, Wiley, 1998.
[18] K. R. Cho, J. K. Seok, D.-C. Lee, "Mechanical parameter identification of servo systems using robust support vector regression", *IEEE PESC Proc.*, Vol. 5, pp. 3425–3430, June 2004.
[19] A. G. Abo-Khalil, H.-G. Kim, D.-C. Lee, J.-K. Seok, "Maximum output power control of wind generation system considering loss minimization of machines", *IEEE IECON Proc.*, Vol. 2, pp. 1676–1681, Nov. 2004.

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