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| Sensorless Control for DFIG Wind Turbines Based on Support Vector Regression<br>3 h 30 | Điều khiển không dùng cảm biến cho Tua-bin gió DFIG dựa trên Hồi Quy Vector hỗ trợ |
| Abstract — In this paper, a sensorless based doubly-fed induction generator (DFIG) control in wind power generation systems is proposed, which is based on the theory of support vector regression (SVR). The inputs of the SVR wind speed | Tóm tắt-Trong bài báo này, chúng tôi đề xuất phương pháp điều khiển máy phát điện sử dụng máy điện cảm ứng nguồn kép không cảm biến trong các hệ tạo điện từ gió, phương pháp điều khiển này dựa trên hồi quy vector hỗ trợ (SVER). Chúng tôi chọn công suất |

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| estimator are chosen as the wind turbine power and rotational speed. During the offline training, a specified model which relates the inputs to the output is obtained. Then, the wind speed is determined online from the instantaneous inputs. Meanwhile, the DFIG rotor dq-axis currents are controlled to optimize the stator active and reactive power. The stator active power is adjusted in order to extract the maximum power from the wind power. The output reactive power of the wind power conversion system is controlled as zero to keep unity power factor of the stator voltage and current. However, the stator reactive power control is used to optimize the generator efficiency by sharing the reactive power between stator and rotor. The experimental results show the excellent of performance of the power, current and pitch angle controllers in the steady state and transient responses for the different modes and wind speed. The experimental results have verified the validity of the proposed estimation and control algorithms. | tua-bin gió và tốc độ quay làm đầu vào của trình ước lượng tốc độ gió SVR. Trong quá trình đào tạo offline, chúng ta sẽ thu được một mô hình nhất định thiết lập mối quan hệ giữa các đầu vào và đầu ra. Sau đó, tốc độ gió được xác định online từ các đầu vào tức thời. Trong khi đó, các dòng trục dq rotor DFIG được điều khiển để tối ưu hóa công suất tác dụng và công suất phản kháng của stator. Công suất tác dụng của stator được điều chỉnh để lấy được công suất cực đại từ năng lượng gió. Công suất phản kháng đầu ra của hệ thống chuyển đổi năng lượng gió được áp đặt là không để giữ cho hệ số công suất của dòng và điện áp stator unity (~~hòa hợp~~, bằng một). Tuy nhiên, việc điều khiển công suất phản kháng stator được dùng để tối ưu hóa hiệu suất máy phát điện thông qua việc chia sẻ công suất phản kháng giữa stator và rotor. Các kết quả thực nghiệm cho thấy hiệu suất năng lượng, dòng và bộ điều khiển góc nghiêng trong trạng thái ổn định và các đáp ứng quá độ đối với các chế độ và vận tốc gió khác nhau rất tốt. Các kết quả thực nghiệm đã minh chứng giá trị của các thuật toán ước lượng và điều khiển đề xuất. |
| I. INTRODUCTION<br>A doubly-fed induction generator is most commonly used in wind power generation. It is a wound rotor type of induction machines with slip rings attached to the rotor and fed by the power converter. With DFIG, generation can be accomplished in variable speed ranging from sub-synchronous speed to super-synchronous speed. The power converter feeding the rotor winding is usually controlled in a current- | [redacted] |

regulated PWM type, thus the stator current can be adjusted in magnitude and phase angle. The rotor-side converter operates at the slip frequency and the power converter processes only the slip power. Thus if the DFIG is to be varied within ± 30% slip, the rating of the power converter is only about 30% of the rated power of the wind turbine. In this control type of machines the net power out of the machine is a summation of the power coming from the stator and the rotor [1], [2]. In the DFIG, the applied rotor voltage controls the real and reactive powers and generator's speed, when its stator terminals are connected to a power system and the stator voltage is held constant by the grid [3]- [6].

In this paper, the stator power which results in a maximum turbine output-power for a measured wind

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used as the reference value for the DFIG outer control loop. In the inner current control loop, the stator-flux vector position is used to establish a reference frame that allows q-axis components of the rotor current to be controlled. The stator reactive power is controlled to the desired value by controlling the reference d-axis rotor current.

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In the most of wind energy generation systems, anemometers are used to measure the wind speed for the MPPT(maximum power point tracking) control [7]. The anemometer installed on the top of

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nacelle may be a source of inaccurate measurement of the wind speed. In wind farms, several anemometers are often placed at some locations to measure the average wind speed [8]. Using of anemometers raises a problem of calibration and measurement accuracy as well as increases the initial cost of the wind generation systems. For these reasons, it is desirable to replace the mechanical anemometers by the digital wind speed estimator based on the turbine characteristics.

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Recently, the wind speed estimation methods have been reported in the literature, which can be categorized into two approaches. The first method is to use a power equation as a function of power coefficient and tip-speed ratio. Since the polynomial order of power coefficient may be higher than the seventh order for accurate estima-tion, the real-time calculation of the roots of the polynomial is a time-consuming task. The other one is to use a look-up table of power-mapping [2]. However, this method requires a lot of memory space, and the estimation speed and accuracy depend on the size of the look-up table.

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In this paper, a novel wind speed estimation scheme for the MPPT control of wind power systems is proposed, which is based on the SVR theory. The effectiveness of the proposed algorithm and the proposed control scheme have been verified by the experimental results.

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## II. SYSTEM DESCRIPTION

DFIGs allow active and reactive power control through a rotor-side

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converter, while the stator is directly connected to the grid. The active part is due to the stator power and rotor power when ignoring the stator copper and core losses. The stator power can be determined by the wind turbine maximum output power corresponding to a particular wind speed, however the rotor power may be either drawn from the grid to compensate the rotor 3456

Fig. 1 Basic configuration of DFIG wind turbine system.

Fig. 2. Equivalent circuit of DFIG. ing modes.

For subsynchronous mode when rotor angular speed is less than the grid angular frequency, the power flows from the grid to the rotor; otherwise the rotor power is supplied to the grid. Hence the net DFIG generated power is the summation of the stator and rotor power. The reactive power is determined by the machine excitation requirement and the desired grid power factor [9]- [12]. A back-to-back converter provides a bidirectional power- flow control thereby enabling the DFIG to operate in ei¬ther subsynchronous or supersynchronous modes. Confi¬guration of the overall wind generation system is shown in Fig. 1. The stator of DFIG is directly connected to the grid and the rotor is connected through back-to-back PWM converters. The DFIG is controlled in a rotating d-q reference frame, with the d-axis aligned with the stator flux vector. The stator active and reactive powers of DFIG are controlled by regulating the current and voltage of the rotor. Therefore the current and voltage of

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the rotor needs to be decomposed into the components related to stator active and reactive power.

A. DFIG model

Figure 2 shows the d-q equivalent circuit of DFIG. Under stator flux-oriented control, the fluxes, currents and vol¬tages can be expressed as [13]

Fig. 3. Vector diagram for stator flux-oriented control.

where

Lm: Magnetizing inductance;

Ls: Stator self-inductance;

Lr: Rotor self-inductance;

ddqs: Stator d-q axis flux linkage;

ddqr: Rotor d-q axis flux linkage;

iqs, idcf: Stator and rotor d-q axis currents. dd = L i d + L id

The aim of the generator's control is to achieve optimal power tracking of the wind turbine power curves. By set¬ting the stator flux vector aligned with d-axis as shown in Fig. 3, then

The stator flux angle is calculated as follows

By neglecting stator resistance, equation (2) can be used to determine the d-axis stator flux as:

The rotor flux equations are calculated from stator flux and currents

The stator voltage vector is consequently in quadrature advance in comparison with the stator flux vector. Then

Fig. 4. Active and reactive power control for synchronization mode and running mode.

the q-axis voltage is given as

And the stator currents are

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| determined from the flux and voltage equations as: | [redacted] |
| Substituting (17) into (19)<br>Adjustment of the q-axis component of the rotor current controls either the generator developed-torque or the sta¬tor-side active power of the DFIG.<br>3, ■ ■ ^ 3 Lm 2 Ls | [redacted] |
| On the other hand, regulating the rotor d-axis current component controls directly the stator-side reactive power. 3 3 L<br>Qs = 2 (Vqsids - Vdsiqs ) = ~ ■ ■ Vqs (ims - idr ) (22) | [redacted] |
| It is noticeable that the stator active and reactive power components are proportional to the iqr, and idr, respec¬tively. Provided the magnitude of ims is kept constant, | [redacted] |
| both power components can be controlled linearly by ad¬justing the relative rotor current components. The control procedure is explained in details in the following section. By calculating the stator active power as (21), the outer stator power feedback loop provides a reference val¬.*ue, i , to the inner current feedback control loop. The ro-<br>The ro BẢN GỐC THIẾU CHỮ | [redacted] |
| active power is controlled to the desired value to produce the reference d-axis rotor voltage. It can be seen how the outer stator power feedback loop provides a reference value, idr , to the inner current feedback control loop. The rotor d-axis current is then determined and controlled to produce the reference q-axis rotor voltage. The overall control system for both synchronization mode and run¬ning mode is shown in Fig. 4 [14]. | [redacted] |
| To achieve the full control of the, the | [redacted] |

dc-link voltage must be boosted to a level higher than the amplitude of the line-line voltage. The power flow of the grid-side converter is controlled so as to keep the dc-link voltage constant. 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 an IP controller and the change in the dc-link voltage represents a change in the q-axis current. A current feed-forward control loop is also used here to improve the dc-link voltage response to load disturbance. For unity power factor, the demand for the d-axis current is zero.

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## III. SUPPORT VECTOR REGRESSION

A regression method is an algorithm to estimate a re¬lationship between the system input and output from the samples or training data. It is known that the estimation with the SVR is very effective for power system applica-tions [10]. In this section, the principle of the SVR is de¬scribed briefly.

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Let us consider a set of training samples {(y1, x1), (yn, xn)}, where X, and y{ denote the in¬put and output spaces, respectively, and n is the dimen-sion of training data. The idea of the regression problem is to determine a function that can identify unknown pa¬rameters accurately [10], [11].

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The general SVR function for

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estimation takes the form [14]:

f (x) = (w $ (x)) + b (23)

where w is a weighting matrix, b is a bias term, $ denotes a nonlinear transformation from an n-dimensional space to a higher dimensional feature space as shown in Fig. 3, and the dot represents the inner vector product. To calculate w , the following cost function should be mini¬mized [15], [16]:

which is subject to

where £ is the permissible error and y is a pre-specified value that controls the cost incurred by training errors. The slack variables, £ and £, are introduced to accommodate the error on the input training set

The constraints include £ which specifies a permissible estimation error. The value of £ influences the number of support vectors used to obtain the regression function. As £ is lager, the support vectors selected are fewer. With a reasonable choice of y, a trade-off between minimizing training errors and minimizing the model complexity term ||w||2 is accomplished.

The key idea to satisfy these constraints is to determine a Lagrange function from the objective function in (24) and the corresponding constraints in (25) using Lagrange multipliers a and a* associated to each sample as

which is subjected to af ,a*,£ ,£ > 0. Now (24) has to be minimized with regard to the primal variables (w, b, £, and £ ) and maximized with regard to the Lagrange multipliers at and a*. Therefore, by setting the gradient of L with respect to the primal variables to

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If the constraints in (27)-(29) are included in Lagrange function in (26), an optimization problem is then obtained as

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only the training samples whose corresponding Lagrange multipliers are nonzero are involved in the solution, which are called as support vectors.

Several choices for the kernel are possible to reflect special properties of approximating functions [17], [18]:

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© Polynomial kernel function

K (x,, x) = [(x,, x) + 1]q where q is the polynomial degree.

© Radial basis function (RBF)

where a is the Gaussian width.

## IV. WIND SPEED ESTIMATION BASED ON SVR

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For the application of the SVR to estimate the wind speed, the training samples for input and output, kernel function, and parameters of C and £ should be firstly decided. Thereafter, training samples are obtained from the turbine power equation with pre-specified rotor speed COm and wind

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speed U samples as [19]

(34)

where p is the specific density of air and R is the radius of the turbine blade.

For each sample, the rotor speed and the correspond-

pitch turbine the power-speed characteristics are fixed for each wind speed without intersection as shown in Fig. 5 [6]. Hence, if the turbine power and the rotor speed are known for any operating condition, the wind speed can be calculated. The RBF as a kernel with £ =0.005, a = 23, and C =500 is used, which are usually selected based on a priori knowledge and/or user expertise. Thereafter, La¬grange multipliers (a, - a*) are decided by using Matlab, and the wind speed is calculated online as depicted in Fig. 6.

During on-line operation, the turbine power is calcu¬lated as

where Pg is the generator power, J is the system moment of inertia, and Bt is the friction coefficient.

V. EXPERIMENTAL RESULTS

Figure 7 shows the proposed configuration of the con¬trol system with the laboratory 3kW system. The charac¬teristics of the wind turbine are simulated using a tor¬que-controlled induction motor drive. Torque reference is calculated using torque equations by a control program running in a DSP TMS320C33 control board. Reference

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the A/D inputs of the gate-driver. In order to calculate reference torque, the control program reads wind velocity.

Fig. 8 shows the estimated wind speed which matches the measured one with a slight delay. This delay occurs not only because the system dynamic characteristic is not in¬cluded in training process but also because the generator speed control response is not instantaneous.

Figure 9 shows the transition through synchronous speed, the speed changes from sub synchronous to super synchronous smoothly when a back-to-back converter is used. As a result of increasing rotor speed, the rotor pow¬er decreases up to zero and the increase in the reverse di¬rection. Theoretically, the zero crossing point occurs at synchronous speed. However, in Fig. 10 the zero crossing occurs at 1875 rpm due to the different sources of loss such as rotor and converter losses.

on the other hand, the stator power is optimized to ex¬tract the maximum power for different wind speed. Re¬gion AB in Fig. 11 shows the power optimization during the wind speed increasing. If the rotor speed reaches the

in Fig. 11. During high speed operation, pitch angle controller is activated to protect the rotating system. In this case, the power is controlled to the rated value as described by the region DE.

VI. CONCLUSIONS

This paper addresses the dynamic modelling and control system of the

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Doubly-fed induction generator in the wind power generation system. The dynamic model of the DFIG is complete with its active power and reactive power control. The stator active power is adjusted in order to extract the maximum power from the wind power. Normally, the output reactive power of the wind power conversion system is controlled as zero to keep unity power factor of the stator voltage and current. However, the stator reactive power control is used to optimize the generator efficiency by sharing the reactive power between stator and rotor. The steady state and transient responses of the power, current and pitch angle controllers show excellent performance for the different modes and wind speed.

## VII. CONCLUSIONS

A novel wind speed estimator using the SVR algorithm has been proposed for wind power generation systems, which is based on off-line training of the input-output samples. The main advantages of the proposed estimation algorithm are the high accuracy and the fast transient performance since a relevant function between system input and output is deduced by off-line training and the output can be calculated directly with the inputs.

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