Grid-Connected Dual Stator-Winding Induction Generator Wind Power System over a Wide Wind Speed Range

Kai Shi†*, Peifeng Xu*, Zengqiang Wan*, Zhiming Fang†, Rongke Liu** and Dean Zhao*

††School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, China
**KTK Group, Changzhou, China

Abstract

This paper presents a grid-connected dual stator-winding induction generator (DWIG) wind power system suitable for wide-ranged wind speed. The parallel connection via a unidirectional diode between dc buses of both stator-winding sides is employed in this DWIG system, which can output a high dc voltage over a wide wind speed range. The grid-connected inverter (GCI) does not need a booster converter, which increases the efficiency of wind energy utilization and simplifies the hardware topology and control strategy of the grid-connected inverter. In view of particularities of parallel topology and the adopted generator control strategy, a novel excitation-capacitor optimization solution is proposed to reduce the volume and weight of the static excitation controller (SEC). Furthermore, when this excitation-capacitor optimization is carried out, the maximum power tracking problem is also considered. All the problems are resolved by a combination control for DWIG and GCI. Experimental results on the platform of 37-kW/600-V prototype show that the proposed DWIG wind power system can output a constant dc voltage over a wide rotor speed range for a grid-connected operation and that the proposed excitation optimization scheme is effective.

Key words: Dual stator-winding induction generator (DWIG), Excitation-capacitor optimization, Grid-connected, Wind power, Wide wind speed

I. INTRODUCTION

Since the beginning of the 21st century, wind energy has become one of the most important ways to resolve the problem of energy crisis. Wind energy has the advantages of vast quantity, wide regional distribution, and non-pollution. As the most commonly used wind turbine, both the direct-drive permanent magnet synchronous generator (PMSG) and doubly-fed induction generator (DFIG) wind turbines have inherent disadvantages [1]. The PMSG wind turbine is very expensive for its rare permanent magnetic material, and the direct-drive structure is large-sized and heavy. The DFIG requires brushes and copper rings for power transfer from/to the rotor windings, which leads to higher maintenance costs [2].

As a novel induction generator proposed at the beginning of this century, DWIG not only inherits some advantages of conventional induction generators (IGs) such as robust brushless construction, lower maintenance cost, and favorable overload protection [3], [4], but also overcomes its inherent drawbacks of poor voltage regulation with load and rotor speed variation [5], [6]. The lack of electrical connection between the two sets of stator windings makes it exhibit a high-quality control performance under variations of speed and load. A pulse width modulation (PWM) controlled SEC connected to the control winding is employed to provide variable compensating reactive power to effectively regulate the magnitude of output voltage and load frequency [7]. At the same time, harmonics induced by the applied power converter connected in series or parallel with the load in a conventional IG system can be minimized and even eliminated [6], [7]. In the last years, researches on DWIG for standalone power systems applications were carried out, and excellent static and dynamic performances for DWIG has been demonstrated [7], [8]. With the increasing need of
offshore wind farms [9], [10], DWIG power generation systems were proposed for offshore wind farms suitable for high-voltage dc (HVDC) transmission [11], [12].

Being suitable for operating under medium-low speed regions realized by the optimal design of DWIG structure allows for the removal of the high-speed gearbox, which is expensive and difficult to maintain, employed in the DFIG wind turbine. The favorable capability of operating in the flux-weakening region broadens the operational speed range of DWIG. Since the ac capacitor bank on the power winding provides the reactive power as well as reduces the inductance of the rectifier load, the bank can be optimized to keep the control-winding current at a minimum level to decrease the capacity of SEC [8], [10], [13]. Thus the DWIG wind power system has been verified to be a strong competitor comparing to other conventional wind turbines.

However, wind energy has its own unique characteristic that it varies with the time of the day, month, or season. Much of the annual gross electricity production of wind turbines depends on the available wind speed range. For this reason, the research attention of wind energy is focused to improve wind energy extraction and extend the operating wind speed range of wind turbines, especially in barren areas. For the limitation of the cost of entire wind turbine system and the capacity of excitation converter, the direct-drive PMSG and DFIG are not cost-effective for extending the operating range of wind speed. For the direct-drive PMSG wind turbine, the more expensive high-gain boost converter is necessary for the higher dc voltage under low wind speed for stable grid-connected operations. As wind speed falls, DFIG reverts to a conventional IG operation mode, with the total electric power flowing from the rotor-side converter to the grid. Hence, the capacity of the rotor-side excitation converter restricts the actual adaptive operation wind speed range of DFIG. Furthermore, particular control strategy for respective wind turbine and reformed maximum power tracking strategy are also proposed to expand the operating range of the wind turbine and increase the output power, especially in areas with low wind speed [14], [15].

To resolve this problem, the topology of DWIG wind power systems is improved to enhance its unsatisfactory capability of wind energy utilization in low wind speed regions [16]. In order to make full use of wind energy, both sides of a dc bus are connected in parallel using a diode. The control-winding-flux-orientation control strategy for DWIG and efficiency optimization scheme in the low-speed range were studied in [16], where different control strategies for low and high wind speeds ensure a stable high dc output voltage over a wider wind speed range. Nonetheless, neither were the topology of GCI or grid-connected operation control strategy involved in the work, nor was the optimization of excitation capacitor in the parallel topology for grid-connected operation studied in [16]. Since the particular topology of parallel connection between two dc bus sides results in an entirely different active and reactive current component in low and high wind speed regions, the excitation optimization scheme should be designed and reconfirmed for an improved system topology and grid-connection operation. Furthermore, the maximum power tracking problem should be considered when excitation capacitances are optimized.

In this paper, a grid-connected DWIG system for wind energy generation applications is explored. The topology of parallel connection with both dc bus sides is still employed to output a stable high dc voltage in a wide wind speed range. Because of this advantage in parallel topology, the booster converter is removed in the hardware structure of GCI for grid-connected operation, which is an outstanding advantage of the proposed grid-connected DWIG wind turbine. The different compositions of active and reactive current in low and high wind speed ranges are fully considered when the capacity of the SEC is optimized while the maximum power tracking requirement is satisfied. Meanwhile, an appropriate control strategy for GCI without a booster converter is presented. Based on a grid-connected DWIG wind turbine prototype, the above work is verified by experimental results.

The rest of this paper is organized as follows. In Section II, a system structure diagram of the proposed grid-connected DWIG wind power system is introduced, and the operational principle is also discussed in detail. Then, the respective and integrated control strategies for the proposed wide-speed-range-operation grid-connected DWIG wind power system are presented in Section III. In Section IV, the optimization scheme for the excitation capacitors and the simulation verification are shown. Finally, experimental results are discussed in Section V, and Section VI concludes this work.

II. GRID-CONNECTED DWIG WIND POWER SYSTEM AND OPERATIONAL PRINCIPLE

The structure diagram of the proposed grid-connected DWIG wind power system is shown in Fig. 1. The first-order step-up gearbox is built to deliver mechanical energy from the wind machine to generator. The DWIG consists of a standard squirrel-cage brushless rotor and a stator with two separate three-phase star windings wound by 30° electrical angle shifted. The power winding is linked with ac excitation capacitors and a rectifier bridge. A filter induction between the control winding and SEC is adopted to minimize SEC-induced harmonics. The dc bus of SEC is connected to the dc filter capacitor. The storage battery isolated from the high dc voltage through a diode, which contributes to the excitation at the beginning of voltage build-up. Both dc buses on the control side and power side are connected parallel via a diode. The positive dc-bus terminal of SEC is connected to the positive one of the rectifier bridge, while their negative
terminals are connected directly. The diode provides a transmission channel for electrical power under low wind speed. The switch status of this diode is determined by the voltage difference between both sides of the dc bus. The dc bus of GCI is linked to the output dc bus of DWIG directly without a booster device, which increases the efficiency of wind energy utilization and simplifies the hardware structure and control of the grid-connected operation.

Under low wind speed, the output dc-bus voltage of the rectifier bridge is too low to reach the given value even if the entire capacity of SEC supplies the reactive excitation power. The voltage-boosting ability of SEC is exploited to acquire a high dc voltage here. Thus, the electrical power is supplied to the load through the dc bus of SEC when the diode is on, while the rectifier bridge on the power side is blocked.

The output voltage of the rectifier bridge increases with the rotor speed of DWIG, and also rises with the wind speed. Under a high wind speed, the diode will turn off once the output voltage of the rectifier bridge exceeds the dc-bus voltage of SEC. The electrical power is transferred from the rectifier bridge to the load, and reactive power is provided by SEC and ac excitation capacitors at that moment. Thus, a stable output dc voltage is achieved by adjusting the reactive power from SEC under such working conditions. The volume and capacity of SEC can be optimized by choosing a reasonable excitation capacitance. Meanwhile, the dc-bus voltage of SEC is also obliged to be constant for the steady operation of SEC.

The active power from generator is transferred from the GCI to grid, and the power factor usually equals 1. If a compensation reactive power is required, the power factor can also be a different value. The maximum power tracking is accomplished by common control schemes of generator and inverter. Therefore, it can be found that the combined system control strategy and corresponding specific excitation capacitor optimization are both important in this grid-connected wind power system.

It should be noted that the two sets of stator windings have the same rated dc-bus output voltage. In order to achieve a better dynamic performance after two sides of the dc bus are connected in parallel, the number of control-winding turns should be fewer than the number of power-winding turns in order to decrease the voltage drop on the impedance of filter inductance. In other words, the terminal voltage of the control winding should be lower than that of the power winding.

III. CONTROL STRATEGY FOR GRID-CONNECTED DWIG WIND TURBINE FOR WIDE SPEED RANGE

The emphasis to stable operation of the proposed grid-connected DWIG wind turbine is to output a constant high dc voltage in a wide speed range, which helps avoid the requirement of a booster converter for the grid-connected inverter. Another emphasis to stable operation is to realize grid-connected operation by the integrated control of generator and inverter while tracking the maximum power. Thus, the dc voltage control strategy where the active and reactive current of SEC are adjusted and the cooperation control between generator and inverter are both important elements in this system. These elements are included in the following control strategies for the grid-connected DWIG wind turbine.

A. Principle of Control-winding-voltage-orientation Control Strategy and Instantaneous Power Theory

Based on the instantaneous reactive power theory [17], [18], the instantaneous active power \( p \) and reactive power \( q \) are defined in (1) using the power-invariance Park transformation and arbitrary reference coordinates,

\[
\begin{align*}
p &= u_x i_x + u_y i_y, \\
q &= u_x i_y - u_y i_x.
\end{align*}
\]

where \( u \) and \( i \) are the instantaneous voltage and current, respectively, for a three-phase circuit, and sub-scripts \( x \) and \( y \) represent the direct and quadrature axes for arbitrary reference coordinates. For example, subscripts \( d \) and \( q \) will be used in two-phase rotating reference coordinates. Similarly, for the stationary coordinate, the subscripts \( \alpha \) and \( \beta \) will be used. Thus, it can be found that, in (1), the values of \( p \) and \( q \) are independent of the defined reference coordinates.

From (1), if the instantaneous power and voltage are known, the corresponding current can be calculated as follows,

\[
\begin{align*}
i_x &= \frac{pu_y - qu_x}{u_x^2 + u_y^2}, \\
i_y &= \frac{pu_x + qu_y}{u_x^2 + u_y^2}.
\end{align*}
\]

Replacing subscripts \( x \) and \( y \) in (2) with \( d \) and \( q \), respectively, the corresponding current components for \( d-q \) rotating reference coordinates are

Fig. 1. Structural diagram of the proposed grid-connected DWIG wind power system.
\[ i_d = \frac{pu_d - qu_d}{u_d^2 + u_q^2} = \frac{pu_d - qu_d}{|U|^2} \]
\[ i_q = \frac{pu_q + qu_d}{u_d^2 + u_q^2} = \frac{pu_q + qu_d}{|U|^2} \]  

The \textit{d}-\textit{q} reference coordinate is oriented by the control-winding terminal voltage vector [16]. A simplified orientation diagram is shown in Fig. 2.

\begin{align*}
\Phi_d &= \frac{u_d}{|u_d|} \\
\Phi_q &= \frac{u_q}{|u_q|}
\end{align*}

Fig. 2. Simplified diagram based on the control-winding terminal voltage orientation.

In this particular voltage-oriented reference frame, the voltage components of \textit{d} and \textit{q} axis are described as follows,
\[ \begin{align*}
|u_d| &= |U| \\
|u_q| &= |U|
\end{align*} \]  

It is clear that the abovementioned orientation method is very useful in analyzing the instantaneous active and reactive power. Substituting current subscripts \textit{x} and \textit{y} with \textit{d} and \textit{q}, respectively, (2) can be rewritten as follows, according to (4),
\[ \begin{align*}
\frac{p}{u_d} &= \frac{i_d}{|U|} \\
\frac{q}{u_d} &= \frac{i_q}{|U|}
\end{align*} \]  

Thus,
\\[ \frac{p}{q} = \frac{i_d}{i_q} \]  

Thus it can be seen that the \textit{q} component of control-winding current \( i_q \) produces instantaneous reactive power \( q \), while \( i_d \) generates \( p \). In addition, electro-magnetic torque \( T_{em} \) can be used to regulate the dc-bus voltage \( U_{dc} \) of SEC, and the manipulation of \( T_{em} \) can be accomplished by controlling \( p \). Moreover, \( q \) can adjust the control winding flux and then change the internal magnetic field of DWIG [8]. Hence, the power- winding terminal voltage \( U_{pdc} \) can be regulated by \( q \). In conclusion, the control relationship can be summarized as follows,
\[ \begin{align*}
\{ i_d \rightarrow p \rightarrow T_{em} \rightarrow U_{dc} \\
\{ i_q \rightarrow q \rightarrow \Phi_m \rightarrow U_{pdc}
\end{align*} \]  

B. Voltage Control Strategy

1) Voltage Control Strategy in Wide Wind Speed Range

Owing to the saturated flux caused by excessive regulation for the dc-bus voltage to reach the set value, a voltage booster function of SEC on the control-winding side is employed to broaden the utilization of wind energy under low wind speed. Under these circumstances, the parallel diode is on, and electrical power is transferred from the dc bus of SEC to the grid-connected inverter.

To acquire a high dc voltage under low wind speed, the voltage booster function of SEC is exploited. As shown in Fig. 3, both the control-winding leakage inductance and filter inductance are used to store electric energy. When zero vectors are chosen, the control windings are short-connected. Under this circumstance, the induced Electro- motive Forces (EMFs) serve as a power supply, which results in increments of both phase current and electric energy being stored in the inductance. When nonzero vectors are selected, electric energy stored in the inductance will be conveyed to the dc bus through an antiparallel diode. Continuous storage and release of electric energy in the inductance will step up the dc-bus voltage as long as the input active power to filter capacitor \( P_m \) is greater than output power \( P_{out} \). The dc-bus voltage rises or drops when \( P_m \) is greater or less than \( P_{out} \).

Thus, the closed-loop regulator of the dc-bus voltage determines the duty cycle of switching tubes. Since output active power variations do not induce reactive current changes in SEC, the active power loss of SEC and the output active power both determine the active current \( i_{sd} \).

In order to improve the dynamic performance and load capacity of DWIG at a low rotor speed, the magnetic flux of DWIG should be kept constant. The induced EMF of the single-phase control winding can be expressed as
\[ E_s = 4.44f_l N_s K_{ms} \Phi_m \]  

where \( f_l \), \( N_s \), \( K_{ms} \), and \( \Phi_m \) are the synchronous frequency, number of turns in the control winding, the winding coefficient, and the main flux of the generator, respectively. Obviously it is necessary for \( \Phi_m \) to be
maintained as a constant by regulating $E_s$ under a variable rotor speed. However, it is difficult for $E_s$ to be controlled directly. In fact, the voltage drop in the control-winding impedance can be ignored here since it is much less than the induced EMF. Therefore, phase voltage $U_s$ approximately equals to $E_s$, and thus main flux $\Phi_m$ can be adjusted by controlling $U_s$ under a variable rotor speed. In this paper, the amplitude of control-winding voltage vector $|U_s|$ is employed to regulate the flux $\Phi_m$.

In order to ensure a constant slope of curve $|U_s|/f_i$ for regulating $\Phi_m$, the reference value $|U_s|$ depends on the synchronous frequency $f_i$ varying continuously with wind speed. The feedback value of $|U_s|$ is calculated by using the sampled control-winding line voltage. Thus, the given reactive current $i_{sq}^*$ is obtained from the PI regulator of $|U_s|$. In addition, it can be deduced from (7) that an increasing $|U_s|$ contributes to a reduction in $i_{sd}$ and $i_{sq}$, which will result in the steady operation of the system.

2) Voltage Control Strategy under High Wind Speed

As soon as the dc-bus voltage of the rectifier bridge on the power-winding side reaches the set value under a high wind speed, the parallel diode turns off. The electrical power is transferred from power winding side. Equation (8) shows that the adjustment of main flux $\Phi_m$ changes the single-phase winding voltage. Consequently, controlling control-winding flux $\Phi_s$ can also regulate output dc-bus voltage $U_{pdc}$ under different rotor speeds and loads for the same magnetic field shared by two sets of stator windings. Since the reactive current from the excitation capacitor is nonadjustable, the controllable reactive current is provided mainly by SEC, and thus the given $i_{sq}^*$ can be obtained from $U_{pdc}$ regulator.

Although there is no active power exported from the control-winding side, limited active losses such as line resistor loss and switching loss still exist. In order to guarantee the stability of SEC, it is necessary to control $i_{sd}$ to keep $U_{pdc}$ steady in real time. The inputs of two dc-bus voltage regulators are the differences between their respective dc-bus voltage reference values and the measured values.

3) Integrated Voltage Control Strategy for DWIG in a Wide Wind Speed Range

Although different active and reactive power control strategies for regulating output voltage are employed under low and high speeds, they can be merged into one kind of integrated voltage control strategy. Only the given and feedback values of one voltage outer loop need to be changed. Respective feedback parameters are measured in real time to guarantee a soft switch between two kinds of operational modes. The specific integrated voltage control strategy for wide-ranged wind speed is shown in Fig. 4. The switchover between low wind speed and high wind speed operation modes is judged by rotor speed.

![Integrated voltage control strategy diagram of proposed DWIG wind power system](image)

Fig. 4. Integrated voltage control strategy diagram of proposed DWIG wind power system.

$i_{sd}$ and $i_{sq}$ are calculated by their own outer regulator. Then, substituting $a$ and $b$ for subscripts $x$ and $y$ in (2) and replacing $d$ and $q$ according to (5), the reference values for $a-b$ stationary coordinates can be expressed as

$$
\begin{align*}
\begin{cases}
i_{sa}^* = i_{sa} - \frac{i_{sq} U_{\beta}}{|U_s|} \\
i_{sb}^* = i_{sb} + \frac{i_{sq} U_{\alpha}}{|U_s|}
\end{cases}
\end{align*}
$$

The references $i_{sa}^*$, $i_{sa}$, and $i_{sb}$ are calculated through the stationary coordinate transformation from $a-b$ into $a-b-c$. The ac-side voltage vector of SEC is regulated by switch signals $S_A$, $S_B$, $S_C$ derived from a two-level current hysteresis comparator. The errors between current references $i_{sa}^*$, $i_{sa}$, $i_{sb}$ and measured currents $i_{sa}$, $i_{sb}$, $i_{sc}$ are regarded as inputs of the hysteresis comparator.

C. Control Strategy for Grid-connected Inverter

A double-closed-loop structure is usually applied in the control strategy for a conventional full-power GCI such as those in PMSM wind turbines. The given active current is dependent on the fluctuation of dc-link voltage, which means that the output of the outer-loop voltage regulator is regarded as the given input of the current inner loop. However, the GCI circuit in a DWIG wind power system is simplified so that a boost converter is not needed since the front-end DWIG outputs a stable high dc bus voltage with wide-ranged wind speed. Therefore, the dc current will fluctuate with the output power if the outer-loop voltage regulator is still applied in a grid-connected DWIG wind turbine.

A special double-closed-loop control scheme is put forth. The output of the outer-loop power regulator serves as the given reference of the current inner loop, and the set value of the power outer loop is derived from the optimal characteristic curve of DWIG output power. The maximum
power point tracking (MPPT) is fulfilled by the optimal output power characteristic and the received feedback output active power. Thus it can be seen that the DWIG controller is combined with an inverter controller, which embodies the control integrality of the proposed grid-connected wind turbine. The entire control-strategy block diagram of the GCI is given in Fig. 5.

![Control schematic diagram of the GCI](image)

Fig. 5. Control schematic diagram of the GCI.

To decrease the impact to the grid at the cutting-in moment, the output voltage vector from GCI is regulated by a space voltage vector PWM to follow the grid-side voltage. At the initial time, the given active power is 0. The feedback current and voltage components from the grid side play a key role in balancing and overcoming any slight fluctuations. The voltage-orientation angle used in the calculation of coordinate transformation is obtained from the digital phase locking loop (PLL), which is implemented by a closed-loop control of the network-side voltage reactive component.

The controllable characteristic of reactive power helps the DWIG wind turbine provide support to the grid during grid faults. The proposed control strategy for GCI can also contribute to better grid-fault ride-through ability for the DWIG wind turbine. Although the output power fluctuates at twice the power-grid frequency during asymmetric grid faults, only the dc-bus current fluctuation at twice the power grid frequency exists in the DWIG wind power system. Thus, the dynamic performance of DWIG is not affected by such a load current fluctuation.

**D. Operational Characteristics of DWIG Wind Power System under Various Wind Speeds**

Depending on the optimal power curve of the wind turbine, different running states, and the corresponding output power in a wide wind speed range, the operation of a grid-connected DWIG wind power system can be divided into four main stages. As shown in Fig. 6, the process from starting generating to maximum-rotor-speed operating occurs in four stages:

1) **Stage I:** Start-up stage shown in the A-B section in Fig. 6. After the wind speed reaches the start-up speed, the vanes start to rotate and the rotor speed of DWIG also increases gradually. Since DWIG has not switched to the power generation mode at this moment, there is no electrical energy output from DWIG.

2) **Stage II:** Voltage build-up stage shown in the B point in Fig. 6. As the rotor speed of DWIG reaches a set minimum value, DWIG begins to build up voltage. In this process, the reactive power is provided by excitation capacitors and SEC together. To guarantee normal operation of SEC, the dc-bus voltage of SEC should be regulated to be stable by compensating for the active power loss of SEC. After this short process, DWIG enters the power-generation state.

3) **Stage III:** Low-wind-speed operation stage shown in the B-C section in Fig. 6. When the wind speed reaches the cut-in speed, the system begins to transfer electric power to GCI from the dc bus of SEC. High dc voltage is acquired by the voltage booster function of SEC. The magnetic flux of DWIG is regulated to maintain a constant less-than-rated value to improve the dynamic performance and load capacity of DWIG. As the B-C section shows in Fig. 6, the current magnitude of SEC is mainly decided by the output active power.

4) **Stage IV:** High-wind-speed operation stage shown in the C-D-E-F section in Fig. 6. The electric power is transferred from the dc bus of the rectifier bridge to the inverter. The adjustable reactive power from SEC is provided to keep the output dc voltage stable, and the adjustable active power keeps the dc-bus voltage of SEC steady. In this stage, the excitation current magnitude of SEC depends mainly on the reactive power since the active loss of SEC is relatively small. The E-F section is regarded as the flux-weakening control region, and the output active power is maintained at a constant value. There is no difference with the C-D-E section for the control strategy, but the excitation reactive current is too excessive to be extracted by SEC.

![Operational characteristics of DWIG wind power system under various wind speeds](image)

Fig. 6. Operational characteristics of DWIG wind power system under various wind speeds.

**IV. OPTIMIZATION SCHEME OF EXCITATION CAPACITOR FOR WIDE WIND SPEED RANGE**

The proposed grid-connected DWIG wind power system is different from previous systems [8], [11]. The control strategy applied in two working conditions leads to different active power flow directions, which brings about a distinct
composition and proportion of the control-winding current. The active current is the major component of control-winding current under low wind speed, while the reactive component is the primary under high wind speed. Hence the influence generated by various excitation capacitors on the control-winding current is also different from that of previous systems. Therefore, the capacity optimization scheme for SEC that is suitable for this proposed grid-connected DWIG wind power system should be investigated.

### A. Control-winding Current under Low Wind Speed

The excitation reactive current provided by SEC is merely acting on maintaining $\Phi_m$, constant under low wind speed, while the active current increases along with the active power output. Thus, the active current occupies the leading position in the control-winding current. To simplify our analysis, the influence of mutual leakage between two sets of stator windings is ignored, and only the fundamental component is taken into consideration. The excitation reactive current fed from SEC to adjust $\Phi_m$ is regarded as a current source [11].

The simplified equivalent circuit of the DWIG wind power system with a resistance load operating under low wind speed is shown in Fig. 7 (a), and the corresponding phasor diagram is shown in Fig. 7 (b).

The amplitude of $\hat{I}_m$ can be derived from the phasor diagram,

$$I_m = I_c + I_p \cos \beta - I_s \sin \gamma - I_r \sin \alpha$$  \hspace{1cm} (11)

where $I_c$ and $I_L$ are the reactive component and the active component of control-winding current. As shown in Fig. 7 (b), all the unknown parameters in (11) can be expressed as follows,

$$\cos \beta = \frac{U_p - I_p X_p}{E_m}, \quad \sin \gamma = \frac{I_s X_s + I_m R_m}{E_m}, \quad \sin \alpha = \frac{I_r X_r}{E_m},$$

$$I_p = U_p \cdot \omega C, \quad I_s = \sqrt{\frac{E^2}{s^2} + X^2_r}, \quad I_m = \frac{E_m}{X_m}.$$

Thus, the reactive component of control-winding current used to adjust the magnetic flux under low wind speed is described as follows,

$$I_{sc} = \frac{E_m}{E_m + I_L R_s} \left( \frac{E_m}{X_m} + \frac{E_s X_s}{(R_s)^2 + X^2_r} - U_p \omega C \frac{U_p - U_p \omega CR_p}{E_m} \right),$$

$$I_r = \frac{-I_s^2 X_s}{E_m + I_L R_s}$$  \hspace{1cm} (12)

So, the magnitude of control-winding current can be calculated by

$$I_s = \sqrt{I_{sc}^2 + I_L^2}$$  \hspace{1cm} (13)

In the generation mode, the slip ratio $s$ is negative and can be given as follows [8], [11],

$$s = \frac{-3E^2_m R_s + \sqrt{9E^4_m R^2_s - 4P^2_m R^2_s X^2_s}}{2P_s X^2_s}$$  \hspace{1cm} (14)

Here, $P_s$ is the electromagnetic power transferred from the rotor to the stator. From (12)-(14), the control-winding current under different rotor speeds and output power can be determined.

The above derivation processes and derivation results reveal that the amplitude and phase of the control-winding current depend on both the excitation capacitor and output active power (represented by $I_L$) under low wind speed. Obviously, $I_L$ plays a decisive role in the control-winding current when operating under low wind speed.

### B. Control-winding Current under High Wind Speed

Under high wind speed, the active component in $I_s$ can be ignored since the active power loss of the SEC is small. This means the phase of $I_s$ stays the same as or is the opposite of $I_m$ if the loss is ignored. The control-winding current can also be seen as a current source. As wind speed increases, the reactive excitation power provided by the excitation capacitor is excessive, and SEC extracts this part of...
excitation power. The adjustable reactive excitation power supported by the SEC can guarantee a stable dc output voltage.

According to [10], the value of \( I_s \) is described as

\[
I_s = \frac{E_m}{X_m} + \frac{E_m X_s}{(R_x s)^2} + \frac{I_s^2 R_x - U_x^2}{E_m} (15)
\]

where \( R_x \) represents the equivalent load. The expression of the slip ratio \( s \) is the same as that in the low-speed operation mode. From (15), the excitation current supplied by SEC in the high-speed operation mode can be attained. The phase diagram for DWIG operating under high wind speed is displayed in Fig. 8.

**Fig. 8. Phasor diagram of DWIG operating under high wind speed.**

**C. Optimal Scheme of Excitation Capacitor**

The variations in the control-winding current for two different working statuses are shown in Fig. 9. The two curves indicate the control-winding current variation when electric energy is transferred from the control-winding side or the power-winding side in a wide wind speed range from 500 to 2000 rev/min. Curve 1 in Fig. 9 shows the control-winding current variation in low-speed mode, and the value of \( I_s \) is always positive. Curve 2 in Fig. 9 indicates the control-winding current variation in high-speed mode, and the value of \( I_s \) becomes negative when the reactive excitation current provided by the excitation capacitor is excessive. The rotor speed \( n_r \) represents the switchover speed between two operation modes.

The maximum positive control-winding current under low wind speed appears at the switch point (point A in Fig. 9), and the minimal negative current \( I_{s_1} \) under high wind speed appears at a high-speed rated-load time (point B in Fig. 9). Therefore, the effect of the switchover speed must be considered in this optimization problem. If the condition \( |I_s| = |I_{s_1}| \) is satisfied, an appropriate excitation capacitor under variable speed and load will be determined. In other words, the minimal capacity of SEC for the proposed grid-connected DWIG wind power system is obtained.

**Fig. 9. Change of control-winding current in different wind speed zones.**

**D. Optimization Results**

To further adjust the optimal value of excitation capacitor, a simulation model for the proposed DWIG wind power generation system is constructed in the platform of MATLAB/Simulink. Some parameters of the DWIG prototype are given in Appendix A.

**Fig. 10. Influence of excitation capacitor on control-winding current.**

In two different operation modes, influences exerted by various excitation capacitors on the control-winding current \( I_s \) are investigated. The simulation results are shown in Fig. 10. The control-winding current in the low-speed range is denoted as \( I_{s_1} \), and simulation results for the control-winding current with a variable excitation capacitance value per 100 rev/min interval are all given. \( I_{s_2} \) is the control-winding current with a full load under a maximum rotor speed of 2000 rev/min. \(-I_{s_2}\) is the mirror curve of \( I_{s_2} \). The intersection point between \( I_{s_1} \) and \(-I_{s_2}\) is where the condition \( |I_s| = |I_x| \) is met. As shown in Fig. 10, the amplitude of \( I_s \) has only a small change as the excitation capacitance varies in a low-speed situation, whereas it depends on the output active power. To the contrary, \( I_s \) has
a close relationship with the excitation capacitance value in high-speed situations.

Because the DWIG prototype is designed to output a voltage 600V at 1000 rev/min, the switchover speed between two operation modes should exceed 1000 rev/min. Therefore, a switchover rotor speed of 1000 rev/min and corresponding excitation capacitance of 205 μF (the intersection between $I_1$ and $I_2$ at 1000 rev/min) are chosen as the initial conditions for the following optimal approximation, as shown in Fig. 11. $P_{opt}(n)$ is the optimal output power for different rotor speeds of the generator. The increment of the excitation capacitance and rotor speed are 5 μF and 20 rev/min, respectively.

$$C = 205 \, \mu F; \ n = 1000 \, \text{r/min}$$

![Fig. 11. Process of optimal approximation for excitation capacitance and switch speed.](image)

After a comprehensive analysis of this simulation, an optimal excitation capacitance of 235 μF and switchover rotor speed of 1100 rev/min are obtained. To avoid frequent switching between the two operation modes, a rotor-speed hysteresis comparison is employed to judge and execute the switching between the two control strategies. The hysteresis width is set as 50 rev/min.

### E. Simulation Results

After the optimization procedure is completed, the simulation verification for the whole DWIG wind power generation system is carried out. The integrated voltage control strategy presented in Section VIII is applied in this simulation model, and the excitation capacitance of 235 μF and the switchover rotor speed of 1100 rev/min are selected. The output power of DWIG is decided by the optimal power characteristic curve. The corresponding simulation results are shown in Fig. 12. In order to facilitate the implementation and control, the amplitude of control-side voltage vector $|U_i|$ used in low speed mode is replaced by $U_{jDC}$ in this paper. Because two stator windings share the same magnetic field, it is a turn ratio relationship between these two quantities. So, this simplified method is still using in the subsequent experimental verification (the feedback and control voltage $U_{jDC}$ are both labeled as $|U_i|$).

As shown in Fig. 12 (a) and (b), when the rotor speed reaches the start rotor speed 500 rev/min at 0.5 s, the DWIG begins to build up voltage. The two dc-bus voltages $U_{jDC}$ and $U_{iDC}$ gradually increase to the given value 600 V and 200 V, then keep nearly unchanged. At this moment, the system runs at the low-speed operation mode. The rotor speed starts to rise at a constant speed after 2 s. The set value of $U_{jDC}$ changes linearly from 200 V to 500V in the low-speed operation mode, and the given value of $U_{iDC}$ is always 600 V. When the rotor speed exceeds the switchover speed of 1100 rev/min, the electrical power is diverted to transfer from the rectifier bridge on the power side. This state transition happens at 4 s. After that, the working stage is all through in the high-speed operation mode. The rotor speed ramps up from 1100 to 2000 rev/min and maintains at 2000 rev/min thereafter. Both of the dc-bus voltages can be regulated to keep stable at 600 V well during this process.

![Fig. 12. Simulation results of the proposed grid-connected DWIG wind power system based on the optimal capacitor](image)

The more detailed simulation results of dc-bus voltages and phase current of control winding at the switchover speed of 1100 rev/min and the maximum speed of 2000 rev/min are shown in Fig. 12 (c) and (d). In these two processes, it can be found that the RMS value of control-winding phase current...
are both 18 A approximately. Therefore, it is obvious that the chosen optimal capacitor can realize the capacity minimization of SEC for the proposed grid-connected DWIG wind power system. The correctness of simulation results will be verified by the following experiments.

V. EXPERIMENTAL VERIFICATION

A 37-kW/600-V prototype of the grid-connected DWIG wind power system is developed to carry out an experiment, as shown in Fig. 13.

![Fig. 13. Experimental prototype of proposed grid-connected DWIG wind power system.](image)

The GCI is designed for 50-kW-rated power. The main circuits of SEC and GCI are composed of three-leg Mitsubishi intelligent power modules (IPMs). The entire control strategy is implemented in a Freescale MC56F8346 digital signal controller (DSC), which has two independent pulse-width modulation interfaces suitable for controlling SEC and GCI simultaneously. The prime mover is simulated by a three-phase induction motor (IM) driven by a Siemens M440 inverter. An industrial PC with LabVIEW software is employed to control the M440 inverter to simulate wind-turbine characteristics and to track wind energy. The parameters of this prototype are shown in the Appendix A.

In order to achieve complete experimental verification of the proposed grid-connected DWIG wind power system, the experiment is divided into four parts: low wind-speed status, high wind-speed status, grid-connected operating mode, and excitation capacitor optimization.

A. Experimental Results under Low Wind Speed

The DWIG begins to build up voltage when the speed exceeds the minimum value of 500 rev/min. The in-service wind turbine blade determines the building-up rotor speed in practical applications. Experimental waveforms during this process are shown in Fig. 14. After the initial excitation generated by the 48 V battery, the dc-bus voltage is built up reliably and stably. Meanwhile, there are no overshoots in voltage or current waveforms. The dc-bus voltage of SEC successfully remains stable at 600 V. The amplitude of control-side voltage \( |U| \), which represents reactive power, is maintained at a given value of 200 V.

Fig. 15 gives voltage and current waveforms of DWIG at 1000 rev/min when outputting 8 kW of active power. The results prove that the dc-bus voltage and the amplitude of the control-winding voltage vector are both regulated to be steady at given values. The system runs steadily in the low-speed operation mode. In Fig. 14, \( u_{ab} \) is the

![Fig. 14. Voltage and current waveforms during the process of building up voltage at 500 rev/min.](image)

![Fig. 15. Voltage and current waveforms when outputting 8-kW active power at 1000 rev/min.](image)

![Fig. 16. Voltage and current waveforms during switching from low-wind-speed mode to high-wind-speed mode.](image)
to the given value of 600 V, the parallel diode enters into the off-state. The electrical power is diverted to transfer from the rectifier bridge. The dc-bus voltage of SEC is kept at the set value of 600 V throughout the transition process without any fluctuations, and the output dc voltage is maintained at a stable level by controlling the reactive power of the system. Fig. 16 shows the voltage and current waveforms of this system during switching from low-wind-speed mode to high-wind-speed mode.

B. Experimental Results under High Wind Speed

To avoid frequent switching between two operating situations, the switchover speed from high-wind-speed mode to low-wind-speed mode is defined as 1050 rev/min. Voltage and current waveforms during switching from the high-wind-speed mode to low-wind-speed mode are shown in Fig. 17. During the transition process, in order to achieve a rapid change in the two dc-bus currents, the control-winding dc-bus voltage drops to less than 20 V.

Voltage and current waveforms operating at the maximum rotor speed of 2000 rev/min in high-wind-speed mode are exhibited in Fig. 18. The excess reactive power supplied by the excitation capacitor to the generator is extracted by SEC. The line current leads the line voltage at the phase position. The dc-bus voltages at both winding sides are regulated to small-scope fluctuations at the given value.

![Fig. 17. Voltage and current waveforms during switching from high-wind-speed mode to low-wind-speed mode.](image1)

![Fig. 18. Voltage and current waveforms during output rated 37 kW at 2000 rev/min.](image2)

C. Experimental Results for Grid-connected Inverter

The three-phase current waveform and single-phase voltage and current waveforms for GCI during output at 11 kW of active power are displayed in Fig. 19. It can be seen that less harmonic content and a high power factor are achieved. This demonstrates the accuracy of the proposed double-closed-loop control strategy and the robustness of the GCI without a boost converter.

D. Experimental Results for Optimization of Excitation Capacitor

To prove the accuracy of the optimization scheme for the excitation capacitor, some experiments are performed at different wind speeds. The goal is to measure the control-winding current from the start of the build-up of rotor speed at 500 rev/min to the maximum rotor speed of 2000 rev/min (per 100 rev/min). The relationship of the output active power and control-winding current RMS value under different rotor speeds is shown in Fig. 20 (negative RMS value means opposite current direction). The maximum RMS value occurs at the switchover speed and the maximum speed. Their corresponding voltage and current waveforms are shown in Fig. 21 and Fig. 18, respectively.

Experimental results reveal that the RMS value of the control-winding current increases with a rise in rotor speed during low-wind-speed mode. Once the rotor speed is higher than the switchover speed, the control-winding current becomes negative during the high-wind-speed mode. Moreover, the RMS value of the control-winding current also rises with the enhancement of rotor speed in high-wind-speed mode. The minimal negative current almost equals the maximum positive current, and the minimal current value is approximately 18A. It can be seen that the results are consistent with the theoretical analysis and simulation results. These demonstrate the accuracy of the proposed optimization
scheme for the excitation capacitors. The maximum capacity of SEC needs only one third of the rated output power. No additional cost is involved for greater wind energy utilization in the rotor speed range of 1:4.

By combining the control of the generator and GCI, the grid-connected DWIG wind turbine runs stably and exhibits good operational performance. To decrease the volume and capacity of the SEC, an appropriate excitation capacitor optimization scheme considering active and reactive current composition of proportions in different operation modes and meeting the requirements of tracking maximum power is put forth. This is only one third of the rated output power. Therefore, a wider scope for wind energy utilization, smaller volume and capacity of the SEC, and a simpler GCI circuit and control without a boost converter make the grid-connected DWIG wind power system more competitive than other wind turbines. In addition, the high-quality dynamic performance of outputting a stable high dc voltage allows the grid-connected DWIG wind turbine to ride through grid faults more easily. This is our next key research work.

VI. CONCLUSIONS

A grid-connected DWIG wind power system for wide wind speed operation is proposed in this paper. To broaden the utilization capability of wind energy at low wind speed, a parallel connection topology between two stator-winding sides is employed. The integrated voltage control strategies help DWIG to output a stable high dc voltage in a wider wind speed range than before (a rotor speed range of 1:4 in this paper). Since there is no need for a extra boost converter, the circuit structure and control strategy of the GCI are both simplified.

By combining the control of the generator and GCI, the grid-connected DWIG wind turbine runs stably and exhibits good operational performance. To decrease the volume and capacity of the SEC, an appropriate excitation capacitor optimization scheme considering active and reactive current composition of proportions in different operation modes and meeting the requirements of tracking maximum power is put forth. This is only one third of the rated output power. Therefore, a wider scope for wind energy utilization, smaller volume and capacity of the SEC, and a simpler GCI circuit and control without a boost converter make the grid-connected DWIG wind power system more competitive than other wind turbines. In addition, the high-quality dynamic performance of outputting a stable high dc voltage allows the grid-connected DWIG wind turbine to ride through grid faults more easily. This is our next key research work.

APPENDIX

Following are the parameters of the designed DWIG (both the rotor and control winding are converted to a power
winding):

\[ R_p = 0.78 \Omega; \quad R'_p = 0.535 \Omega; \quad R''_p = 0.384 \Omega; \]

\[ L_w = 5.84 \text{mH}; \quad L'_w = 2.86 \text{mH}; \quad L''_w = 4.38 \text{mH}; \]

\[ L_m = 165.5 \text{mH}; \quad L_m = 0.57 \text{mH}; \]

Turns ratio: \( N : N_p = 52 : 60; \)

Rated power: 37 kW;

Rated speed: 1500 rev/min;

The maximum speed: 2000 rev/min;

Pole pairs: 2;

Rated dc output voltage: 600 V;

Filter inductor: \( 3 \times 4 \text{mH}; \)

Excitation capacitor: \( 3 \times 235 \mu\text{F}; \)

DC bus capacitor: \( 1100 \mu\text{F} / 900 \text{V} \);

Voltage of battery: 48 V;

The designed parameters for the GCI are as follows:

Rated power: 50 kW;

Filter inductor: \( 3 \times 4 \text{mH}; \)

Voltage on grid side: 155 V;

DC bus capacitor array: \( 17 \text{mF} / 900 \text{V} \).

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**REFERENCES**


Kai Shi was born in 1980 in Suzhou, China. He received his B.S. in Automation and M.S. in Power Electronic and Power Transmission from Jiangsu University, Zhenjiang, China, in 2002 and 2005, respectively. He received the Ph.D. in Power Electronic and Power Transmission from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2012. From 2002 to today, he has
been always working at the School of Electrical and Information Engineering. Since 2013, he has been an Assistant Professor in Jiangsu University. His current research interests include wind power generators control, grid-connected control, and control strategies of low voltage ride through.

Peifeng Xu was born in 1980 in Nantong, China. She received her B.S. and M.S. in Electrical Engineering from Jiangsu University, Zhenjiang, China, in 2002 and 2005, respectively. From 2002 to today, she has been working at the School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, China. Since 2007, she has been a lecturer at Jiangsu University. Her current research interests include the design and control of high efficiency wind power generators.

Zenqiang Wan was born in 1991 in Nantong, China. He received his B.S. in Electrical Engineering from Jiangsu University, Zhenjiang, China, in 2014. Since 2014, he has been a graduate student at the School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, China. His current research interests include the grid-connected control of high efficiency wind power generators and low-voltage ride-through control.

Zhiming Fang was born in 1978 in Zhenjiang, China. He received his M.S. degree in Control Theory and Control Engineering from Jiangsu University, Zhenjiang, China, in 2003. He received his Ph.D. degree in Control Theory and Control Engineering from Nanjing University of Science and Technology, Nanjing, China, in 2012. Since 2000, he has been a faculty member and he is currently a lecturer at Jiangsu University. His main research interests include switched systems, nonlinear control, robust control, and parallel robot control.

Rongke Liu was born in 1977 in Changzhou, China. He received his B.S. degree in Mechanical Engineering from Southwest Traffic University, Chengdu, China, in 2000. Since 2003, he has been a senior engineer at KTK Group, Changzhou, China. His main research interests include the mechanical design and integrated design of power supply systems.

Dean Zhao was born in 1956 in Changzhou, China. He received his B.S. in Industrial Electric Automation and M.S. in Machine Manufacturing from Jiangsu University, Zhenjiang, China, in 1982 and 1989, respectively. He received Ph.D. in Power Electronic and Power Transmission from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2007. Since 2000, he has been a Professor at the School of Electrical and Information Engineering, Jiangsu University. He is currently an Academic Leader in Agriculture Electrification and Automation, Jiangsu University. His current research interests include the production process research of intelligent automation and network control, the computer intelligent control, and robot control.