Indirect Vector Control for Stand-alone Operation Brushless Doubly Fed Induction Generator Employing Power Winding Stator Flux Orientated Approach

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Abstract. The brushless doubly-fed induction generator (BDFIG) provides an interesting alternative to the commonly applied conventional doubly-fed induction generator in wind turbines. In this paper, a novel voltage control strategy of stand-alone operation BDFIG for variable speed constant frequency wind energy conversion systems was presented. Based on the model of the generator, the power winding stator voltage and flux for stand-alone operation BDFIG are only determined by the equivalent PW stator magnetizing current which are independent of load, but PW stator terminal output power is only determined by load. An indirect PW stator flux orientated vector control scheme is employed to control the BDFIG by regulating the amplitude and frequency of the control winding stator current appropriately, and this results in constant generator terminal voltage and frequency for variations in both load and wind speed. In addition, simulation results prove the feasibility and validity of the proposed scheme, and excellent steady and dynamic state performance is achieved.

1. Introduction
Among variable-speed constant-frequency wind energy conversion systems, a brushless doubly-fed induction generator (BDFIG) as a reliable option shares with the doubly-fed induction generator (DFIG)'s benefits of low cost construction in that no permanent magnets materials used and only a fractionally rated converter needed. Simultaneously, the absence of electric slip rings obviates one of the main failure modes of the DFIG [1].

The control of BDFIG systems have has received much more attention. In particular, power winding (PW) stator flux oriented vector control (VC) presented in [2] decouples the control winding (CW) stator current in the PW stator synchronous reference frame, and control of instantaneous PW stator powers by regulating the CW stator currents, employing proportional integral (PI) controllers and also with feed-forward compensation [3]. Moreover, VC-based unbalanced operation capability is investigated, the typical improved algorithm include employing two PI regulators implemented in the positive and negative counter-rotating synchronous reference frame respectively [4], or using PI plus resonant regulators in positive synchronous reference frame [5]. The fractional drawback for VC is that the performance involving system stability and dynamic response highly relies on the tuning of the parameters. On the other hand, direct control (DC) of the machine reduces the complexity and minimizes
the use of machine parameters. Initially, the lookup table DC selects the proper voltage vectors directly from a predefined optimal switching signals table [6]. Moreover, the finite-set model predictive control evaluate and selects the possible switching state that optimizes the defined cost function, it thus achieve fast dynamic response by avoiding the cascaded control structure and the modulation step [7]. Nevertheless, the main disadvantage of the schemes is that the converter switching frequency varies, as a result, the PW stator side filter needed to prevent broad-band harmonics spectrum from injecting the connected grid. A modulated model predictive control was presented to solve this issue [8], the each voltage vector duration times were optimized with the cost function target of reduce ripple, whereas, it required complicated online calculations. Besides, the sliding mode control illustrates the disturbance rejection and strong robustness, but may exhibit undesired chattering. Furthermore, the super-twisting sliding mode control is proposed to suppressing chattering [9], nevertheless, tuning the control parameters is a challenging task.

The investigation been primarily focused on grid-connected mode application. On the other hand, the stand-alone generation system is imperative. Meanwhile, little literature has addressed the stand-alone operation relatively. The direct VC is designed and verified in [10]. Furthermore, VC-based inner loops decoupling is investigated in [11], moreover, PIR regulators implemented to elimination harmonic of unbalanced and nonlinear loads [12]. Nevertheless, VC scheme have the weak robustness to parameters variations. Besides, the dead beat control achieve faster transient [13], however, it was quite sensitive to parameters variations. A resonant sliding-mode control directly obtained the required CW stator voltage so as to eliminate the instantaneous errors of PW stator voltage [14], although without involving extra current control loops, but it required complicated online calculations.

This paper presents a novel control strategy of stand-alone operation BDFIG for variable speed constant frequency wind energy conversion systems. An indirect PW stator flux orientated vector control approach is employed to control the BDFIG by regulating the CW stator current appropriately, and results in constant generator terminal voltage. Then, enhanced transient performance and steady-state harmonic spectra is achieved.

2. BDFIG Stand-alone Operation and Model

2.1. Operation and Configuration of Stand-alone BDFIG

The stator of the BDFIG is furnished with two separate stator windings, known as the PW and CW, which share one stator lamination and differ in pole pair numbers distribution to avoid direct coupling. The rotor employs a special design enabling it to couple to both stator windings [1]. Generally speaking, PW stator is connected to the point of common coupling directly, whereas the CW stator is fed by a back-to-back VSC, handling only a fraction of the rated power, as shown in Fig.1. The CW stator side converter (CSC) is designed to control the PW stator voltage amplitude and frequency constant with variable-speed turbine. And the load side converter (LSC) keeps the direct-current (DC)-link voltage constant, meet the grid side harmonic acceptance indicator and guarantees the operation with an expected power factor. Quiet unlike the grid-connected mode application, a stand-alone power system itself has to generate a voltage in the generator terminal irrespective of varying rotational velocity due to turbine speeds and varying loads.

![Figure 1. Topology of stand-alone BDFIG operation.](image-url)
The BDFIG is normally operated in the synchronous mode, in which the shaft velocity is determined by the excitation frequencies of the two stator windings, independent of the torque exerted on the machine, the synchronous angular frequencies can be expressed as:

$$\omega_r = \left(\omega_p + \omega_c\right) / \left(p_p + p_c\right)$$ (1)

Where $\omega_p$ and $\omega_c$ are the excitation angular frequencies supplied to PW stator and the CW stator respectively. Defining the equivalent slip angular frequency $\omega_s$ as:

$$\omega_s = \omega_p - \left(p_p + p_c\right)\omega_r$$ (2)

2.2. Model of BDFIG

The BDFIG consists of a complicated structural arrangement and model. The Π type equivalent circuit of a BDFIG represented in the common synchronous rotating reference frame of the PW stator is shown in Fig. 2, the generic vector model [15] in $p_p$ type pole pairs distribution can be expressed.

\[ U_p = R_p I_p + d\Psi_p / dt + j\omega_p \Psi_p \] (3)

\[ U_c = R_c I_c + d\Psi_c / dt + j\left[\omega_p - \left(p_p + p_c\right)\omega_r\right] \Psi_c \] (4)

\[ U_r = R_r I_r + d\Psi_r / dt + j\left(\omega_p - \left(p_p + p_c\right)\omega_r\right) \Psi_r \] (5)

The flux linkage vectors can be given as:

$$\Psi_p = L_{sp} I_p + L_{mp} I_r$$ (6)

$$\Psi_c = L_{sc} I_c + L_{mc} I_r$$ (7)

$$\Psi_r^p = L_r I_r^p + L_{mp} I_p^p$$ (8)
The electromagnetic torque equation can be expressed:

\[
T_e = 3 \rho_p \text{Im}[\Psi_p I_p] / 2 + 3 \rho_c \text{Im}[\Psi_c I_c] / 2
\]  
(9)

Where \( U, I, \Psi, R, \) and \( L \) denote the voltage, current, flux, resistance, and inductance parameters, respectively, \( T_e \) and \( \omega \) is the electromagnetic torque and angular frequency, \( j \) represents the unit imaginary, Subscript \( m, s, r, p \) and \( c \) expresses the mutual and self, the rotor, PW and CW stator parameters respectively, the operator \( \text{Im} \) denote imaginary part of vector.

In order to simplify the analysis and the control process, the model complexity needs be simplified. Based on the simplified model of a BDFIG [16], the PW and CW stator flux linkage vectors can be can be simplified as follows:

\[
\Psi_p = A_p I_p + A_m I_c
\]  
(10)

\[
\Psi_c = A_c I_c + A_m I_p
\]  
(11)

Where \( A_p = L_{sp} - I_{mp}^2 / L_r \), \( A_c = L_{sc} - I_{mc}^2 / L_r \), and \( A_m = -L_{mc} I_{mp} / L_r \). In the Equs. (10) and (11), the two stator electromagnetic coupling relationship is represented directly.

3. Indirect VC for Stand-alone Operation BDFIG

3.1. Calculation of the CW stator Current References

Indirect control of the PW stator voltage is achieved by regulating the PW stator flux via the \( d \)-axis CW stator current while the \( q \)-axis CW stator current is controlled to assure correct orientation of the reference frame and hence control the output frequency. The generic expressions for the BDFIG can be simplified by using the \( d \)-axis of reference frame aligned with the PW stator flux vector, and splitting it into \( d-q \) components, that is \( \psi_{pd} = |\psi_p| \) and \( \psi_{pq} = 0 \). According to PW stator flux orientation, the relationship between the PW and CW currents may be given as:

\[
i_{cq} = -A_p i_{pq} / A_m
\]  
(12)

The PW stator resistance \( R_p \) is small and negligible, that can be assumed:

\[
u_{pd} \approx 0
\]  
(13)

Defining the equivalent PW stator magnetizing current \( i_{pm} \) as:

\[
\psi_{pd} = A_m i_{pm} = A_p i_{pd} + A_m i_{cd}
\]  
(14)

Eliminating \( i_{pd} \) using the definition for \( i_{pm} \), given in eqn. (3) then splitted into \( d-q \) components, and eliminating \( i_{pq} \) using eqn. (12) yields, with \( \psi_{pq} = 0 \).
\[ T_p \frac{di_{pm}}{dt} + i_{pm} = i_{cd} + (1 + \sigma_p) \frac{u_{pd}}{R_p} \tag{15} \]

\[ T_p i_{pm} \omega_p = i_{cq} + (1 + \sigma_p) \frac{u_{pq}}{R_p} \tag{16} \]

Where \( T_p = A_p / R_p \) is the equivalent PW stator time constant and \( \sigma_p = A_p / A_m - 1 \) is the equivalent leakage factor. Eqn. (15) shows that, since the influence of \( u_{pd} \) is small, \( i_{pm} \) can be controlled using \( i_{cd} \). The CW currents \( i_{cq} \), constitutes a degree of freedom and can be controlled via eqn. (12) to force the orientation of the reference frame along the stator flux vector position. Eqn. (16) could also be used to force the orientation however this is not a good approach in practice since \( i_{cq} \) is given by the difference between two larger quantities which are subject to noise. The orientation condition (eqn. (12)) also means that the PW stator flux angle is not derived from integration of the PW stator voltages, but can be derived directly from a free running integral of the stator PW voltage frequency demand \( \omega_p^* \).

\[ \theta_p = \int \omega_p^* dt \tag{17} \]

Eqn. (17) forces the PW stator flux to rotate at the reference frequency during both steady state and dynamic conditions for any shaft rotational velocity. This has the benefits of that the orientation is shielded from measurement noise and PW stator voltage harmonics in a stand-alone application. With this control scheme, \( i_{cq} \) no longer be used to control the generator torque as in the case of grid connected BDFIG [2, 3]. In this case the torque is entirely appropriate for capture the maximum energy available in the wind through controlling the load power. The generator torque is given by:

\[ T_e = 3 \left( p_p + p_c \right) A_m^2 i_{pm} i_{cq} / \left( 2 A_p \right) \tag{18} \]

It is clear that a change in the load power is reflected in a change in \( i_{pq} \), hence \( i_{cq} \), and \( T_e \).

\[ i_{pm} = \psi_{pd} / A_m \tag{19} \]

\[ \psi_{pd} = \psi_{p\alpha} \cos \theta_p + \psi_{p\beta} \sin \theta_p \tag{20} \]
\[ \psi_{pab} = \int \left( u_{pab} - R_p i_{pab} \right) dt \]  

(21)

Where \( \alpha, \beta \) denotes the PW stator stationary reference frame. The angle \( \theta_p \) is used to demodulate both the PW stator flux. The derived \( i_{pm} \) is compared with the reference value and the error forms the command \( i^*_{pq} \) via a controller as shown in Fig. 3, the \( i_{pm} \) closed-loop was designed.

3.2. CW stator Current Control Loops

Substituting CW stator flux linkage vector equ. (14) To CW stator voltage vector equ. (3), and systematizing it, then, the instantaneous CW stator voltage can be derived as:

\[ U_c = R_c I_c + \sigma A_c dI_c / dt + j \omega_s \sigma A_c I_c + j \omega_s A_m \left( A_p \psi_p \right) + \left( A_m / A_p \right) d\psi_p / dt \]  

(22)

Splitting it into \( d-q \) components then, the relationship between the CW stator voltages and the currents is obtained:

\[ u_{cd} = R_c i_{cd} + \sigma A_c d i_{cd} / dt - \omega_s \sigma A_c i_{cq} + \left( A_m / A_p \right) d\psi_p / dt \]  

(23)

\[ u_{cq} = R_c i_{cq} + \sigma A_c d i_{cq} / dt + \omega_s \sigma A_c i_{cd} + \omega_s \psi_p A_m / A_p \]  

(24)

Figure 4. Plant of the CW stator current control loop.

During well regular operation, when the PW stator terminal voltage is constant in amplitude, the derivative of the flux \( \psi_p \) is zero and therefore the last term of the equ. (23) Disappears. The resulting equations are graphically represented in the block diagram of Fig. 4. From the control point of view, the term \( \omega_s A_c \psi_p A_m / A_p \) of the equ. (24) is a perturbation, since it depends on the PW stator flux, an external variable independent of the loop. As it is constant, it will easily be compensated for by the controller. The cross terms appear because the reference frame turns at a different speed than the CW stator terminals. Although these terms are constant during a permanent regime and do not affect the functioning of the control loops, frequently they are estimated and compensated for by the control to
notably reduce its negative effects during transitory stages, as shown in Fig. 5. By compensating the cross terms, the control loop employing proportional integral controllers is notably simplified. Both axes are now identical and their plant is now reduced to a first-order transfer function.

Figure 5. CW stator current control loop with feed-forward compensation of the cross terms.

3.3. Reference Frame Coordinate Transformations

In this control scheme as described, CW stator voltage and current magnitudes are expressed in a PW stator common synchronous rotating d-q reference frame. To express a magnitude \( Y \) from the CW stator (\( p_c \)-type pole pairs) stationary \( \alpha-\beta \) reference frame transform into PW stator (\( p_p \)-type pole pairs) common synchronous rotating d-q reference frame, the following relation can be used.

\[
Y^{dq_p} = e^{-j\theta_c}Y^{\alpha\beta_c} = e^{-j[\theta_p - (2\pi p_c/(p_p + p_c))(\theta_p + \chi) - p_c\kappa]}Y^{\alpha\beta_c}
\]  

(25)

Figure 6. The CW and PW stator reference frames.

The spatial relationship of CW and PW stator reference frames and reference axis is shown in Fig. 6(a), it should be noticed that rotor position angular \( \theta_p \) measurement is needed to transform CW stator stationary reference frame to PW synchronous rotating reference frame. The initial rotor position \( \chi \) is needed to
obtain correct alignment. The coefficient $\kappa$ is the mechanical angular displacement between the two windings of the stator. The different mechanical angular is shown in Fig. 6(b).

### 3.4. Control System Implementation

Based on the developed control strategies, the overall schematic diagram of proposed indirect PW stator flux orientated vector control for a stand-alone operation BDFIG system is shown in Fig. 7. As can be seen and previously described, the PW stator magnetizing current can be directly estimated according to equs. (19) - (21). The demanded CW stator $d$-$q$ axis reference currents is obtained according to equ. (12) and Fig. 3 respectively. The dual independent regulation paths are implemented as in the vector control schemes: one path regulates the $d$-axis CW currents to directly control the PW voltage magnitude and the other is dedicated to control $q$-axis CW currents to force orientation. The PI controllers are acted on the $d$-$q$ axis CW current components errors and feed-forward compensations are employed so as to enhance transient performance. Besides, it is worth noting that the proposed control scheme is implemented in the PW stator common synchronous rotating reference frame hence synchronous rotating coordinate transformations and angular information involved. Finally, the space vector modulation technique is employed to generate the required switching voltage vectors and their respective duration times based on the required average CW stator voltage vector, thus, achieve fixed switching frequency which results in deterministic narrowband harmonic spectra with dominant harmonics around the carrier frequency and its multiples.

![Figure 7](image_url)

**Figure 7.** Schematic diagram of the proposed control strategies for a stand-alone operation BDFIG.

### 4. Simulation and Discussion

In order to verify the performance and effectiveness of the proposed control strategy, the Matlab simulation tests were carried out on the prototype BDFIG whose parameters is shown in Table I respectively. The CSC and LSC are fed by an insulated gate bipolar transistor (IGBT) based PWM VSC, the AD sampling and switching frequencies are 2 kHz and 1 kHz, respectively. The simulation tests were performed as follows. The DC-link voltage is 600 V invariably. The reference amplitude and frequency of the PW stator terminal voltage is set at 440 V and 50 Hz respectively in both case.
The stand-alone operation BDFIG fed with a linear balanced loads is run at super-synchronous rotor rotational velocity of 1.067 p.u. (800 rpm), and a sudden resistance and inductance impact load at 0.35s, then lasts for 0.35s, and dump load at 0.7s, it inevitably draws sudden varying high inrush current. As Fig.8(a)-(f) illustrated, even if the controlling bandwidth frequency is not high, both the amplitude and frequency of the PW stator terminal voltage are constant and accurately consistent with reference value, and sinusoidal PW stator voltage was generated with low harmonic distortion. The CW stator frequency is equal to 3.33 Hz, and met the relationship of Equ. (1) To maintain constant PW stator frequency. Only in the moment of load sudden change, the PW stator voltage has a slight transient fluctuation, the instantaneous PW stator voltage drop and the overshoot is negligibly small, and they can be recovered to the set reference values within few cycle by regulating the CW stator currents rapidly with the load currents changed. The stand-alone BDFIG operation is satisfactory.

**Table 1.** The prototype BDFIG specification

| Parameter            | Value      | Parameter            | Value      | Parameter            | Value      |
|----------------------|------------|----------------------|------------|----------------------|------------|
| frame size           | D250       | rotor type           | Wound      | capacity             | 30kVA      |
| PW pole-pairs        | 1          | CW pole-pairs        | 3          | PW connection        | star       |
| PW rated volt.       | 380V       | CW volt.             | 0-350V     | CW connection        | star       |
| PW rated freq.       | 50Hz       | CW freq. range       | -10-30Hz   |                       |            |
| PW rated current     | 45A        | CW current range     | 0-40A      |                       |            |
|                       | R_p        | L_r                  | 0.0366H    | L_mc                 | 0.3359H    |
|                       | 2.73 ohm   |                       |            |                      |            |
|                       | L_{app}    |                       | 0.1175H    | L_c                  | 0.4977H    |
|                       | 1.16ohm    |                       |            |                      |            |

![Waveform of stand-alone BDFIG’s performance with load sudden change (t: 0.1s/div)](image)

**Figure 8.** Waveform of stand-alone BDFIG’s performance with load sudden change (t: 0.1s/div)

The dynamic performances of this proposed control method are observed at continuous variation wind turbine speed as shown in Fig.9 (a)-(f). For vary in wind speed, the rotational velocity is also varying. In this case, the rotational velocity will be decreased from super-synchronous velocity of 1.267 p.u. (950 rpm) to sub-synchronous velocity of 0.733 p.u. (550 rpm) during 0.9s with a constant linear
balanced loads. It can be observed that the PW stator terminal voltage are stably maintained constant responding to reference value and independent of the rotational velocity variation, the CW stator currents frequency accordingly change depending upon rotational velocity, and met the relationship of Equ. (1). To maintain constant frequency of the PW stator terminal voltage. Specialty, it is worth noting that during a transition synchronous velocity, the phase sequence of CW stator currents is changed, which is manifested the sign of the CW stator frequency reversed, in corresponding natural synchronous velocity, the frequency of CW stator currents is zero. Furthermore, the load and PW stator current is constant, and the amplitude of CW stator current is same to maintain constant amplitude of the PW stator terminal voltage, in spite of change in rotational velocity, nevertheless, the amplitude of CW stator voltage is varied depending on the rotational velocity to balance the varying back EMF. Moreover, in this whole process, both the PW stator and CW stator were running smoothly, and thus constant and sinusoidal PW stator terminal voltage was generated with low harmonic distortion. In both cases, the generator proves good power output performance.

![Waveform of stand-alone BDFIG's performance with varying rotational velocity](image)

**Figure 9.** Waveform of stand-alone BDFIG’s performance with varying rotational velocity ($t$: 0.1s/div)

### 5. Conclusion

This paper has addressed the stand-alone operation BDFIG control solution for variable speed constant frequency wind energy conversion systems. Based on the simplified model of the BDFIG, the corresponding excitation control model for stand-alone operation according to control target is established, and how to deal with system coupling is researched. The pretty well contribution of the proposed control method is to regulate the CW stator current appropriately employing indirect PW stator flux orientated vector control, and results in constant generator terminal voltage. The theory analysis and experiment results are all shown that the PW stator output voltage and flux for stand-alone BDFIG are only determined by the equivalent PW stator magnetizing current, which are independent of load but PW stator port output power is only determined by load. Then, enhanced transient performance and steady-state harmonic spectra is achieved.
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