Robust Position Observer for Sensorless Direct Voltage Control of Stand-Alone Ship Shaft Brushless Doubly-Fed Induction Generators

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Abstract—The aim of this paper is to investigate an adaptive sensorless direct voltage control (DVC) strategy for the stand-alone ship shaft brushless doubly-fed induction generators (BDFIGs). The proposed new rotor position observer using the space vector flux relations of BDFIG may achieve the desired voltage control of the power winding (PW) in terms of magnitude and frequency, without any speed/position sensors. The proposed algorithm does not require any additional observers for obtaining the generator speed. The proposed technique can directly achieve the desired DVC based on the estimated rotor position, which may reduce the overall system cost. The stability analysis of the proposed observer is investigated and confirmed with the concept of quadratic Lyapunov function and using the multi-model representation. In addition, the sensitivity analysis of the presented method is confirmed under different issues of parameter uncertainties. Comprehensive results from both simulation and experiments are realized with a prototype wound-rotor BDFIG, which demonstrate the capability and efficacy of the proposed sensorless DVC strategy with good transient behavior under different operating conditions. Furthermore, the analysis confirms the robustness of the proposed observer via the machine parameter changes.

Index Terms—Brushless doubly-fed induction generator (BDFIG), direct voltage control (DVC), PW voltage-oriented vector control, rotor position observer, ship shaft applications.

I. INTRODUCTION

The brushless doubly-fed induction generator (BDFIG) is a promising machine in adjustable control drive applications for its high structural reliability. Usually, BDFIG has two isolated windings arranged in the same fixed frame, i.e. the power winding (PW) and the control winding (CW) [1]. Both of the windings have different pair-poles to prevent the direct coupling between them. The rotor structure mainly determines the magnetically coupling effect between PW and CW. The wound rotor structure is more distinguished with respect to the cage and reluctance types for its flexible and simple arrangement. The main merit of BDFIG based wound-rotor is the efficient usage of windings in rotor frame with a high reduction in the rotor harmonics and referred leakage reactance as described in the most recent literatures [2].

In recent years, the electric power generation is necessary in ship applications for supplying its various loads such as the operational equipment and crew accommodation (e.g. galley and cabin lighting). For this aim, the driven generator will in turn consumes large quantities of the ship fuel which increases the cost, air pollution and the system maintenance. Saving in fuel consumption is an important issue for a ship and is attracting significant attention nowadays.

A ship shaft power generator driven by the main engine can generally reduce the fuel consumption and hence improve the overall ship system efficiency [1]. Therefore, the ship shaft generator has become an effective component in the ship power generation systems which will influence with its great role on the overall efficiency in terms of fuel cost, maintenance requirements, and reliability issues.

BDFIGs also give superior performance for their application in wind power [3] and ship shaft generation systems [1] with its reliable and flexible configuration [4]-[6]. Therefore, the BDFIGs involved in ship shaft applications has become a promising interested area for research work [1].

The operational case for ship shaft power generation systems comprises of two modes, i.e. the grid-connected mode and the stand-alone generation mode. The main target for grid-connected systems is to control the generator power flow (active and reactive power). In [3], [7], the preferred vector-control technique is used to attain the desired control objectives in terms of active and reactive power for a
grid-connected BDFIG system under different operating conditions.

On the other hand, the main task of the control system in the stand-alone applications is to regulate the generated voltage (magnitude and frequency) by applying the direct voltage control (DVC) scheme under various operating conditions.

Many different control schemes were presented in [8]-[16] for stand-alone operation of BDFIGs. The poor dynamic performance is the main demerit of the scalar voltage control method [9]. In [1], [10], [15], a CW current-orientation technique-based DVC method was presented to improve the performance. Moreover, in [14], the reactive-current transient control technology via the control of line-side converter in ship shaft BDFIG system is also discussed for the high-quality generated voltage.

Most of these control strategies are based on the knowledge of the rotor speed/position from an encoder. The required rotor position signal is needed to realize the desired angle of frame transformation for CW-side variables. In [3], the speed signal was used to attain the desired CW current based on the feedforward component. In [9] and [14], the desired CW frequency was obtained using the sensing speed signal with the principle of scalar control technology. In [11], the control objective of PW frequency was realized from the corresponding CW frequency and from the actual speed of the generator.

However, the encoder in most drive systems is undesirable because it increases the system cost and decreases the system reliability, besides the need of shaft extension and mounting arrangement. For a robust and low-cost operation of BDFIG, it is required to use a sensorless control scheme [1], [17]. To ensure better performance, the simplicity and robustness of the speed/position estimation method is the main target in the sensorless DVC systems.

From the point of control view, the main procedure of DVC strategy for stand-alone generation systems is dependent on the knowledge of the rotor position signal. Therefore, the main target of sensorless algorithm for DVC is to effectively estimate the rotor position of the generator. This aim can be realized by either directly detecting the position signal or estimating the machine speed and then integrate it to obtain the desired rotor position. For simplicity purpose and to reduce the overall system cost, the direct estimation of rotor position is the main challenge for DVC target.

Different techniques for speed estimators have been developed day by day which are based on either model or signal methodologies [18], [19]. However, very few publications have handled the direct estimation methods of rotor position signal for brushless doubly fed machines [20]. Furthermore, according to the author’s knowledge, the sensorless DVC strategy without any observation for the speed signal [21] based on the direct detection of rotor position is not discussed for wound-rotor BDFIGs in ship shaft stand-alone systems, as yet.

This paper aims at proposing an adaptive sensorless control strategy for regulating the load-side voltage with the principle of DVC for the adopted ship shaft stand-alone BDFIG, without the need of any speed or position sensors. A new simple rotor position observer is proposed using the generator space-vector flux relations. In addition, the effectiveness of the proposed observer is tested under different operating conditions including the speed and load changes. Moreover, the stability analysis of the new observer is investigated and validated with the concept of quadratic Lyapunov function and using the multi-model representation. Furthermore, the sensitivity analysis of the proposed sensorless system is also assured with different uncertainties.

II. STRUCTURE AND MODELING OF BDFIG

A. Main Structure and Operation

In a BDFIG, the stator side is composed of two windings separated in the same frame with different pair-poles [1]. The PW is considered as the primary winding with a direct connection to the load side and \( p_1 \) pair-pole. Furthermore, the CW is considered as the secondary winding, with \( p_2 \) pair-pole, which is generally connected through a bi-directional power electronic converter with the load side.

On the other hand, the wound-rotor configuration is the main structure of the rotor side for its high electrical efficacy compared with other rotor configurations [2]. As briefly discussed in Ref. [2], the effect of copper losses associated with the internal resistance of the rotor windings will not have much impact on the overall performance of the adopted BDFIG due to the great benefits resulted from the high reduction in the rotor harmonics and referred leakage reactance.

The mechanical speed relation [1], at which the adopted BDFIG should rotate, can be written as

\[
\omega_{rm} = \frac{\omega_1 + \omega_2}{p_1 + p_2}
\]

where \( \omega_1 \) and \( \omega_2 \) denote the PW and CW electrical angular frequency, respectively.

Generally, the operational states of the adopted BDFIG can be classified into three modes (synchronous, sub-synchronous, and super-synchronous) depending on the CW frequency, \( \omega_2 \). The synchronous mode represents the natural speed, \( \omega_n \), at which \( \omega_2 \) is equal to zero. Moreover, the low-speed operation (below its natural value) and the high-speed operation (above its natural value) denote the sub-synchronous and the super-synchronous modes, respectively. Aided with (1), the control of PW frequency can be attained based on the variation of \( \omega_2 \) along with the mechanical speed changes according to

\[
\omega_2 = (p_1 + p_2) \omega_{rm} - \omega_1
\]

B. Modeling of BDFIG

This subsection presents a complete dq model of the presented BDFIG [10].

The intended dq-axis voltages of the generator windings can be represented, in the arbitrary frame \( \omega_n \), as
where \( s \) is the differential operator \( d/dt \). The PW and CW dq-axis voltage components are denoted as \( u_{1dq} \) and \( u_{2dq} \), respectively. Also, \( i_{1dq} \), \( i_{2dq} \) and \( i_{2dq} \) are the PW, CW and rotor-winding dq-axis current components, respectively. In addition, \( \Psi_{1dq} \), \( \Psi_{2dq} \) and \( \Psi_{rdq} \) are the PW, CW and rotor-winding dq-axis flux linkages, respectively. Moreover, \( R_1 \), \( R_2 \) and \( R_r \) are the PW, CW and rotor-winding resistances, respectively. Furthermore, \( \omega_a \) denotes the angular speed of dq-axis reference frame.

Furthermore, the corresponding relations of the dq-axis flux linkage are written with respect to PW, CW, and rotor side, as

\[
\begin{align*}
\Psi_{1d} &= L_1i_{1d} + L_{1r}i_{rd}
\Psi_{1q} &= L_1i_{1q} + L_1i_{rd}
\Psi_{2d} &= L_2i_{2d} + L_2i_{rd}
\Psi_{2q} &= L_2i_{2q} + L_2i_{rd}
\Psi_{rd} &= L_r i_{rd} + L_1i_{1d} + L_2i_{2d}
\Psi_{rq} &= L_r i_{rq} + L_1i_{1q} + L_2i_{2q}
\end{align*}
\]  

where \( L_1 \), \( L_2 \) and \( L_r \) are the PW, CW and rotor-winding self-inductance, respectively. In addition, \( L_{1r} \) is the coupling-inductance between the PW and the rotor-winding. Moreover, \( L_{2r} \) represents the coupling-inductance between the CW and the rotor-winding.

By ignoring the whole copper losses of both the PW, CW, and the rotor winding, the corresponding active-power relationship between the PW side, \( P_1 \), and the CW side, \( P_2 \), is expressed as

\[ P_1 = P_2 = \frac{P_m}{\omega_2} \]  

Aided with (5), the power flow between the stator two windings can be considered for the adopted stand-alone system based BDFIG. As mentioned before and aided with (2), the CW frequency, \( \omega_2 \) can be with a positive or a negative value under the super-synchronous and the sub-synchronous modes, respectively. Therefore, and according to (5), the direction of the CW power flow is based on the mode of operation. In other words, the PW always outputs the active power to the load side. However, the active power of CW can be extracted from the windings to the load under the super-synchronous mode and can be absorbed to the windings under the sub-synchronous mode. The power balance equation is the same for both modes and can be described as

\[ P_m = P_1 + P_2 = P_{out} \]  

where the input mechanical power from the prime mover is denoted as \( P_m \), and the output active power to the load side is represented as \( P_{out} \).

From which, the input mechanical torque of the prime mover is expressed as

\[ T_m = \frac{P_m}{\omega_{rm}} \]  

III. CONTROLLER DESIGN ASPECTS FOR DVC PURPOSE OF STAND-ALONE BDFIG

The main configuration of a proper ship shaft BDFIG system is shown in Fig. 1. The generator prime mover is represented in the main engine. The BDFIG is connected to the load terminals with its PW (directly connected) and CW (connected through a bidirectional converter), as shown in Fig. 1.

**A. Current Control Topology of CW side**

In order to control the CW current, the set value of the d-axis CW current, \( i_{2d}^* \), is directed to the desired current magnitude of \( i_{2d} \). To obtain this target, the reference q-axis CW current, \( i_{2q}^* \), is adjusted to be equal zero. The CW-side current control loop is illustrated in Fig. 2.

Aided with [11], the following relationship expressions can be obtained as

\[ i_{2d} = K_d u_{2d} + D_d \]  

\[ i_{2q} = K_q u_{2q} + D_q \]  

**Fig. 1. System stucture of the ship shaft stand-alone BDFIG.**

**Fig. 2. CW-side current control loop.**
where, $D_d$ and $D_q$ are the cross-coupling relations between PW and CW and can be given as in [11]. In addition, $K_d$ and $K_q$ denote the direct relationship between the CW $dq$-axis current and voltage components and can be expressed as

$$K_d = K_q = 1/(R_2 + \sigma_2 L_2 \rho)$$

$$\sigma_2 = 1 - L_2 \rho^2 / (L_2 L_r)$$

B. Control Design for DVC Strategy

In Ref. [10], a DVC strategy has been studied and implemented for ship shaft BDFIG system where the rotor position signal is detected using an encoder. The control of the PW voltage in terms of magnitude and frequency is the main target of this strategy.

The PI controller is adjusted to regulate the magnitude of CW current, $I_2$ which in turns will keep the magnitude of PW voltage to be constant along with both the speed and load variations. Furthermore, the PW frequency control is obtained through the adjustment of CW frequency, aided with (2), under the BDFIG speed changes.

According to (2), the mechanical speed signal, $\omega_{rm}$, is required for this control method. By measuring the rotor position, $\theta_{rm}$, the speed signal can be attained through the differential operator. The low-pass filter is used to clear the speed signal from any noise resulted from the differentiation step.

In order to get a high performance, the current control topology of CW side is applied. To obtain this target, the reference $q$-axis CW current, $i_{2q}^\star$, is adjusted to be equal zero. Hence, the set value of the $d$-axis CW current, $i_{2d}^\star$, is directed to the desired current magnitude of CW, $I_2^\star$. Based on the presented control loop of CW current, the required pulses of the machine-side converter, shown in Fig. 1, can be obtained based on the intended set values of PW voltage.

IV. SENSORLESS DVC STRATEGY BASED ON THE PROPOSED NEW ROTOR POSITION OBSERVER

A. Overall DVC System based on PW Voltage-Oriented Vector Control

From the point of view for vector control target and aided with (3), the controllable vector quantities appear as $dq$-components based on the selection of $\omega_l$ and $\omega_2$ rotating frames. Fig. 3 illustrates the relationship of the BDFIG phase-axis. It is obvious from Fig. 3 that the alignment of the reference frame $d$-axis with its total vector is attained to obtain the intended orientation of PW voltage for DVC purpose. This is realized by adjusting the PW $d$-axis voltage, $u_{1d}$, to be directed to the total PW voltage ($u_{1d} = U_1$) and hence, the PW $q$-axis voltage, $u_{1q}$ is set to be equal to zero ($u_{1q} = 0$).

Fig. 4 illustrates the block diagram of the proposed sensorless voltage-oriented vector control strategy for DVC of the ship shaft stand-alone BDFIG.

The PW $d$-axis voltage, $u_{1d}$, tracks the desired PW voltage magnitude, $U_1^\star$, as illustrated in Fig. 4. This can be attained through the adjustment of the reference CW current magnitude, $i_{2d}^\star$, aided with the current loop of CW side by setting ($i_{2q}^\star = 0$).

Furthermore, the PW $q$-axis voltage, $u_{1q}^\star$, is set to zero through the regulation of the intended frame frequency of PW voltage, $\omega_l$. From which, the corresponding angle, $\theta_l$, is obtained to realize the desired orientation target of the PW voltage through the alignment of the reference frame $d$-axis with the PW voltage vector.

Aided with the estimated rotor position, $\theta_{r, est}$ which will be obtained in details in the next subsection based on the proposed robust observer, the corresponding angle $\theta_l^\star$ can be realized directly using the angle $\theta_l^\star$ calculated from the integration of the reference PW frequency, as illustrated in Fig. 4. The proposed position observer is used directly for sensorless DVC without any need to obtain the angular speed using any additional observation methods [20], [22]. This ensures the reliability and efficacy of the proposed strategy for sensorless DVC of BDFIG systems.

B. Design of the Proposed New Methodology for Rotor Position Observer

The main target of sensorless algorithm for DVC is to effectively predict the rotor position of the generator. This aim can be realized by either directly detecting the position signal or estimating the machine speed and then integrate it to obtain the desired rotor position. For simplicity purpose and to reduce the overall cost of the control system, the direct estimation of rotor position signal is the main challenge for DVC target.

In an attempt to fill this void, this paper aims at proposing a theoretical approach for predicting the position signal of the adopted wound-rotor BDFIG using the space-vector flux relations without the need for speed integration or any additional observation methods to obtain the speed signal.

Based on the rotor-winding $dq$-axis voltage equations (3), the space-vector rotor flux linkage, $\Psi_r$, can be represented, in the PW synchronous frame, at steady state as

$$\Psi_r = -R_r I_r \frac{j(\omega_l - p_1 \omega_{rm})}{j(\omega_l - p_1 \omega_{rm})}$$

where ‘$I_r$’ denotes the space-vector rotor current and ‘$j$’ represents the unit imaginary.

It should be noted that the resistance of the BDFIG
rotor-winding, $R_r$, has a small value for a well-designed generator and the rotor current, $I_r$, is below or equal to the rated value in steady state. In addition, the corresponding value of the term $(\omega_1 - p_1 \omega_m)$ is larger for the adopted BDFIG and hence, the resulted value of the term $[R_r I_r J (\omega_1 - p_1 \omega_m)]$ would be very small. Consequently, the rotor flux, $\Psi_r$, is so smaller which can be approximately equals to zero, $\Psi_r \approx 0$.

Based on the dq-axis flux linkage relations (4), the space vector flux linkage of PW and rotor windings, $\Psi_1$ and $\Psi_r$, respectively, can be expressed as

$$
\begin{align*}
\Psi_1^{PW} &= L_1 I_1^{PW} + L_2 I_2^{PW} \\
\Psi_r^{PW} &= L_r I_r^{PW} + L_2 I_1^{PW} + L_2 I_2^{PW}
\end{align*}
$$

(11)

where ‘$I_1$’ and ‘$I_2$’ denotes the space-vector of PW and CW currents, respectively. In addition, the superscript ‘$PW$’ represents the PW stationary $\alpha\beta$ reference frame.

Aided with (11) and using the assumption $\Psi_r \approx 0$, then the rotor current is expressed as

$$
I_r^{PW} = -\frac{L_r I_1^{PW}}{L_r} - \frac{L_2 I_2^{PW}}{L_r}
$$

(12)

Substituting (12) into (11), the space vector of CW current is simplified as

$$
I_2^{PW} = \frac{\Psi_1^{PW} - A_p I_1^{PW}}{A_m}
$$

(13)

where $A_p = L_1 - L_2^2 / L_r$ and $A_m = -L_1 L_2 / L_r$.

The transformation from the PW stationary $\alpha\beta$ frame to the corresponding CW stationary $\alpha\beta$ frame can be given as

$$
I_2^{PW} = e^{j\omega_1} \left( I_2^{CW} \right)^{conj}
$$

(14)

where ‘$conj$’ is the conjugate of vector. Moreover, the superscript ‘$CW$’ is the CW stationary $\alpha\beta$ reference frame.

Substituting (12) in (11), the estimated rotor position can be derived as

$$
e^{j\theta_{est}} = \frac{\Psi_1^{PW} - A_p I_1^{PW}}{A_m} I_2^{CW}
$$

(15)

By measuring the terminal voltages and currents of PW side, the associated $dq$-axis components can be obtained using the $abc$/$dq$ transformation with the angle, $\theta_1$ which will be obtained based on the presented PW voltage-orientation loop as described in the previous section.

Then, the corresponding PW $dq$-axis flux linkages can be calculated, aided with (3) and assuming that the flux of PW side can be considered as fixed in one sampling period, as

$$
\Psi_{id} = \left( u_{iq} - R_i i_{iq} / \omega_1 \right)
$$

$$
\Psi_{iq} = \left( -u_{id} + R_i i_{id} / \omega_1 \right)
$$

(16)

From which and using the $dq/\alpha\beta$ transformation with the angle $\theta_1$, the $\alpha\beta$-axis PW flux linkage relations, $\Psi_{1\alpha\beta}$, can be easily obtained without any voltage-integration to obtain the flux linkage. On the other hand, the $\alpha\beta$-axis PW and CW currents are also evaluated using the $abc/\alpha\beta$ transformation of the measured three-phase currents of PW and CW.

Flowchart of the proposed rotor position observer is shown in Fig. 5.

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**Flowchart of the Proposed Rotor Position Observer**

Fig. 4. The proposed sensorless DVC system for the adopted BDFIG.
Finally, the estimated rotor position can be represented, based on (15) and using the $\alpha\beta$-axis components, as

$$\theta_{\text{rest}} = N + j M$$  \hspace{1cm} (17)

From which,

$$\theta_{\text{rest}} = \tan^{-1} \frac{M}{N}$$  \hspace{1cm} (18)

where,

$$M = \left( \Psi_{1\alpha} - A_p i_{1\alpha} \right) i_{2\beta} + \left( \Psi_{1\beta} - A_p i_{1\beta} \right) i_{2\alpha}$$

$$N = \left( \Psi_{1\alpha} - A_p i_{1\alpha} \right) i_{2\alpha} - \left( \Psi_{1\beta} - A_p i_{1\beta} \right) i_{2\beta}$$  \hspace{1cm} (19)

C. Stability Analysis of the Proposed Position Observer

In order to ensure the efficacy of the introduced position observer for sensorless DVC, the stability issue of the whole control system should be clearly satisfied.

Considering that the sensorless system is started with an error between the predicted position, $\theta_{\text{rest}}$, and the actual value, $\theta_r$. Therefore, the actual $d$-$q$ frame allocated on the PW $\alpha\beta$-axis stationary reference frame, used to get $\dot{I}_1^{\text{PW}}$ in (14), cannot be localized. Therefore, a fictitious reference frame $d'$-$q'$ is used as illustrated in Fig. 6.

The error between the two frames is determined as the estimation error of rotor position $\phi = (\theta_{\text{rest}} - \theta_r)$. This position error will result in a coupling component $\Delta I_2^{\text{PW}}$ to be appeared in the $q'$-axis. Consequently, this coupling term can be completely omitted by controlling the estimation error to be equal to zero.

Based on the fictitious reference frame $d'$-$q'$, presented in Fig. 6, the coupling component $\Delta I_2^{\text{PW}}$ can be expressed as

$$\Delta I_2^{\text{PW}} = \left( e^{j\theta_{\text{rest}}} - e^{j\theta_r} \right) \left( I_2^{\text{CW}} \right)^{\text{conj}}$$  \hspace{1cm} (20)

$$\Delta I_2^{\text{PW}} = (e^{j\phi} - 1)e^{j\theta_r} \left( I_2^{\text{CW}} \right)^{\text{conj}}$$  \hspace{1cm} (21)

Therefore, aided with (13)

$$\Delta I_2^{\text{PW}} = \frac{\Psi_{1\text{PW}}^{\text{PW}} - A_p I_1^{\text{PW}}}{A_m} (e^{j\phi} - 1)$$  \hspace{1cm} (22)

By considering the speed estimation error as

$$\Delta \omega_m = K_o (\Delta I_2^{\text{PW}} + \frac{1}{K_i} \int \Delta I_2^{\text{PW}} \, dt)$$  \hspace{1cm} (23)

Then, the derivative formula of the error in position estimation is given as

$$\frac{d}{dt} \phi = (p_1 + p_2) K_o (\Delta I_2^{\text{PW}} + \frac{1}{K_i} \int \Delta I_2^{\text{PW}} \, dt)$$  \hspace{1cm} (24)

where $K_o$ and $K_i$ are the control parameters for the adopted the sensorless system.

$$\frac{d}{dt} \left[ \begin{array}{c} \sigma \\ \phi \end{array} \right] = \left[ \begin{array}{cc} 0 & B_2 f(\phi) \\ K_i & B_2 B_1 f(\phi) \end{array} \right] \left[ \begin{array}{c} \sigma \\ \phi \end{array} \right]$$  \hspace{1cm} (25)

where

$$B_1 = \frac{\Psi_{1\text{PW}}^{\text{PW}} - A_p I_1^{\text{PW}}}{A_m}, \quad B_2 = (p_1 + p_2) K_o$$

with $\sigma = \int \Delta I_2^{\text{PW}} \, dt$ and

$$f(\phi) = \frac{e^{j\phi} - 1}{\phi}$$  \hspace{1cm} (26)

It is dedicated that $f(\phi)$ is a continuous even function and $f(0)$ =1. Hence, the stability domain of (26) is expected to be symmetric at $\phi = 0$ (desired operating point).

To verify the stability of the large system signal, the multi-model is used to represent (26) as

$$\dot{x} = \left[ \mu_1 (\phi) \cdot D_1 + \mu_2 (\phi) \cdot D_2 \right] \cdot x$$  \hspace{1cm} (27)

For $0 \leq \text{absolute}(\phi) \leq \phi_{\max}$ with $x = [\sigma \quad \phi]'$

$$\mu_1 (\phi) = \frac{f(\phi) - f(\phi_{\max})}{1 - f(\phi_{\max})}$$

$$\mu_2 (\phi) = \frac{1 - f(\phi)}{1 - f(\phi_{\max})}$$  \hspace{1cm} (28)
D_1 = \begin{bmatrix}
0 & B_1 \\
B_2 & \frac{B_2}{K_i}
\end{bmatrix}, \quad D_2 = \begin{bmatrix}
0 & B_1 f(\varphi_{\text{max}}) \\
B_2 & \frac{B_2}{K_i} B_1 f(\varphi_{\text{max}})
\end{bmatrix}

It can be observed that both (26) and (27) are totally equivalent: no approximation, no linearization and no simplification are done. Also, considering that equivalent: no approximation, no linearization and no approximation:

\[ \mu_1(\varphi) + \mu_2(\varphi) = 1 \]
\[ \mu_1(\varphi) \geq 0 \]
\[ \mu_2(\varphi) \geq 0 \]

To confirm the stability analysis of the adopted sensorless system (27), the following quadratic Lyapunov function is determined as

\[ V(x) = x^t \cdot M \cdot x \]
\[ M = M^t > 0 \]

Aided with the above analysis, it is noted that the proposed sensorless control system, both (26) and (27), is stable by getting a symmetric matrix, \( M \), achieving the following

\[ M > 0 \]
\[ (D_1^t \cdot M + M \cdot D_1) > 0 \]
\[ (D_2^t \cdot M + M \cdot D_2) > 0 \]

The convergence domain is defined by determining the maximum position error, \( \varphi_{\text{max}} \), related to the linear matrix inequalities obtained in (31). Finally, and aided with above relations, it is dedicated that the estimation of the convergence domain can be concluded as \( 0 \leq \text{absolute}(\varphi) \leq 90 \). This verify that the theoretical convergence domain is the largest possible which confirms the stability of the proposed sensorless position observer.

V. SIMULATION RESULTS

In this section, the simulation analysis is introduced to ensure the functionality of the proposed sensorless vector control strategy for DVC target based on the presented new rotor position observer.

The obtained results are based on a 30-kVA wound-rotor BDFIG with main parameters illustrated in Table I. Moreover, the intended set values of the PW voltage magnitude and frequency are adjusted at 311 V and 50 Hz, respectively.

| PARAMETER | VALUE |
|-----------|-------|
| Capacity  | 30 kVA |
| Range of speed | 600 –1200 rpm |
| \( p_1, p_2 \) | 1, 3 |
| PW voltage and current | 380 V, 45 A |
| Range of CW voltage | 0–350 V |
| Range of CW current | 0–40 A |
| \( R_1, R_2, R_c \) | 0.4034 \( \Omega \), 0.2680 \( \Omega \), 0.3339 \( \Omega \) |
| \( L_1, L_2, L_c \) | 0.4749 H, 0.03216 H, 0.2252 H |
| \( L_{1r}, L_{2r} \) | 0.3069 H, 0.02584 H |

A. Effectiveness of the Proposed Rotor Position Observer

This subsection aims at confirming the capability of the proposed new rotor position observer for sensorless DVC of the adopted BDFIG in the stand-alone ship shaft applications under both speed and load variations.

During the first operating condition, the load is kept constant and the speed is increased. Then, the dynamic behavior of the adopted BDFIG is studied while the load is changed under a constant speed.

Figs. 7(a), (b), (c), and (d) denote the actual and estimated rotor position during different operating conditions of speed and load changes with both the dynamic and steady state responses, PW dq-axis voltages and PW frequency, dq-axis CW current components, and PW & CW three-phase currents, respectively. The operation of the adopted BDFIG is started under the low-speed condition with 600 rpm while the applied resistive load is 11.6 kW. Then, the generator speed accelerates to the high-speed condition with 900 rpm and a rate change of 300 rpm per second from 2.5 s to 3.5 s while the load is the same. Finally, at \( t = 5.5 \) s, the speed is kept the same and the load is decreased from 11.6 to 9.7 kW. It is observed from Fig. 7(b) that the PW voltage successfully tracks the desired quantities for DVC purpose \((U_{1r}^* = 311 \text{~V} \text{~and} f_{1r}^* = 50 \text{~Hz})\).

In addition, it is obvious from Fig. 7(b) that the PW dq voltage components are kept fixed to attain the intended quantities \([u_{dq}^* = U_{1r}^*] \) and \([u_{dq}^* = 0] \) adjusted for the desired target of PW voltage orientation.

Moreover, the results ensure the good correlation between the estimated rotor position and its corresponding actual value, as illustrated in Fig. 7(a). This confirms the effectiveness of the proposed rotor position observer for sensorless DVC of stand-alone BDFIG.

Furthermore, Fig. 7(c) illustrates that the q-axis CW current tracks the desired value \((i_{dq}^* = 0) \) for the intended current control topology of CW side. This confirms the capability of the presented CW current controller.

B. Robustness Confirmation Against Parameter Uncertainty

It is obvious from (15) that the proposed position observer is dependent in its calculations on the parameters of the adopted BDFIG. In other words, and for example, it can be stated from (15) and (16), that the effectiveness of the presented calculations for the generator rotor position are dependent on the inductances that affect the value of the control parameter, \( A_p \) and also the correct estimation of the PW flux vector, \( \Psi_{\text{PW}} \), which in turn is dependent on the PW resistance. Therefore, the BDFIG parameter sensitivity is more important to verify the robustness of the proposed position observer and its effectiveness for sensorless DVC of the ship shaft stand-alone BDFIG under different uncertainties.

The variation effect of the machine inductances \((L_1, L_{1r}, L_c)\) on the value of the control parameter, \( A_p \), is checked, as shown in Fig. 8, by assuming a change of 30% increasing in this parameter which in turn means the same change percentage in the value of each of all these inductances.

In practical operation, the PW resistance can be changed.
with the winding temperature variations [23]. According to the generator designer, the maximum change in the temperature of the windings can be considered as 180 °C. Hence, the maximum change in the PW resistance can be considered as 130% as shown in Fig. 9.

Figs. 8 and 9(a), (b), (c), and (d) denote the actual and estimated rotor position during different operating conditions of speed and load changes with both the dynamic and steady state responses, PW dq-axis voltages and PW frequency, dq-axis CW current components, and PW & CW three-phase currents, respectively.

![Estimated and actual rotor position](image1)

![PW dq-axis voltages and frequency](image2)

![CW dq-axis currents](image3)

![Three-phase PW & CW currents](image4)

Fig. 7. Performance test of the proposed sensorless control system.

![Estimated and actual rotor position](image5)

![PW dq-axis voltages and frequency](image6)

![CW dq-axis currents](image7)

![Three-phase PW & CW currents](image8)

Fig. 8. Performance test of the proposed observer under 130% change in the machine inductances ($L_1, L_2, L_3$).
It can be concluded from Fig. 7, Fig. 8 and Fig. 9 that the effectiveness of the proposed rotor position observer and its capability for sensorless DVC strategy are not affected by any change in the adopted generator inductances and also the PW resistance. This confirms and proves the robustness of the adopted position observer and its efficacy for sensorless DVC of the adopted ship shaft stand-alone BDFIG system.

VI. EXPERIMENTAL RESULTS

To validate the functionality of the proposed control strategy, the progress towards the experimental work is completely outlined in this section. In addition, comprehensive results of experiments to investigate the proposed sensorless control strategy are also presented which ensures the effectiveness of the proposed rotor position observer. For this purpose, the preparation of the BDFIG setup and the control system are illustrated in Fig. 10.

In Table I, the detailed parameters are listed for the BDFIG. In addition, an induction motor with a power rating of 37-kW is used to drive the BDFIG and fed from a Siemens MM430 inverter. All required voltage and current signals for the proposed sensorless control system are provided by LEM LV 100 and LEM LT 208-S7/SP1 sensors, respectively.

A. Capability Confirmation of the Proposed Rotor Position Observer for Sensorless DVC Strategy

In this subsection, the obtained experiments are analyzed to validate of the proposed position observer under the start-up operation of the adopted BDFIG system.

In addition, the capability of the new observer for sensorless DVC is also confirmed under the whole operation period of the presented generating system through both the load variation state and the speed change condition. In the presented experimental results, the intended desired PW voltage in terms of the rms value and frequency are adjusted at 150 V and 50 Hz, respectively.

Firstly, the adopted BDFIG is started with a mechanical rotor speed of 600 rpm and with a balanced three-phase resistive load, which has a resistance set value of 25 Ω for each phase. Then, at \( t = 9.16 \) s, the balanced load is suddenly reduced to its half power in each phase. Fig. 11, Fig. 12 and Fig. 13 show the obtained experimental results of the adopted BDFIG system under the proposed new rotor position observer for the start-up operation, the load variation state, and the speed change condition, respectively.

Fig. 11 denotes the estimated and actual rotor position in (a) and (b) for different periods of the start-up dynamic response and its steady state, the rotor position estimation error in (c), the
q-axis CW current component in (d), the PW phase voltage in (e) and its expanded view in (f), the PW phase current in (g) and expanded view in (h), the CW phase current in (i) and expanded view in (j). In addition, Figs. 12(a), (b), (c), and (d) denote the estimated and actual rotor position with the dynamic effect under load change, PW phase voltage, phase current of both PW and CW sides, respectively. Furthermore, Fig. 13 denotes the performance under the speed change from 600 rpm to 700 rpm with the estimated and actual rotor position in (a) and (b) for different periods of the speed variation, the rotor position estimation error in (c), the q-axis CW current component in (d), the PW phase voltage in (e) and its expanded view in (f), the PW phase current in (g) and expanded view in (h), the CW phase current in (i) and expanded view in (j).

It is observed from Figs. 11, 12 and 13 that the PW voltage tracks successfully the desired values for DVC target under the whole operation period. Moreover, the results effectively confirm the good correlation between the estimated and actual rotor position as illustrated in Fig. 11(a) and (b), Fig. 12(a), and Fig. 13(a) and (b) for both the starting condition, load change condition and speed variation state, respectively. This ensures the capability of the proposed position observer for sensorless DVC of the adopted stand-alone BDFIG system.

Furthermore, Figs. 11(d) and 13(d) illustrate that the CW q-axis current tracks the desired value ($i_{2q}^* = 0$) to attain the intended CW current controller which confirms the capability and efficacy of the presented CW current topology.

### B. Experimental Verification of the Robustness Against Parameter Uncertainty

To verify the functionality of the proposed position observer via any changes in the BDFIG parameters, e.g. the variation of inductances that affect the value of the control parameter, $A_p$ and also the PW resistance variation, some of the experimental results are introduced as illustrated in Fig. 14.

Figs. 14(a), (b), (c), and (d) denote the estimated and actual rotor position, the PW phase voltage, the phase current of both PW and CW sides, respectively.

In practical experimental operation, the actual parameters of BDFIG are not easy to be changed because of the generator structure. Hence, to confirm the robustness of the proposed position observer under the case of parameter variation, the experiments are carried out with 130% uncertainties of the whole parameters that affect the complete procedure process of the proposed observer (15) by modifying the generator parameters in the controller instead of the actual generator parameters.

It is obvious from Fig. 14 that the efficacy of the proposed position observer and its capability for sensorless DVC target are not affected by any uncertainties in the BDFIG parameters, e.g. the generator inductances and also the PW resistance. This confirms and proves the robustness and effectiveness of the proposed position observer for sensorless DVC of the stand-alone BDFIG.
Experimental results of the proposed position observer under the load change condition (50% reduction).

Experimental results of the proposed rotor position observer for sensorless DVC under the start-up operation.

Fig. 11. Experimental results of the proposed position observer for sensorless DVC under the start-up operation.

Fig. 12. Experimental results of the proposed position observer under the load change condition (50% reduction).
Fig. 13. Experimental results of the suggested position observer under the speed change state (600 rpm to 700 rpm).
All the presented experimental results assure the efficacy and functionality of the presented sensorless DVC strategy based on a proposed position observer for the promising BDFIG in stand-alone applications.

VII. CONCLUSION

This paper has proposed a sensorless vector control strategy for DVC of ship shaft stand-alone BDFIG systems. The proposed control method has relied on the orientation technique of PW voltage. In addition, an adaptive observer for rotor position estimation algorithm has been proposed. Furthermore, the stability analysis of the new observer has also been studied with the concept of quadratic Lyapunov function and using the multi-model representation. The obtained results of both simulation and experimental have confirmed the efficacy of the proposed sensorless control strategy for DVC. Moreover, the obtained results have verified the functionality of the proposed position observer for sensorless control target of stand-alone BDFIGs under both cases of speed and load variations. Furthermore, the analysis has validated the robustness of the proposed position observer for different uncertainties.

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