Finite-State Predictive Current Control of a Standalone DFIG-Based Wind Power Generation Systems: Simulation and Experimental Analysis

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Abstract
This paper presents an improved stator voltage magnitude and frequency control for standalone doubly fed induction generators (DFIGs) based wind power generation systems (WPGSs). The proposed technique uses a simple finite-state predictive current control (FS-PCC). In this control method, the switching vector for the IGBT is selected to minimize the error between the reference value and the predicted value of the rotor current. Moreover, the discrete-time models of (DFIG) are needed to predict the future value of the rotor current for all possible voltage vectors generated by the rotor-side converter (RSC). Since the classic control methods in the literature use inner control loops and are based on pulse width modulation (PWM), this method does not require complex modulation stages and omits the current control loops, which reduces the control requirements. The main objective in a standalone DFIG system is to keep the stator voltage has constant in amplitude and frequency and equal to the reference value, regardless of the changes in rotor speed or load. The proposed control strategy was implemented through a 3 kW DFIG prototype platform-based dSPACE 1104 card. The simulation and experimental results show that the proposed FS-PCC offers excellent reference tracking with less total harmonic distortion (THD) in stator voltages and rotor currents.

Keywords
Standalone DFIGs • WPGSs. FS-PCC • Field-oriented control (FOC) • Rotor-Side Converter RSC • dSPACE 1104 card.

1 Introduction
Owing to the diminution of fuel fossil reserves and increased concern about CO2 emissions, which can cause a critical climate change, the wind energy systems (WESs) have become attractive and developed rapidly over the last few decades as a clean renewable energy source (Barra et al., 2016; Kumar, 2016; Soued et al., 2017). Despite the impacts of Covid-19, the most exclusively published statistics energy has appeared that the total additions of wind energy capacity in 2020 are expected to reach 65 GW, which increased by 8% compared with 2019 (Jaladi et al., 2020; Sadorsky, 2021; Slimane et al., 2020).

Most wind power generation systems (WPGSs) around the world are using the doubly fed induction generators (DFIGs) due to their additional benefits, for instance, wider power capture capability over a large range of wind speeds. Besides, compared to permanent magnet synchronous generators (PMSGs) which require high-power converters, the DFIGs are more economical because they utilized back-to-back converters limited at 25%–30% of the DFIG size for supporting a rotor speed variation of ±30 percentage (Dida & Benattous, 2015a, 2015b; Ouanjli et al., 2017).

The field-oriented control (FOC) is an extremely traditional control technique that can be used for DFIG-based systems. This method has been extensively utilized especially in industrial applications. The principle of this method is to transfer the rotor current into a dq rotational reference frame. The FOC technique is implemented through a conventional inner PI controller beside the pulse width modulation (PWM) which can apply the switching sequences to the voltage source converter (VSC). The advantages and disadvantages of this algorithm have been already discussed in many works (Abbeddaim & Betka, 2013; Abbeddaim et al., 2013).
2 Standalone DFIG System Topology

Figure 1 shows the configuration of a standalone WPGS integrated DFIG. Two-level voltage source converters with back-to-back structures have been included between the stator and rotor in this topology, which is well recognized as the load side converter (LSC) and (RSC). This paper concerns only the RSC and the standalone DFIG.

3 Mathematical Models of DFIG and RSC

3.1 DFIG Mathematical Model

The mathematical equations of the DFIG in complex-domain can be defined by referring all the rotor and stator quantities of the DFIG to the stator-windings as (Abad et al., 2011; Chikha & Barra, 2016). The stator and rotor voltage equations of the DFIG are

\[ v_s = R_s i_s + \frac{d}{dt} \psi_s + j \omega_m \psi_s \]  
\[ v_r = R_r i_r + \frac{d}{dt} \psi_r \]  
\[ \psi_s = L_s i_s + L_m i_r \]  
\[ \psi_r = L_r i_r + L_m i_s \]

where \( v_s, v_r, i_s, \) and \( i_r \) represent the voltage in stator and rotor, the currents in stator and rotor, respectively. \( \psi_s, \psi_r \) denote the stator and rotor flux vectors, respectively. \( R_s, R_r \) and \( L_s, L_r \) are the resistances per phase in stator and rotor, respectively. \( L_m \) is the mutual inductance, respectively, and \( L_m \) is the electrical speed.

The leakage factor of the DFIG can be defined as

\[ \sigma = 1 - \frac{L_m^2}{L_s L_r} \]

The stator and rotor fluxes relationship can be achieved by the manipulation of (3, 4, 5) as

\[ \psi_s = \frac{L_s}{L_m} (\psi_r - \sigma L_r i_r) \]

3.2 RSC Mathematical Model

In this work, the RSC is a two-level (VSC) that has six IGBT power switches intended for applying the FS-PCC method. The structure of the RSC and all rotor voltage vectors is depicted in Fig. 2. The switching sequences \( S \) can be composed as the following equation:

\[ S = \frac{2}{3} \left( S_a + a S_b + a^2 S_c \right) \]

where \( a = e^{-j2\pi/3} \), \( S_i \) means \( S_i \) on, \( \overline{S_i} \) means off, and \( i = a, b, c \). All rotor voltage vector \( v \) is linked to the switching state \( S \) by

\[ v = v_{dc} S \]

where \( v_{dc} \) is the dc-link input voltage that supplies the RSC.
Considering the possible eight voltage \( v_i \) \((v_0–v_7)\) vectors switching states \( S \) \((S_0–S_7)\) is obtained as shown in Table 1.

The switching states of the RSC are controlled by the switching pulses \( S_a, S_b, S_c \) as follows:

\[
S_a = \begin{cases} 
1 & \text{if } S_a \text{ on and } \overline{S_a} \text{ off} \\
0 & \text{if } S_a \text{ off and } \overline{S_a} \text{ on} 
\end{cases} 
\]

\( S_a \) as follows:

\[
S_a = \begin{cases} 
1 & \text{if } S_a \text{ on and } \overline{S_a} \text{ off} \\
0 & \text{if } S_a \text{ off and } \overline{S_a} \text{ on} 
\end{cases} 
\]

\( S_b \) as follows:

\[
S_b = \begin{cases} 
1 & \text{if } S_b \text{ on and } \overline{S_b} \text{ off} \\
0 & \text{if } S_b \text{ off and } \overline{S_b} \text{ on} 
\end{cases} 
\]

\( S_c \) as follows:

\[
S_c = \begin{cases} 
1 & \text{if } S_c \text{ on and } \overline{S_c} \text{ off} \\
0 & \text{if } S_c \text{ off and } \overline{S_c} \text{ on} 
\end{cases} 
\]

### Table 1: Voltage vectors and switching states with index number

| States Switching | Vectors Voltage | Vectors | Number |
|------------------|-----------------|---------|--------|
| \( S = [S_a \ S_b \ S_c] \) | \( v_i = [v_{iA} \ v_{iB}] \) | \( v_1 = [v_0 \ v_0] \) | \( v_1 = [2V_{dc}/3, 0] \) | 0 |
| \( S_0 = [0 \ 0 \ 0] \) | \( v_2 = \left[ V_{dc}/3 \ , \ \sqrt{3}V_{dc}/3 \right] \) | 1 |
| \( S_1 = [1 \ 0 \ 0] \) | \( v_3 = \left[ -V_{dc}/3 \ , \ -\sqrt{3}V_{dc}/3 \right] \) | 2 |
| \( S_2 = [1 \ 1 \ 0] \) | \( v_4 = \left[ -2V_{dc}/3 \ , \ 0 \right] \) | 3 |
| \( S_3 = [0 \ 1 \ 0] \) | \( v_5 = \left[ V_{dc}/3 \ , \ -\sqrt{3}V_{dc}/3 \right] \) | 4 |
| \( S_4 = [0 \ 0 \ 1] \) | \( v_6 = \left[ V_{dc}/3 \ , \ -\sqrt{3}V_{dc}/3 \right] \) | 5 |
| \( S_5 = [1 \ 0 \ 1] \) | \( v_7 = [0 \ , \ 0] \) | 6 |
| \( S_6 = [1 \ 1 \ 1] \) | \( v_8 = [0 \ , \ 0] \) | 7 |

Fig. 1 Basic diagram of the standalone WPGSs

Fig. 2 Left: two-level voltage source inverter; right: voltage vectors
4 FOC for Standalone DFIG

FOC is applied for the standalone DFIG to achieve the current decoupling control. The stator flux vector is oriented along the $d$-axis, while the stator voltage vector needs to align along the $q$-axis to achieve voltage-decoupling control (Chabani et al., 2017).

By forcing, the stator flux $\psi_{sq}$ and stator voltage $v_{sd}$ to be null the orientation are achieved. This leads to a dynamic first-order transfer function with a derivative-time equal to $\tau_s$ as below:

$$
\psi_{sd} = |\psi_s| = \frac{L_m}{\tau_s}i_{rd}
$$

(12)

where stator time constant $\tau_s = \frac{L_m}{R_s}$, and

$$
\psi_{sq} = 0 = L_s i_{sq} + L_m i_{rq}
$$

(13)

That is

$$
i_{rq} = -\frac{L_s}{L_m}i_{sq}
$$

(14)

5 Proposed Finite-State Predictive Current Control for Standalone DFIG

The rotor currents can be predicted for all sectors of the rotor voltage, in the proposed FS-PCC algorithm, these predicted rotor currents will contrast with the reference value of rotor voltage, in the proposed FS-PCC algorithm, these predicted rotor currents will be null the orientation are achieved. This leads to a dynamic first-order transfer function with a derivative-time equal to $\tau_s$ as below:

$$
\psi_{sd} = |\psi_s| = \frac{L_m}{\tau_s}i_{rd}
$$

(12)

where stator time constant $\tau_s = \frac{L_m}{R_s}$, and

$$
\psi_{sq} = 0 = L_s i_{sq} + L_m i_{rq}
$$

(13)

That is

$$
i_{rq} = -\frac{L_s}{L_m}i_{sq}
$$

(14)

According to Barra et al., (2016); Soued et al., 2017), the rotor current is predicted through the expression as follows:

$$
i_r(k+1) = \left(1 + \frac{T_i}{\tau_s}\right)i_r(k) + \frac{T_i}{\tau_s + T_r}.
$$

$$
\times \left[\frac{1}{\sqrt{R_s}}\left(\frac{k_s}{\tau_s} + k_j w_{0m}\right)\psi_s(k) + v_r(k) - k_s v_s(k)\right]
$$

(17)

where $k_s = \frac{L_m}{L_m} \tau_s = \frac{L_m}{R_s} \tau_s = \frac{(L_r* \sigma)}{R_s} R_\sigma \tau_s = R_r - R_s k_s^2$

In the actual systems that perform predictive control, a large amount of time calculation is required, and a large amount of retard time introduced during the excitation must be compensated. The time delay compensation of the FS-PCC algorithm must be accomplished by advancing the current prediction two steps ahead (Chebaani et al., 2017; Vazquez et al., 2017). For instance, supposing that the determined vector will be used at the time $(k + 1)$, and then, it is necessary to predict the current value at $(k + 2)$ time. By moving (15) one time-step forward, the equation of $i_r(k+2)$ can be written as:

$$
i_r(k+2) = \left(1 + \frac{T_i}{\tau_s}\right)i_r(k+1) + \frac{T_i}{\tau_s + T_r}.
$$

$$
\times \left[\frac{1}{\sqrt{R_s}}\left(\frac{k_s}{\tau_s} + k_j w_{0m}\right)\psi_s(k+1) + v_r(k+1) - k_s v_s(k+1)\right]
$$

(18)

5.2 Minimization of the Cost Function

For the seven vectors of the rotor voltage which can be produced through the RSC, the rotor current will be predicted at the future sampling time. A cost function is made to evaluate all predicted rotor currents, and it is used as a condition for selecting the best vector of the rotor voltage. The vector of the rotor voltage that minimizes the cost value will choose to use in the next period. The cost function is expressed by the absolute error between the predicted and reference rotor current, as the below equation:

$$
g = \left|i_{ra}(k) - i_{ra}^p(k+2)\right| + \left|i_{pb}(k) - i_{pb}^p(k+2)\right|
$$

(19)

where $i_{ra}(k)$ and $i_{pb}(k)$ are the reference of rotor currents in $\alpha\beta$ coordinate frame. Besides, $i_{ra}^p(k+2)$ and $i_{pb}^p(k+2)$ are the predictive rotor currents.

5.3 Proposed Controller Design

Figure 3 shows the global control scheme of stator voltage and frequency control-based FS-PCC, and the output voltage magnitude in the stator of DFIG is controlled by regulating the d-rotor current ($i_{rd}$). While the d-rotor current reference ($i_{rd}^*$) can be generated after reducing the error between the desired and measured voltage magnitude ($v_{an}^*$ and $v_{an}$) through a PI (Proportional Integral) controller (Kanojiya, 2012). The stator of the DFIG is connected in Y-mode; the
stator voltage magnitude \(|v_s|\) is given by Ahmed et al. (2019) wind energy conversion system.

\[
|v_s| = V = \sqrt{\left(v_{sd}^2 + v_{sq}^2\right)} \tag{20}
\]

For the standalone DFIG, the system produces electric power as much as the load demand. So, the reference of q-rotor current \((i_{rq})\) is calculated from the q-stator current \((i_{sq})\) as (Abbeddaim & Betka, 2013):

\[
i_{rq}^* = -\frac{L_s}{L_m}i_{sq}^* \tag{21}
\]

This proposed FS-PCC is developed to be realized in a fixed \(\alpha\beta\) rotor reference frame. The Park transformation matrix and the reference rotor currents in \(dq\) are transformed to \(\alpha\beta\) coordinates by:

\[
\begin{bmatrix}
i_{rq}^* \\
i_{r\beta}^*
\end{bmatrix} =
\begin{bmatrix}
\cos(\theta) & -\sin(\theta) \\
\sin(\theta) & \cos(\theta)
\end{bmatrix}
\begin{bmatrix}
i_{rd}^* \\
i_{r\beta}^*
\end{bmatrix} \tag{22}
\]

Finally, to control the output stator frequency at the desired value \(fs = 50\text{ Hz}\), all the stator quantities must be synchronized with the \(dq\) rotating reference frame. Hene, the \(d\)- and \(q\)-axis of both stator voltages and stator currents are generated by transforming the three-phase stator quantities through the Park transformation with angle \((\theta_s)\), which is obtained by integrating the reference stator frequency \(\omega_s\) (314 rad/sec) (Benamor et al., 2019) where

\[
\theta_r = \theta_s - \theta_m \tag{23}
\]

6 Simulation Results and Experimental Validation

This section presents simulation and experimental examination test results to verify the behavior of the developed FS-PCC. The simulation model has been built in MATLAB/Simulink together with the Sim Power Systems software. Moreover, the experimental results have been obtained using a test platform developed in the laboratory. The characteristics of the DFIG that used for simulation and experimental are reported in Appendix (A). Figure 4 portrays the descriptive diagram and a picture of the experimental prototype setup, and it is composed of a prime mover 3 Kw DC motor, 3 Kw DFIG, 4 Kw/420Ω three-phase resistive load, Semikron module IGBT inverter, dSPACE 1104 control card, a host PC running with MATLAB/Simulink software. The hardware DS1004 card is exploited to implement the FS-PCC strategy, with a sampling time of 100 μs.
To determine the performance of the proposed control method, the behavior of the controlled system is evaluated during the blow running conditions:

6.1 Stator Voltage Magnitude Variation

Firstly, the DFIG is driven with a constant speed of 1450 rpm and supplies a fixed 2 Kw of resistive load. To show the dynamic performance of the suggested technique, a variation in the reference of output voltage has been applied. The reference of the stator voltage amplitude has been varied from 200 to 280 V at 1.7 s from 280 to 200 at 3.7 s. The various simulation and the experimental test results are shown in Figs. 5–6. Figure 6 (a), (b) illustrates the reference and actual stator voltage amplitude stator phase voltage and rotor phase current. It is easily seen that the stator voltage amplitude has a perfect reference tracking capability for any change in reference value. Both simulation and the experimental show that the stator voltage and the rotor current have good sinusoid waveform due to the application of FS-PCC. The transient behaviors of the applied FS-PCC method for rotor current in the αβ axis are studied. Figure 5a, b presents the reference and measured rotor currents in the αβ axis in the presence of stator voltage steps. It can be noticed that the rotor cur-
rents are controlled successfully by the proposed FS-PCC method, which achieved a perfect transient response during step change of the stator voltage. Also, Fig. 6a, b shows the variation of stator active power and electromagnetic torque of the generator with low ripples when the stator voltage amplitude is varied by increasing and decreasing its value.

### 6.2 Load Change

To investigate the impact of the load change, which is connected to the stator of DFIG, the load is increased from 2 to 4 kW at 1.7 s and is decreased from 4 to 2 kW at 3.7 s when the DFIG operates with a constant rotor speed of 1450 r/min. The various simulation results and experimental tests are obtained with the proposed FS-PCC strategy under the variation in load value. Figures 7–8 illustrate the reference and measured stator voltage amplitude, stator current, and rotor current. It is obvious that stator voltage amplitude has been affected by load application, by showing an undershoot, then the amplitude has been recovered quickly because of the regulation loop. Also, the increase and decrease in the stator and rotor current are due to...
Fig. 8 System response under step variation in the reference of stator voltage amplitude. a Simulation results. b Experimental. CH1: reference of stator voltage magnitude (50 V/div), CH2: stator voltage magnitude (50 V/div), CH3: stator active power (1KW/div), CH4: electromagnetic torque (20 N.m/div)

Fig. 9 System response under load variety. a Simulation results. b Experimental. CH1: reference of stator voltage magnitude (50 V/div), CH2: stator voltage amplitude (50 V/div), CH3: stator phase voltage (200 V/div), CH4: rotor phase current (20A/div)

to the increase and decrease in load value. Figure 9a and b shows that the stator voltage remains fixed at the desired value of 250 V despite the load variations. Figure 8a and b shows that the variation of stator active power and electromagnetic generator torque is evident due to the load variation. The negative value indicates that the delivered quantity is toward the load.

6.3 Rotational Speed Variation

To reveal the stability of the suggested FS-PCC strategy, the responses of the system are analyzed during emulating, and a different wind gust scenario has been considered. The speed of the DFIG is suddenly decreased from 1450 to 1300 rpm at 1.7 s and increased from 1300 to 1450 rpm at 3.7 s. This test has been done with a fixed load of 2 kW and stator voltage 250 V. The obtained results during this rotor speed
change are shown in Figs. 10–11. Figure 10a and b illustrates the rotational speed, the reference, and actual stator voltage amplitudes, the rotor current. It can be seen that the magnitude is not affected at all and tracks the reference perfectly for the entire period of test, Fig. 11a and b illustrates the rotational speed, the slip angle, stator voltage, and rotor current, it is also seen that the variation of the frequency of rotor current is evident due to the rotor mechanical speed variation. Thus, from zoom (1) and (2), it is observed that the stator voltage frequency remains constant at 50 Hz despite the variation in rotor speed due to the sum of the mechanical and electrical rotor current frequency (Fig. 12).

6.4 THD Assessment

The other important issue in standalone DFIG mode is the power quality since the loads are mostly need balanced and non-polluted stator voltage. Therefore, to evaluate the proposed controller scheme, the power quality of the standalone DFIG system is investigated. The THD of the rotor $I_{ra}$ current and stator voltage $V_{sa}$ is obtained at rotor speed 1450 rpm. In Fig. 13a and b, the THD of $I_{ra}$ is 3.41% for fundamental rotor frequency: $f_r = 1.667$ Hz and THD in the stator voltage windings for fundamental rotor frequency 50 Hz is and 4.24%.

Fig. 10 System response under load variety. a Simulation results. b Experimental. CH1: reference of stator voltage magnitude (50 V/div), CH2: stator voltage amplitude (50 V/div), CH3: stator active power (1KW/div), CH4: electromagnetic torque (20 N.m/div)

Fig. 11 System response under rotor speed variety. a Simulation results. b Experimental. CH1: rotor speed (200 rpm/div), CH2: reference of stator voltage amplitude (50 V/div), CH3: stator voltage magnitude (50 V/div), CH4: rotor phase current (20A/div)

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7 Conclusion

In this paper, a simple and effective FS-PCC algorithm for the stator voltage and frequency control for a standalone DFIG has been developed. The proposed controller does not require an inner PI controller or a complex modulation stage, which greatly simplifies the design process. Moreover, it is easy to implement in the $\alpha\beta$ synchronizes rotor reference frame, thereby keeping the proposed control algorithm straightforward for the handling of constraints. Simulation results and experimental tests in a laboratory with a 3 kW DFIG scale setup confirm the proposed control algorithm and show the feasibility and effectiveness of the proposed FS-PCC concerning different operating conditions.

Appendix 1

See Tables 2 and 3.
Table 2 DFIG main parameters

| Parameters               | Value | Unit |
|--------------------------|-------|------|
| Nominal power            | 3     | kW   |
| Stator voltage           | 325.26| V    |
| Stator frequency         | 50    | Hz   |
| Number of pairs poles    | 2     |      |
| Nominal speed            | 1450  | Rpm  |
| Stator resistance        | 1.6000| H    |
| Rotor resistance         | 2.6200| Ω    |
| Stator inductance        | 0.1950| H    |
| Rotor inductance         | 0.1950| H    |
| Mutual inductance        | 0.1770| H    |

Table 3 PI regulator parameters

| kp  | Ki  |
|-----|-----|
| 0.07| 3.4 |

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