Predictive Control of Outer-Rotor Five-Phase BLDC Generators Applicable for Off-Shore Wind Power Plants

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Abstract—Model predictive control algorithms have recently gained more importance in the field of wind power generators. One of the important categories of model predictive control methods is improved deadbeat control in which the reverse model of generator is used to calculate the appropriate inputs for the next iteration of controlling process. In this paper, a new improved deadbeat algorithm is proposed to control the stator currents of an outer-rotor five-phase BLDC generator. Extended Kalman filter is used in the estimation step of proposed method, and generator equations are used to calculate the appropriate voltages for the next modulation period. Two aspects of proposed controlling method are evaluated including its sensitivity to generator parameter variations and its speed in following the reference values of

required torque during transient states. Wind power generators are kept in mind, and proposed controlling method is both simulated and experimentally evaluated on an outer-rotor five-phase BLDC generator.

Keywords— Multiphase generators, improved deadbeat control, extended Kalman filter, wind power generators

1. Introduction

Due to their high power density, high efficiency and wide speed range, permanent magnet (PM) generators are receiving more attention in wind power plants. Among different topologies of PM generators, brushless direct current (BLDC) generators have the advantage of higher torque density, simpler winding distribution and more fault tolerance [1]. As a result, these machines are a practical option for low-maintenance and high power applications such as off-shore wind power farms. Several methods are proposed in literature to have a better control on stator phase currents of BLDC generators.

Among these algorithms, model predictive control (MPC) has become a suitable option recently. MPC concept is easy to understand, and various constraints and nonlinearities can be directly included in its structure. Moreover, the resulting controller is easy to implement [2], [3]. These types of controllers can be effectively implemented in generator controlling algorithm because linear models of BLDC generators are quite well known and developed through analytical methods.

In the field of generator power control, MPC algorithms can be generally divided into two main categories. The first group is an extension of traditional direct-torque control (DTC) in which the lookup table is removed and optimized switching state of the inverter is computed directly in MPC algorithm to minimize a predefined cost function [4][5]. This cost function should be computed for all possible switching states, and as a result the computational burden of controlling algorithm is relatively high. By appearance of powerful digital processors, it is now possible to use this algorithm for fast dynamic

systems such as PM drives [6]. Considering the finite amount of possible switching states in the converter unit, this type of control algorithm is also famous as “finite set model predictive control” (FS-MPC).

On the other hand, the second group can be considered as an extension of traditional field-oriented control of generator. In this group, the inner PI controllers are removed and replaced by predictive controllers. Moreover, reverse model of generator is used to calculate appropriate reference voltages, and a modulator is usually used to generate the computed reference voltages [7].

Model predictive control has also been examined successfully in the case of multiphase generators [8]. Comparing to standard three-phase generators, multi-phase structure of a BLDC generator results in several advantages such as lower power per inverter leg, lower current per phase, and lower amplitude and higher frequency of generated torque ripple. However, higher number of inverter legs and possible switching states, results in higher computational burden of MPC algorithm in multiphase generator drives [9][10].

While controlling the stator currents of a multiphase generator by MPC algorithms, machine model is directly used to estimate the future values of system outputs (electrical torque and stator currents) [6]. Consequently, the precision of model parameters play an important role in final accuracy of the estimated values [11].

Extended Kalman filter (EKF) is a powerful recursive estimation algorithm which can be used to reduce the effect of generator parameter variation. All available measurements are processed by EKF regardless of their accuracy to provide a fast and precise estimation of all system states [12].

In [12] and [13] EKF is used to estimate the rotor position and rotor speed of a permanent magnet synchronous machine. Moreover, by comparing final estimations of this algorithm with measured values of system states a fault detection and isolation algorithm is developed in [14]. As the mathematical model of BLDC generator is sufficiently well developed, EKF is ideally suited for the case of five-phase BLDC generator applications.

In this paper, extended Kalman filter based predictive deadbeat control (EKF-PDC) is developed for five-phase BLDC generator. Proposed controlling algorithm includes two main steps namely “current estimation step” and “voltage application step”. EKF is developed for five-phase BLDC generator, and is executed during “current estimation step” to reduce the effect of generator parameter variation. Two main aspects of proposed controlling algorithm are evaluated both by simulations and experimental tests. These two aspects are sensitivity respect generator variations, and its ability in following reference currents (and electrical torque) during transient states.

The remaining sections of this paper are organized as follows. Electrical model of five-phase BLDC generator and general concepts of deadbeat current control are explained in section 2. In section 3, EKF theory and its application for improved predictive deadbeat control of five-phase BLDC generator are developed. Section 4 is dedicated to sensitivity analysis of proposed controlling method by means of simulations. Experimental verifications of proposed deadbeat control are presented in section 5, and finally, section 6 presents a summary of results drawn from this study.

2. Deadbeat Control of Stator Currents in a Five-Phase BLDC Generator

In this section, the electrical model of a five-phase BLDC generator is briefly reviewed, and after that, general concept of deadbeat control is developed its application.

2.1. Generator Stator Windings

The machine is considered symmetric, and moreover, it is assumed that there is no iron saturation. The first step of model development is the general equation of electrical parameters in generator windings:

$$v_s = r_s i_s + \frac{\partial}{\partial t} \psi_s \quad (1)$$

where r_s represents stator winding resistance, i_s is stator phase currents and v_s is stator phase voltages:

$$v_s = \begin{bmatrix} v_{an} & v_{bn} & v_{cn} & v_{dn} & v_{en} \end{bmatrix}^T$$

$$i_s = \begin{bmatrix} i_a & i_b & i_c & i_d & i_e \end{bmatrix}^T$$
(2)

Moreover, stator winding flux is represented by ψ_s which is produced by rotor magnets and stator phase currents:

$$\psi_s = L_s i_s + \psi_{pm}$$
(3)

where L_s is the stator inductance matrix.

In the case of a five-phase BLDC generator, the flux generated by rotor magnets can be estimated by its fundamental and third harmonic components:

$$\psi_{pm} = \psi_{pm1} \begin{bmatrix} \sin(\theta) \\ \sin(\theta - \alpha) \\ \sin(\theta - 2\alpha) \\ \sin(\theta - 3\alpha) \\ \sin(\theta - 4\alpha) \end{bmatrix} + \psi_{pm3} \begin{bmatrix} \sin(3\theta) \\ \sin 3(\theta - \alpha) \\ \sin 3(\theta - 2\alpha) \\ \sin 3(\theta - 3\alpha) \\ \sin 3(\theta - 4\alpha) \end{bmatrix}$$
(4)

where θ is the electrical angle of rotor position, ψ_{pm1} and ψ_{pm3} are fundamental and third harmonic components of magnet flux in generator windings, and $\alpha = 2\pi/5$ rad.

Similar to Park transformation in three-phase systems, it is possible to transfer the electrical parameters of a five-phase BLDC generator into two rotating reference frames (namely d_1q_1 -frame and d_3q_3 -frame), and one homopolar axis. Equation (5) presents the transformation matrix for a five-phase system.

$$F_{d_1q_1d_3q_3o} = T F_{abcde} ,$$

$$T(\theta) = \frac{2}{5} \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/5) & \cos(\theta - 4\pi/5) & \cos(\theta - 6\pi/5) & \cos(\theta - 8\pi/5) \\ -\sin(\theta) & -\sin(\theta - 2\pi/5) & -\sin(\theta - 4\pi/5) & -\sin(\theta - 6\pi/5) & -\sin(\theta - 8\pi/5) \\ \cos 3(\theta) & \cos 3(\theta - 2\pi/5) & \cos 3(\theta - 4\pi/5) & \cos 3(\theta - 6\pi/5) & \cos 3(\theta - 8\pi/5) \\ -\sin 3(\theta) & -\sin 3(\theta - 2\pi/5) & -\sin 3(\theta - 4\pi/5) & -\sin 3(\theta - 6\pi/5) & -\sin 3(\theta - 8\pi/5) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (5)$$

Electrical equations of five-phase BLDC generator in two rotating reference frames are:

$$v_{d1} = r_s i_{d1} + L_{d1} \frac{d}{dt} i_{d1} - \omega L_{q1} i_{q1} \quad (6)$$

$$v_{q1} = r_s i_{q1} + L_{q1} \frac{d}{dt} i_{q1} + \omega(\psi_{pm1} + L_{d1} i_{d1}) \quad (7)$$

$$v_{d3} = r_s i_{d3} + L_{d3} \frac{d}{dt} i_{d3} - 3\omega L_{q3} i_{q3} \quad (8)$$

$$v_{q3} = r_s i_{q3} + L_{q3} \frac{d}{dt} i_{q3} + 3\omega(\psi_{pm3} + L_{d3} i_{d3}) \quad (9)$$

$$v_o = r_s i_o + L_o \frac{d}{dt} i_o \quad (10)$$

where ω is the electrical rotational velocity, and L_{d1} , L_{q1} , L_{d3} , L_{q3} and L_o are the inductance values of stator windings in their corresponding directions. In addition, generated Electrical torque of five-phase BLDC generator in synchronous reference frames can be calculated as:

$$T_e = T_{e1} + T_{e3}$$

$$T_{e1} = \frac{5P}{2} [i_{d1} i_{q1} (L_{d1} - L_{q1}) + \lambda_{m1} i_{q1}]$$

$$T_{e3} = \frac{5P}{2} [-3i_{d3} i_{q3} (L_{d3} - L_{q3}) + 3\lambda_{m3} i_{q3}]$$

$$(11)$$

2.2. General Concept of Deadbeat Current Control for a Five-Phase BLDC Generator

In the case of BLDC machine applications, the main purpose of deadbeat control algorithm is to eliminate the stator current errors in the smallest possible number of switching periods. As it is shown in

Fig. 1, stator phase currents are sampled at the beginning of k^{th} modulation period. In addition, the duty cycles of each voltage vector are getting updated by the beginning of each modulation period.

Fig. 1: Deadbeat MPC controlling sequences

By knowing the measured values of phase currents (I_k) and applied voltage values (V_k) during k^{th} modulation period, it is possible to calculate the estimated value of stator currents ($\hat{I}_k$) by the end of current modulation period.

The main objective of deadbeat control is to generate reference values of stator currents (I^*) at the end of next modulation period. Considering (6)-(9) and by knowing the estimated value of ($\hat{I}_k$), the desired voltage values for the next modulation period would be:

$$V_{d1}(k+1) = \frac{L_{d1}}{T_m} (i_{d1}^* - \hat{i}_{d1}) + r_s \hat{i}_{d1} - \omega L_{q1} \hat{i}_{q1}$$

$$V_{q1}(k+1) = \frac{L_{q1}}{T_m} (i_{q1}^* - \hat{i}_{q1}) + r_s \hat{i}_{q1} + \omega (L_{d1} \hat{i}_{d1} + \psi_{pm1})$$

$$V_{d3}(k+1) = \frac{L_{d3}}{T_m} (i_{d3}^* - \hat{i}_{d3}) + r_s \hat{i}_{d3} - 3\omega L_{q3} \hat{i}_{q3}$$

$$V_{q3}(k+1) = \frac{L_{q3}}{T_m} (i_{q3}^* - \hat{i}_{q3}) + r_s \hat{i}_{q3} + 3\omega (L_{d3} \hat{i}_{d3} + \psi_{pm3})$$

(12)

As it can be seen from (12), calculated values of reference voltages $V_{d1q1d3q3}^*$ are dependent on estimated values of stator currents in their corresponding directions. As a result, the accuracy of estimation

method can affect the final precision of predictive deadbeat control. Extended Kalman Filter is an estimation method which can reduce the impact of system parameter variation. In this paper, Extended Kalman Filter is developed for five-phase BLDC machine to estimate the stator phase currents in each direction. This method will be explained in the following section.

3. Generator Current Estimation

In the proposed controlling algorithm, EKF is used to estimate generator currents at the end of current modulation period. Due to its more practical aspects, stationary $\alpha\beta$ reference frame is selected in the development of EKF equations. The transformation matrix between phase- and stationary-reference frames can be simply derived by setting $\theta=0$ in (5):

$$F_{\alpha 1 \beta 1 \alpha 3 \beta 3 o} = T \Big|_{\theta=0} F_{abcde} \quad (13)$$

Nonlinear state model presentation of five-phase BLDC generator can be written as:

$$\begin{aligned} \dot{x} &= f(x) + Bu(t) + w(t) \\ y(t) &= cx(t) + v(t) \end{aligned} \quad (14)$$

where

$$\begin{aligned} x &= [i_{\alpha 1} \quad i_{\beta 1} \quad i_{\alpha 3} \quad i_{\beta 3} \quad i_o \quad \omega_e \quad \theta_e]^T \\ u &= [v_{\alpha 1} \quad v_{\beta 1} \quad v_{\alpha 3} \quad v_{\beta 3} \quad v_o]^T \\ y &= [i_{\alpha 1} \quad i_{\beta 1} \quad i_{\alpha 3} \quad i_{\beta 3} \quad i_o]^T \end{aligned} \quad (15)$$

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$$f(x) = \begin{bmatrix} -\frac{R_s}{L_{d1}}i_{\alpha1} + \frac{\psi_{pm1}}{L_{d1}}\omega_e \sin \theta_e \\ -\frac{R_s}{L_{q1}}i_{\beta1} - \frac{\psi_{pm1}}{L_{q1}}\omega_e \cos \theta_e \\ -\frac{R_s}{L_{d3}}i_{\alpha3} - \frac{\psi_{pm3}}{L_{d3}}3\omega_e \sin 3\theta_e \\ -\frac{R_s}{L_{q3}}i_{\beta3} + \frac{\psi_{pm3}}{L_{q3}}3\omega_e \cos 3\theta_e \\ -\frac{R_s}{L_o}i_o \\ 0 \\ \omega_e \end{bmatrix}$$

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(16)

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$$B = \begin{bmatrix} 1/L_{d1} & 0 & 0 & 0 & 0 \\ 0 & 1/L_{q1} & 0 & 0 & 0 \\ 0 & 0 & 1/L_{d3} & 0 & 0 \\ 0 & 0 & 0 & 1/L_{q3} & 0 \\ 0 & 0 & 0 & 0 & 1/L_o \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

171

(17)

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$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

173

(18)

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In addition, $w(t)$ represents system noise vector, and $v(t)$ is the measurement noise vector, and it is assumed that $w(t)$ and $v(t)$ are uncorrelated and have zero-mean stochastic values.

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Implemented EKF consists of two main steps. In the first step, a prediction of digitalized system states ($\hat{x}_{k|k-1}$) and its covariance ($\hat{P}_{k|k-1}$) is performed by knowing the previous estimation of system states ($\hat{x}_{k-1|k-1}$) and system inputs (u_{k-1}) during one sampling period:

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$$\hat{x}_{k|k-1} = \hat{x}_{k-1|k-1} + T_s f(\hat{x}_{k-1|k-1}, u_{k-1})$$

$$\hat{P}_{k|k-1} = \hat{P}_{k-1|k-1} + F \hat{P}_{k-1|k-1} F^T + Q$$

(19)

In the second step, the measured quantities will be used to correct the estimated states and covariance matrix:

$$\hat{x}_{k|k} = \hat{x}_{k-1|k-1} + K_k [y_k - h(\hat{x}_{k|k-1})]$$

$$\hat{P}_{k|k} = \hat{P}_{k|k-1} - K_k H \hat{P}_{k|k-1}$$

$$K_k = \hat{P}_{k|k-1} H^T (H \hat{P}_{k|k-1} H^T + R)^{-1}$$

(20)

where H is the measurement matrix and K is famous as Kalman gain [15].

Estimated values of system states ($\hat{x}_{k|k}$) can now be used in MPC algorithm to calculate the required reference voltages of the next modulation period. Figure 2 illustrates the general structure of proposed EKF-based deadbeat control while modulation frequency is 10 kHz, and controlling algorithm frequency is 4 kHz.

Fig. 2: General structure of proposed EKF-based deadbeat control

197 **4. Sensitivity of Proposed EKF-PDC - Simulations**

198 Simulations are conducted to evaluate the sensitivity of proposed EKF-PDC method. Five-phase BLDC
199 generator is simulated at 1-pu of its rated speed, and while delivering its nominal power. The parameters
200 of simulated generator are brought in Table I which are also correspondent to their real values in
201 laboratory test bench.

202 Table I: Electrical (measured) parameters of five-phase BLDC generator
203 (used both in simulations and experimental evaluations)

Stator Resistance		0.1 Ω
Stator Inductance	L_{aa}	1500 μH
	L_{ab}	35 μH
	L_{ac}	42 μH
Nominal Torque		32 Nm
Nominal Phase Current		19 Amp (rms)
DC-bus Rated Voltage		48 V
Permanent Magnet Flux		0.0178 Wb

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206 **4.1. Simulation Steps**

207 Simulations consist of five different steps. In each step a different source of disturbance is introduced to
208 the system. Five steps of simulations are summarized in Table II.

209

210 Table II: Considered parameters during each simulation

Test number	Introduced disturbance
1	Ideal Condition
2	dc-link voltage drop
3	Nonlinear Inverter Characteristics
4	Inaccurate phase resistance
5	Inaccurate PM flux

211

The first case (test-1) is dedicated to ideal operation. Precise model of generator is used in the estimation block, and ideal switches are used in inverter block.

The second case (test-2) is related to the impact of dc-bus voltage drop in the inverter block. During test-2, dc-link voltage is reduced to 0.8 its rated value.

The third case (test-3) is related to inverter nonlinear characteristics. Considered inverter characteristics include $3\mu s$ of dead time, 0.016Ω and 0.014Ω of forward resistance for anti-parallel diodes and IGBTs in each leg, and moreover, 2.17 V and 1.85 V of voltage drop for anti-parallel diodes and IGBTs respectively.

Generator parameters are the main concern of next simulations (tests 4 and test 5). Higher operational temperature and conductor skin effect can lead to higher values of operational stator resistance. During test-4 stator resistance is increased from 0.1Ω to 0.2Ω to study the sensitivity of proposed method to resistance changes.

High temperatures, aging and mechanical stresses can reduce the strength of rotor magnets in a BLDC generator. To evaluate the sensitivity of proposed method to magnet flux variations, during test-5 magnetic flux of generator rotor is reduced to 0.8 its rated value.

4.2. Simulation Results

Under each condition, the behaviour of proposed controlling method can be evaluated by measuring stator current errors in different directions. In each simulation test, stator current errors are measured at the end of “*current estimation step*” and “*voltage application step*”. That is the error between estimated ($\hat{I}_k$) and measured (I_{k+1}) current values by the end of current modulation period (e_1), and the error between real (I_{k+2}) and reference current values (I^*) at the end of next modulation period (e_2). In each case the energy of e_1 and e_2 are integrated on one period of fundamental frequency under steady states. As a result, during each test E_1 represents the error energy in “*current estimation step*”, and E_2 is the energy of stator current errors after completely executing one round of control algorithm:

$$E_1 = \int_T \sum_{j=d1,q1,d3,q3,o} \left[\hat{I}_j(K) - I_j(K+1) \right]^2$$

$$E_2 = \int_T \sum_{j=d1,q1,d3,q3,o} \left[I_j^* - I_j(K+2) \right]^2$$

(21)

Computed values of estimation error energy (E_1) and voltage application error energy (E_2) are summarized in Fig. 3. Moreover, simulated values of generated electrical torque under each condition are summarized in Fig. 4. In all conditions, rated value of torque is generated while the generator is rotating in its nominal speed and under steady state.

Fig. 3: Simulated values of current errors in estimation step (E_1) and voltage application step (E_2) of control algorithm

Fig. 4: Generated electrical torque of five-phase BLDC generator during test-1 to test-5

4.3. Discussion on Simulation Results

In each case, the estimation step of control algorithm is realized by EKF, and after that, the required reference voltages are directly calculated by using generator equations. As it can be seen from Fig. 3, implementation of EKF in the estimation step leads to lower values of error energy (E_1) for all of the

simulated tests. Standard deviations of E_1 and E_2 after completing all of these tests are $S_1=4.007\text{e-}004$ and $S_2=0.0124$, respectively. Lower amplitude of S_1 is due to automatic adaptation of EKF to system variations in each test. Error energy values of E_1 and E_2 while working with a healthy machine and under ideal conditions are respectively $8.92\text{e-}005$ and 0.0178 .

During test 2, the amplitude of dc-link voltage is reduced by 20% while its correspondent value in controlling algorithm is not changed. Comparing to healthy conditions, the increment of current error in estimation level (E_1) is 22%.

However, as generator equations are directly used during voltage application level, the increment of E_2 during this step is higher (108%). Again, the main reason of less error in the estimation step is adaptation of EKF to system variations. Equation (12) is used during voltage application step. Considering this equation, in the case of dc-link voltage drop it is possible to write the following equation in d_1 -direction:

$$\begin{aligned}
 i_{d1}(k+2) &= \hat{i}_{d1}(k) + \frac{T_m}{L_{d1}} \left[V_{d1}(k+1) + \Delta V_{d1}(k+1) - r_s \hat{i}_{d1}(k) + \omega L_{q1} \hat{i}_{q1}(k) \right] \\
 &= \hat{i}_{d1}(k) + \frac{T_m}{L_{d1}} \left[V_{d1}(k+1) - r_s \hat{i}_{d1}(k) + \omega L_{q1} \hat{i}_{q1}(k) \right] + \frac{T_m}{L_{d1}} \Delta V_{d1}(k+1) \\
 &= i_{d1}(k+2)_{norm} + \Delta i_{d1}(k+2)
 \end{aligned} \tag{22}$$

where $\Delta V_{d1}(k+1)$ is the imposed voltage in d_1 -direction due to existing error in dc-bus voltage, $i_{d1}(k+2)_{norm}$ is calculated current amplitude under normal operation, and $\Delta i_{d1}(k+2)$ is the additional current component which is generated due to existing error in dc-link voltage. As it can be seen, increasing the switching frequency (reduction of T_m) and increasing the stator inductances can directly reduce the error of stator current. However, final amount of current error is also dependent on the amplitude of applied voltage $V_{d1}(k+1)$ in $(k+1)^{th}$ modulation period. Following the same procedure, stator current error in other directions due to dc-link voltage drop can be calculated as:

$$\Delta i_{q1}(k+2) = \frac{T_m}{L_{q1}} \Delta V_{q1}(k+1)$$

$$\Delta i_{q3}(k+2) = \frac{T_m}{L_{q3}} \Delta V_{q3}(k+1)$$

$$\Delta i_{d3}(k+2) = \frac{T_m}{L_{d3}} \Delta V_{d3}(k+1)$$

(23)

Test 3 is dedicated to nonlinear characteristics of the inverter. As it can be seen from Fig.3, this test is correspondent to the highest amplitude of E_I and highest torque ripples. In other words, implemented EKF during estimation step has more difficulties in adapting the system to reduce the impact of inverter nonlinear characteristics. The main reason of this fact is continuous variation of voltage drop along simulated semiconductors. Forward voltage drops in semiconductors can be considered as a periodic disturbance in dc-link voltage. The amplitude of this voltage disturbance changes each time the current flow path changes from an IGBT to its anti-parallel diode or vice versa. Simulated values of stator phase currents and applied voltage of phase A are shown in Fig. 5 while nonlinear characteristics of the inverter are included in simulations. As it can be seen, continuous periodic change of applied voltage (while stator current is crossing the zero) is the main reason of higher estimation error and higher torque ripple.

Fig. 5: Simulated values of stator phase current including nonlinear characteristics of inverter

Nonlinear characteristics of the inverter have also led to higher values of E_2 . This time, generated voltage drops along the conducting semiconductors change the effective value of applied voltages to generator stator phases, and this fact leads to higher values of current error. Similar to the case of dc-link voltage reduction, in this case higher values of stator inductance and modulation frequency can reduce the amplitude of E_2 .

During test 4, stator resistance is changed from 0.1Ω to 0.2Ω in generator block while its value is remained fixed in controlling algorithm. Comparing to test-1 (ideal operational conditions), E_I increment is 22% which is much less than E_2 increment (44%). This fact is due to effective adaptation of EKF respect to resistance change. In addition, a fixed change in stator resistances will not lead to noticeable torque ripples. By the end of each modulation period, stator phase current in d_I -direction can be calculated as:

$$\begin{aligned}
 i_{d1}(k+2) &= \hat{i}_{d1}(k) + \frac{T_m}{L_{d1}} \left[V_{d1}(k+1) - 2r_s \hat{i}_{d1}(k) + \omega L_{q1} \hat{i}_{q1}(k) \right] \\
 &= \hat{i}_{d1}(k) + \frac{T_m}{L_{d1}} \left[V_{d1}(k+1) - r_s \hat{i}_{d1}(k) + \omega L_{q1} \hat{i}_{q1}(k) \right] - \frac{T_m}{L_{d1}} \left[r_s \hat{i}_{d1}(k) \right] \\
 &= i_{d1}(k+2)_{norm} + \Delta i_{d1}(k+2)
 \end{aligned} \tag{24}$$

where $i_{d1}(k+2)_{norm}$ is stator current value in the case of operating under normal conditions, and $\Delta i_{d1}(k+2)$ is the error which is imposed to the system due to higher values of stator phase resistance. This error in other directions can be calculated as:

$$\begin{aligned}
 \Delta i_{q1}(k+2) &= \frac{T_m}{L_{q1}} \left[r_s \hat{i}_{q1}(k) \right] \\
 \Delta i_{d3}(k+2) &= \frac{T_m}{L_{d3}} \left[r_s \hat{i}_{d3}(k) \right] \\
 \Delta i_{q3}(k+2) &= \frac{T_m}{L_{q3}} \left[r_s \hat{i}_{q3}(k) \right]
 \end{aligned} \tag{25}$$

As it can be seen, generated value of E_2 is directly proportional with stator resistance error and modulation period. Moreover, higher inductance values can lead to less error in stator phase currents.

During test 5, generated flux of PM generator is decreased by 20%. This case can happen by aging, high operational temperatures, long-time mechanical vibration or high current amplitudes in d-directions. Although, generated torque ripples are negligible in this case, but comparing to the ideal case (normal operation), both E_I and E_2 are increased by 22% and 46% respectively. Again the increment of E_I is not as high as E_2 which is due to automatic adaptation of estimation step by its implemented EKF. The main effect of PM flux variations on proposed controlling algorithm will show its effect on q_1 - and q_3 -directions. Considering (12) it is possible to write:

$$\begin{aligned}
 i_{q1}(k+2) &= \hat{i}_{q1}(k) + \frac{T_m}{L_{q1}} \left[V_{q1}(k+1) - 2r_s \hat{i}_{q1}(k) + \omega L_{d1} \hat{i}_{d1}(k) + \omega \psi_{pm1} + \omega \Delta \psi_{pm1} \right] \\
 &= \left[\hat{i}_{q1}(k) + \frac{T_m}{L_{q1}} \left(V_{q1}(k+1) - 2r_s \hat{i}_{q1}(k) + \omega L_{d1} \hat{i}_{d1}(k) + \omega \psi_{pm1} \right) \right] + \left[\frac{T_m}{L_{q1}} (\omega \Delta \psi_{pm1}) \right] \\
 &= i_{q1}(k+2)_{norm} + \Delta i_{q1}(k+2)
 \end{aligned} \tag{26}$$

$$\begin{aligned}
 i_{q3}(k+2) &= \hat{i}_{q3}(k) + \frac{T_m}{L_{q3}} \left[V_{q3}(k+1) - 2r_s \hat{i}_{q3}(k) + 3\omega L_{d3} \hat{i}_{d3}(k) + \omega \psi_{pm1} + 3\omega \Delta \psi_{pm3} \right] \\
 &= \left[\hat{i}_{q3}(k) + \frac{T_m}{L_{q3}} \left(V_{q3}(k+1) - 2r_s \hat{i}_{q3}(k) + \omega L_{d3} \hat{i}_{d3}(k) + 3\omega \psi_{pm3} \right) \right] + \left[\frac{T_m}{L_{q3}} (\omega \Delta \psi_{pm3}) \right] \\
 &= i_{q3}(k+2)_{norm} + \Delta i_{q3}(k+2)
 \end{aligned} \tag{27}$$

where $i_{q1}(k+2)_{norm}$ and $i_{q3}(k+2)_{norm}$ are stator current in q_1 - and q_3 -directions by the end of $(k+1)^{th}$ modulation period and under normal conditions. In addition, $\Delta i_{q1}(k+2)$ and $\Delta i_{q3}(k+2)$ are the introduced error in this direction due to variation of rotor PM flux.

5. Experimental Evaluation of Proposed EKF-PDC Method

5.1. Test Bench Structure

Experimental tests are conducted in laboratory to evaluate the behaviour of proposed controlling method. Figure 6 illustrates the experimental test bench.

Fig. 6: General configuration of experimental test bench

Implemented five-phase BLDC generator incorporates a double-layer winding with fractional-slot structure. Similar to [16] and [17], induced back-EMF waveform of this machine contain 11% of 3rd harmonic.

A five-leg two-level inverter is used to generate the required voltages. This inverter is controlled by a dSpace. The main three tasks of the dSpace module include 1) control algorithm execution, 2) five-phase carrier-based modulation, and 3) pulse generation for IGBT gate drivers. The frequency of control

algorithm in dSpace is set on 4 kHz. This frequency is different from modulation frequency which is 10 kHz. Current measurement signals are generated by five Hall Effect sensors, and rotor position is measured by using an incremental encoder with 9000-pulses per revolution.

The speed is fixed by the load system, and generated torque is controlled by five-phase BLDC generator. As a result, developed controlling algorithms for five-phase BLDC generator are equivalent to torque/current control. The load system is a commercial three-phase servo drive known as SINAMICS-S120. A real-time controller known as compact Rio (made by National Instruments) is used to establish the required interference between SINAMICS-S120 and host PC.

5.2. Experimental Results and Discussion

Measured values of generator stator currents and mechanical torque are shown in Fig. 7 while changing the reference value of torque from 0.33 pu $\rightarrow$ 0.66 pu $\rightarrow$ 1.0 pu $\rightarrow$ 0.66 pu $\rightarrow$ 0.33 pu. Due to limited number of available oscilloscope channels, each part of this figure only contains 4 measurements. In addition, to have a better evaluation on dynamic behaviour of proposed controlling method, measured values of mechanical torque and stator currents are shown in Fig. 8 for two periods of fundamental current component.

Proposed current controlling method does not include any integrator, and as a result there is almost no overshoot in measured values of stator phase currents and generated torque.

5.3. Transient Analysis of Proposed EKF-PDC Method

Regarding the deadbeat nature of implemented control algorithm, torque rise time is expected to be as long as one modulation period (0.25 ms). However during transient states, measured value of torque rise-time is 0.53 ms which is almost 2 times its expected value.

(a)

(b)

Fig. 7: Dynamic behaviour of proposed controlling method while changing reference torque from 0.33 pu $\rightarrow$ 0.66 pu $\rightarrow$ 1.0 pu $\rightarrow$ 0.66 pu $\rightarrow$ 0.33 pu., (a) first measurement - generator currents in four phases. Due to limited number of oscilloscope channels, I_E is not measured directly, (b) second measurement - reference and real values of torque

Fig. 8: Measured value of generated torque during transient states, (a) changing reference torque from 0.33 pu $\rightarrow$ 0.66 pu, (b) changing reference torque from 0.66 pu $\rightarrow$ 1.0 pu. Due to limited value of oscilloscope channels, only I_A , I_B , I_C and torque are shown in each case

382 The main reason of longer rise-time is limited value of dc-link voltage. Assuming that the main
 383 component of stator currents in each situation is i_{q1} and stator currents in the remaining directions are
 384 almost zero, the required voltage during transient states in different directions can be calculated from
 385 equation (12) and Table II. Table III is a summary of required voltages in $d_1q_1d_3q_3$ -directions during
 386 transient states, and their required peak-to-peak voltage in phase reference frame.

387 Table III: The required voltage to complete the transient state in one controlling loop (0.25 ms)

Transient state	V_{d1}	V_{q1}	V_{d3}	V_{q3}	V_{ABCDE} (p-p)
0.33 pu $\rightarrow$ 0.66 pu	-3.5096 V	58.6317 V	0 V	0.6873 V	58 V
0.66 pu $\rightarrow$ 1.0 pu	-7.0191 V	59.5184 V	0 V	0.6873 V	59 V

388
 389 As it can be seen, the required peak-to-peak value of applied voltage during each transient is more than
 390 dc-link value (48 V), which extends the rise-time to two consecutive controlling loops. It is important to
 391 note that the controlling algorithm is being executed with a frequency of 4 kHz while modulator frequency
 392 is 10 kHz. Higher frequency of modulator is the main reason of existing ripples during transient states
 393 (rise-time) of stator currents and electrical torque in Fig. 8.

394 Dynamic behaviour of generated torque is also considered. To have an analytical evaluation, the energy
 395 of torque error is integrated on four consecutive periods of stator phase currents. Both transient and steady
 396 state operation are considered in this evaluation. 20000 torque samples are measured, and in the case of
 397 transients, reference value of torque is changed in the middle of integration period. Integrated values of
 398 torque error are summarized in Table IV for each operational condition.

399 Table IV: The energy of torque error during different operational conditions

	Torque Error Energy [Nm^2] (pu)	
Steady State	Rated Conditions	1.08e-005
Transient State	0.33 pu $\rightarrow$ 0.66 pu	1.83e-005
	0.66 pu $\rightarrow$ 1.0 pu	1.98e-005

4.1 As it can be seen, the minimum value of torque error energy is related to steady-state operation. Under
 4.2 this condition, dc-link voltage is used to cope with stator resistance voltage drop, and induced back-EMF.
 4.3 While working in transients, dc-link voltage should also be used to cope with inductance voltage drops in
 4.4 each direction. As it can be seen, the energy of torque error is higher in transient states. The main reason of
 4.5 higher torque error in transients is dc-link limitations during rise time periods.

4.6 **5.4. - Sensitivity Analysis of Proposed EKF-PDC**

4.7 Sensitivity of proposed controlling method is experimentally evaluated respect to various system
 4.8 changes. Comparing to simulation section, experimental evaluation of sensitivity has some limitations.
 4.9 The first limitation is related to inverter block. As five-phase BLDC generator is always controlled by an
 4.10 inverter, it is not possible to evaluate the ideal case (no voltage drop in semiconductors and zero value of
 4.11 dead time). In addition, magnetic flux of rotor magnets is a fixed value during all tests. Conducted tests to
 4.12 evaluate the sensitivity of proposed method are summarized in Table V.

4.13 Table V: The differences between controlling block assumptions and real situation

	difference between controlling unit assumption and real situation	
experiment	controlling unit Assumption	real situation
experiment-1	Ideal inverter with no voltage drop and no dead time	Real inverter
experiment-2	Ideal inverter and nominal value of dc-link voltage	Real inverter and 20% voltage drop in dc-link voltage
experiment-3	Ideal inverter and rated value of stator resistance (0.1Ω)	Real inverter and 0.2Ω as stator resistance

4.14
 4.15 In the first experiment (experiment-1), precise values of generator parameters are used in control
 4.16 algorithm. In addition, inverter block is considered ideal and nonlinear characteristics of its
 4.17 semiconductors are not considered in controlling algorithm.

In the next step (experiment-2), stator phase resistances are changed from 0.1Ω to 0.2Ω by adding external resistances to generator terminals, and at the same time, rated values of stator resistances are used in controlling algorithm.

In the third step (experiment-3), the amplitude of dc-link voltage is reduced by 20%, and at the same time rated value of dc-link voltage is used in controlling algorithm.

Similar to simulation section, in each experiment the difference between real and reference values of stator phase currents are measured (current error), and after that, its energy is integrated over one period of fundamental electrical frequency:

$$E = \int_T \sum_{j=d1,q1,d3,q3,o} \left[I_j^* - I_j(K+2) \right]^2$$

(28)

Figure 9 shows the energy of stator current errors for each experiment.

Fig. 9: The energy of current errors during each experiment

The minimum energy value of stator current errors is correspondent to experiment-1. During this experiment the main source of current error is nonlinear characteristics of inverter. As it can be seen from Fig. 9, the energy of current errors during experiment-1 is more than 50% its value during other experiments (51% its value during experiment-2 and 63% its value during experiment-3). As electrical machine is always fed by a real inverter, it is possible to write:

$$E_{nonlinear\ INV} > 0.5 (E_{nonlinear\ INV} + E_{dc-link})$$

(29)

438 and

439
$$E_{nonlinear\ INV} > 0.5 (E_{nonlinear\ INV} + E_{Rs})$$

440 (30)

441 while $E_{nonlinear\ INV}$, $E_{dc-link}$, and E_{Rs} are respectively the energy of stator current errors due to “nonlinear
442 inverter characteristics”, “inaccurate dc-link voltage” , and “stator resistance increment”.

443 Equations (29) and (30) respectively result in:

444
$$E_{nonlinear\ INV} > E_{dc-link}$$

445 (31)

446 and

447
$$E_{nonlinear\ INV} > E_{Rs}$$

448 (32)

449 In other words, the energy of stator current errors due to “inverter nonlinear characteristics” is higher than
450 its value due to “inaccurate dc-link voltage” and “inaccurate stator resistance”. This result is in accordance
451 with simulation results where the maximum value of stator current errors was due to inverter nonlinear
452 characteristics.

453 In addition, the energy of stator current errors in experiment-3 is higher than its value in experiment-2.

454 Regarding Table V, it is possible to write:

455
$$(E_{nonlinear\ INV} + E_{dc-link}) > (E_{nonlinear\ INV} + E_{Rs})$$

456 (33)

457 or

458
$$E_{dc-link} > E_{Rs}$$

459 (34)

In other words, the energy of stator current errors due to “inaccurate dc-link voltage” is higher than its value due to “inaccurate stator resistance” which is again in accordance with simulation results.

1. Conclusion

Five-phase BLDC generators are becoming more popular in low maintenance applications of wind power plants. In such applications, fast and robust control of stator phase currents has a high priority. To improve these two aspects, a new predictive deadbeat controlling method is proposed in this paper to control the generated electrical torque and stator currents of a five-phase BLDC generator. Extended Kalman Filter is used in the estimation step of proposed method. Simulations are developed to evaluate the sensitivity of proposed method respect to different system variations. In each case, the energy of stator current errors is measured by the end of estimation step and voltage application step of proposed algorithm. It is shown that inverter nonlinear characteristics and dc-link voltage drop result in more current error both in estimation step and voltage application step. In addition, proposed controlling method is experimentally evaluated on a five-phase BLDC generator. Although the objective of proposed EKF-PDC method is to eliminate the stator current errors in one modulation period, but limited values of dc-link capacitor can reduce the speed of proposed controlling method. Proposed method is able to generate constant torque with no overshoot.

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