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A Novel Model Predictive Voltage Control of Brushless Cascade Doubly-fed Induction Generator in Stand-Alone Power Generation System

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ABSTRACT

The aim of this paper is to present a model predictive voltage control (MPVC) strategy for stabilizing the amplitude and frequency of the output voltages in a Brushless Cascade Doubly-Fed Induction Generator (BCDFIG) under load changing and variable speed of generator shaft in stand-alone mode. BCDFIGs are a particular model of BDFIGs that consist of two induction machines called the control machine and the power machine, so that their rotors are electrically and mechanically coupled together. In this paper, unlike previous studies, which the BCDFIG rotor was integrated, the generator rotor is analyzed as a complex of two rotors of two separate induction machines. Also, the output voltages of generator are predicted and regulated in different operating conditions by using model predictive voltage control. In order to stabilize the amplitude and frequency of BCDFIG output voltages, the appropriate voltage vector is determined to apply to the stator of control machine. This generation system is simulated and simulation results prove the accuracy of proposed method. Experimental results on prototype BCDFIG are provided to validate the proposed methods. Finally, the effectiveness of the proposed controller brings better power capture optimization under variable speed wind turbine.

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NOMENCLATURE

PM, CM	Power machine and control machine	k	Sample number
$\omega_p,\ \omega_{rp}$	PM and its rotor angular frequency	sp, sc, r	PM stator, CM stator and rotor
$\omega_c,\ \omega_{rc}$	CM and its rotor angular frequency	rp, rc	PM rotor, CM rotor
T_s	Sampling time	l, mp, mc	Leakage, PM and CM mutual Inductance
$V,\ i,\ \lambda$	Voltage, current and flux	d, q	d-q rotating frame
R, L	Resistance and Inductance		

1. INTRODUCTION

Nowadays, the wind energy plays an important role in generating renewable energy. Many generators have been used in wind turbines which among them DFIG due to its advantages has the largest share of the market [1]. The controllability of active and reactive power of DFIG is one of the important advantages of this generator. Despite many advantages of DFIG, this generator must be frequently repaired and maintained due to its slip-rings, brushes, and it has a poor performance against network voltage drops [2–5].

In order to take advantages of DFIG and solve its related problems, many studies have been conducted on brushless doubly-fed induction generators (BDFIGs) as future generators of wind turbines [6–13]. Here, BCDFIG is a particular model of DFIG that, instead of putting power and control coils in a structure, are created from the cascade connection of two induction motors and that they are easily implemented. The high controllability and reliability of these generators are their important advantages due to eliminating of slip-rings, brushes and the ease of cascading two separate induction machines [14, 15]. Although there are many studies about the control methods of connected-network BDFIG in different operating conditions, there are few studies on this generator in stand-alone generation systems [16, 17].

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To control the grid-connected generator system, the control of active and reactive power generators is remarkable. Whereas for stand-alone generation systems, the stabilization of the amplitude and frequency of the output voltages of generator during load changing and variable speed of generator shaft are very important. Thus, the control methods of grid-connected generator system cannot be used directly in the case of stand-alone generation systems. Among the advanced control techniques, model predictive control is one that has been successfully used in industrial application [18]. This method is a high-performance technique that has advantages such as flexibility in controlling different variables and good dynamic response. To date, this method has been utilized in different drives applications for the aforementioned reasons [8, 15, 19, 20].

In literature, to analyze the dynamic model of BDFIGs, two types of models including coupled-circuit and Unified reference frame model are used. Although the coupled-circuit model of BDFIG, discussed by Kashkooli et al. [21] showed a high accuracy, the physical analysis for the dynamic behavior of the machine using this model due to its complexity, large number of parameters and also their dependence on the position of the rotor is very crucial [21, 22]. The Unified reference frame model of BDFIG by Posa was presented and it for applying new control methods on the generator such as predictive control is very troublous [21].

Extensive researches have been attributed to controller method of DFIG. These control schemes are based on method such as current control, direct torque control (DTC) and direct power control (DPC) [23, 24]. The conventional proportional–integral (PI) method was widely proposed [25]. To design the vector controller based on PI, the resistance of stator or rotor is neglected as well controlling parameter during power generation [26]. The other design is based on controlling the stator current which is neglected the resistance voltage loss [27]. These methods suffer from transformations in structure control during reference frames conversion. Furthermore, the voltage-source converters (VSCs) and DTC were developed for controlling of the machine's torque or power [28]. Nevertheless, during variations of speed and load machine, switching frequency changes for controlling the active and reactive powers [29]. Also, the model predictive control (MPC) has been developed for DFIG with uncertain parameters. The DPC and predictive torque control (PTC) based on MPC has been proposed more recently DFIG [30]. But, this suffers from complex algorithms due to stator flux orientation.

In most studies in the field of BDFIG analysis and even BCDFIG, the rotor of this generator is integrated which causes the voltage and current of different parts of this generator are not detectable, separable and controllable. If a problem occurred, to identify the location of the problem and disturbed machine is not easy. Thus, using the different control methods on this generator with an integrated rotor is more difficult.

In this paper, to stabilize the amplitude and frequency of BCDFIG output voltages in stand-alone mode and their quick dynamic response against the load changing and variable speed of generator shaft, a model predictive voltage control (MPVC) strategy has been presented. In this method, the future output voltages of the generator according to the other parameters of the machine in the presence of electrical and mechanical changes applied to the system are predicted. In addition, the desirable voltages of control machine for stabilizing the output voltages of the generator are determined. Unlike previous studies, the equivalent circuit of BCDFIG with using the electrical connection and mechanical coupling of two induction machines as Power Machine (PM) and Control Machine (CM) are presented and the expansion of their equations are exhibited in the d-q frame. To stabilize the stator voltage of the power machine, the enough current must be injected into rotor of PM. Therefore, one of the main problems of control methods for BCDFIG is the control of rotor current.

By applying voltage to the stator of control machine with a external converter, the current is inductted in the rotor coils of the control machine. Due to the electrically connection between rotor of CM and PM, the generated current in CM is injected to rotor coil of PM. Finally, the injected current and the rotational motion of the rotor stimulate the stator winding field and amplify the generated the energy.

The contribution of this paper is summarized as follows:

- Evaluation of operation BCDFIG
- Comprehensive design and digital implementation of the predictive voltage control method
- Comparison PI controller to MPVC
- Considering of dynamic response in variable load and wind speed

In this study, the mathematic model of BCDFIG and predictive voltage control method are presented and modeled in MATLAB/Simulink/M-File. The consideration simulation results are presented in order to evaluate performance of proposed method under load change and wind speed variation. Then the experimental results will be shown that with using the proposed control method, the voltage and frequency stability of BCDFIG in the above-mentioned changes are maintained and is more effectiveness comparing than the other controller methods. Finally, concluding remarksare summarized in the last section.

2. BCDFIG MODEL

2. 1. Power Machine At first, the structure and performanc e of the BCDFIG are described and then the mathematical equations of this generator are presented. The schematic structure of BCDFIG is shown in Figure 1.

As shown in Figure 1, this generator consists of two induction machines called the control machine and the power machine so that their rotors are electrically and mechanically coupled together. Figures 2 and 3 show the steady state equivalent circuit of BCDFIG consisting of two induction machines on d-q axes.

$$\begin{cases} L_{sp} = L_{lsp} + L_{mp} \\ L_{sc} = L_{lsc} + L_{mc} \end{cases} \qquad \begin{cases} L_{rp} = L_{lrp} + L_{mp} \\ L_{rc} = L_{lrc} + L_{mc} \end{cases} \tag{1}$$

The equations of the rotors flux and the stator flux of power and control machines, in the d-q system stated as follows:

$$\begin{cases} \lambda_{sp}^{dq} = L_{sp} i_{sp}^{dq} + L_{mp} i_{rp}^{dq} \\ \lambda_{rc}^{dq} = L_{rc} i_{rc}^{dq} + L_{mc} i_{sc}^{dq} \end{cases} \qquad \begin{cases} \lambda_{rp}^{dq} = L_{rp} i_{rp}^{dq} + L_{mp} i_{sp}^{dq} \\ \lambda_{sc}^{dq} = L_{sc} i_{sc}^{dq} + L_{mc} i_{rc}^{dq} \end{cases} \tag{2}$$

Also, the equations for the voltage of stators and the rotors of power and control machines can be written as follows:

$$v_{sp}^{dq} = R_{sp} i_{sp}^{dq} + \frac{d\lambda_{sp}^{dq}}{dt} \pm \omega_p \lambda_{sp}^{dq} \tag{3}$$

$$v_{rp}^{dq} = R_{rp} i_{rp}^{dq} + \frac{d\lambda_{rp}^{dq}}{dt} \pm \omega_{rp} \lambda_{rp}^{dq} \tag{4}$$

$$v_{rc}^{dq} = R_{rc} i_{rc}^{dq} + \frac{d\lambda_{rc}^{dq}}{dt} \pm \omega_{rc} \lambda_{rc}^{dq} \tag{5}$$

$$v_{sc}^{dq} = R_{sc} i_{sc}^{dq} + \frac{d\lambda_{sc}^{dq}}{dt} \pm \omega_c \lambda_{sc}^{dq} \tag{6}$$

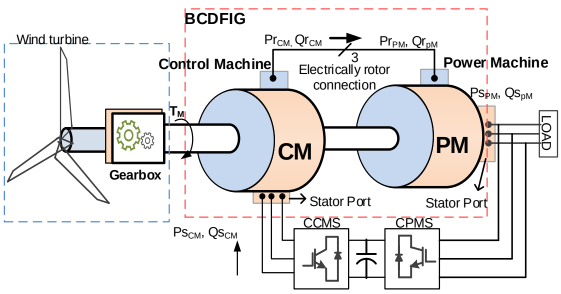


Figure 1. The schematic structure of BCDFIG

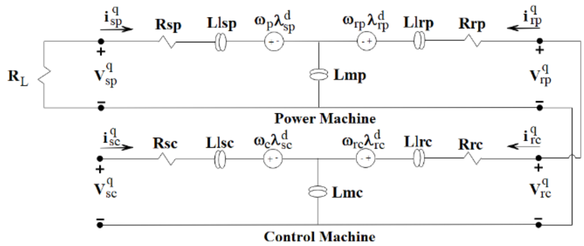


Figure 2. The equivalent circuit of BCDFIG on q axis

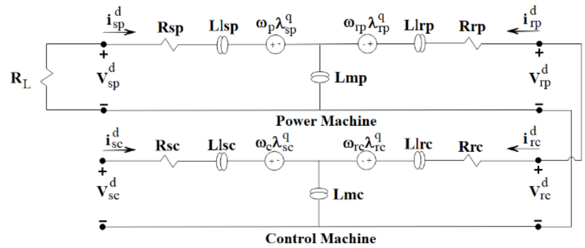


Figure 3. The equivalent circuit of BCDFIG on d axis

In previous studies, which considered the rotor to be integrated, to simplify, the BCDFIG rotor voltage was considered to be zero, which $v_{rp}^{dq} = v_{rc}^{dq}$ is considered in this paper. Recently, predictive control method applied to power and renewable energy systems [15, 16]. However, the modeling of MPVC is based on the voltage derivative relationship of PM stator in dq frame.

According to electrically coupling of BCDFIG rotors, the rotor voltages and current are equal.

$$\begin{aligned} vr_{pm} &= vr_{cm} \\ ir_{pm} &= ir_{cm} \end{aligned} \tag{7}$$

Hence, Equations (4) and (5) can be concluded equal, assuming $j_1 = 1 + \frac{R_{sp}}{R_L}$.

The stator voltage of PM equations in the *dq* reference frame can be expressed as follows:

$$\frac{dv_{sp}^{q}}{dt} = \frac{R_L}{L_{mp}}\left[R_r i_{rp}^{q} + L_r \frac{di_{rp}^{q}}{dt} - L_{mc}\frac{di_{sc}^{q}}{dt} - \omega_{rp}(\lambda_{rc}^{d} - \lambda_{rp}^{d}) \right] \tag{8}$$

It is worth to be mentioned that the rotor winding is shorted in both PM and CM, practically. It causes the rotor voltage equal to zero. Substituting Equations (7) and (3), the current rotor of PM can be found in Equation (9). where, $j_2 = -L_{mp} + \frac{L_r L_{sp}}{L_{mp}}$; so,

$$\frac{di_{rp}^{q}}{dt} = \frac{1}{j_2}\left[-j_1 v_{sp}^{q} - \frac{L_{sp}}{L_{mp}} R_r i_{rp}^{q} + \frac{L_{sp} L_{mc}}{L_{mp}} \frac{di_{sc}^{q}}{dt} + \frac{L_{sp}}{L_{mp}} \omega_{rp}(\lambda_{rc}^{d} - \lambda_{rp}^{d}) + \omega_p \lambda_{sp}^{d} \right] \tag{9}$$

Substituting Equation (9) into Equation (6) results obtained in Equation (10), assuming $j_3 = L_{sc} - \frac{L_{mc}^2 L_{sp}}{j\,2L_{mp}}$

$$\frac{di_{sc}^q}{dt} = \frac{1}{j_3}\Bigg[v_{sc}^q - R_{sc} i_{sc}^q - \frac{j_1}{j_2} L_{mc} v_{sp}^q - \frac{L_{mc}}{j_2}\frac{L_{sp}}{L_{mp}} R_r i_{rp}^q + \frac{L_{mc}}{j_2}\frac{L_{sp}}{L_{mp}} \omega_{rp}(\lambda_{rc}^d - \lambda_{rp}^d) + \frac{L_{mc}}{j_2}\omega_p \lambda_{sp}^d - \omega_c \lambda_{sc}^d\Bigg] \tag{10}$$

Based on Equation (6), as the above procedure continues for the d axis, the rotor and stator equations of PM and CM can be obtained as follows, respectively.

$$\frac{dv_{sp}^d}{dt} = \frac{R_L}{L_{mp}}\left[R_r i_{rp}^d + L_r \frac{di_{rp}^d}{dt} - L_{mc}\frac{di_{sc}^d}{dt} + \omega_{rp}(\lambda_{rc}^q - \lambda_{rp}^q)\right] \tag{11}$$

$$\frac{di_{rp}^d}{dt} = \frac{1}{j_2}\Bigg[-j_1 v_{sp}^d - \frac{L_{sp}}{L_{mp}} R_r i_{rp}^d + \frac{L_{sp}L_{mc}}{L_{mp}}\frac{di_{sc}^d}{dt} - \frac{L_{sp}}{L_{mp}}\omega_{rp}(\lambda_{rc}^q - \lambda_{rp}^q) - \omega_p \lambda_{sp}^q\Bigg] \tag{12}$$

$$\frac{di_{sc}^d}{dt} = \frac{1}{j_3}\Bigg[v_{sc}^d - R_{sc} i_{sc}^d - \frac{j_1}{j_2} L_{mc} v_{sp}^d - \frac{L_{mc}}{j_2}\frac{L_{sp}}{L_{mp}} R_r i_{rp}^d - \frac{L_{mc}}{j_2}\frac{L_{sp}}{L_{mp}}\omega_{rp}(\lambda_{rc}^q - \lambda_{rp}^q) - \frac{L_{mc}}{j_2}\omega_p \lambda_{sp}^q + \omega_c \lambda_{sc}^q\Bigg] \tag{13}$$

2. 2. Control Machine The main contribution of the machine side converter is to control the power rotor of cascaded power machine, which is magnetically transferred to secondary stator terminals. The supplied energy of PM can be further through CM and its converter. Moreover, according to constant speed electrical field, the stator winding relative to rotor winding gives an extra degree of freedom. Consequently, the CM helps to achieve close to unity power factor of PM in variable or asymmetry load. The other advantage is controlling the reactive power by current component of CM's-axis stator and the active power is generated through the stator of PM.

3. MODEL PREDICTIVE CONTROL VOLTAGE

Recently, the Model Predictive Control (MPC) is more attracted for power controlling system which can optimally predicted the main parameters and system variables to provide fast dynamic response while improved overall performance. To achieve this target, the sampling time based on predictive time is fixed to the sampling time. A cost function is defined to identify the optimum controller parameters so that optimizes switching state value is applied to the next sample step. The control system of BCDFIG involved of the rectifier which is provided the controllable DC source voltage for second voltage source inverter that acting as main controller of CM. In this paper the proposed predictive voltage control (MPVC) approach is presented in Figure 4. The proposed MPVC generates an optimize cost function along with the stator voltage to predict the future trajectories. It is worth to be mentioned that this function affects to improve the performance of the system against disturbance, variable speed turbine and load.

The MPVC approach evaluates the PM stator voltage error during sampling time and then identifies the best voltage vector that has the least voltage error value though the over predictive time. The typical sampling sequence of the system shows Figure 5.

3. 1. MPVC Modelling According to continuous-time equations, for simplifying the model system, the discrete-time model is defined by the forward Euler derivative approximation [29]. The equation of Euler derivative approximation is given below:

$$\frac{di}{dt} = \frac{i(k) - i(k-1)}{T_s} \tag{14}$$

where k is the sampling number and Ts is the time scale of these samples. Accordingly, substituting Equation (9) and (12) rotor current into Equations (7) and (11), stator voltage prediction in the synchronous reference frame at the sampling point (k+ 1) are calculated as follows:

$$v_{sp}^q(k+1) = \frac{T_S R_L}{L_{mp}}\Big[R_r i_{rp}^q(k) + L_r i_{rp}^q(k+1) - L_{mc} i_{sc}^q(k+1) - \omega_{rp}(k)[\lambda_{rc}^d(k) - \lambda_{rp}^d(k)]\Big] + v_{sp}^q(k) \tag{15}$$

$$v_{sp}^d(k+1) = \frac{T_S R_L}{L_{mp}}\Big[R_r i_{rp}^d(k) + L_r i_{rp}^d(k+1) - L_{mc} i_{sc}^d(k+1) + \omega_{rp}(k)[\lambda_{rc}^q(k) - \lambda_{rp}^q(k)]\Big] + v_{sp}^d(k) \tag{16}$$

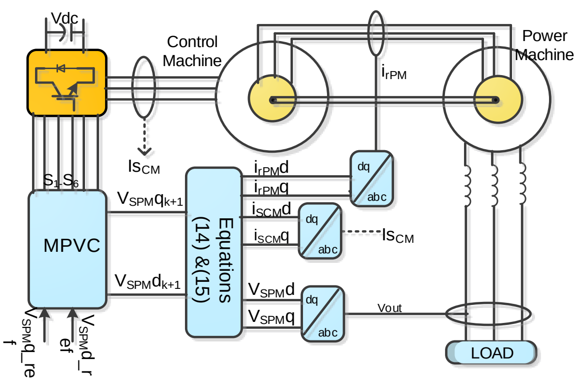


Figure 4. MPVC sachem of BCDFIG

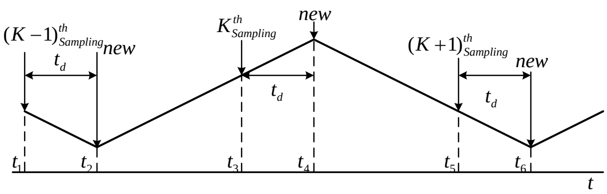


Figure 5. Typical sampling sequence

3. 2. MPVC Voltage Vector

In Equations (15) and (16) the values $i_{rp}^{q}, i_{sc}^{q}, i_{rp}^{d}, i_{sc}^{d}$ in the instantaneous (k+1) can be easily extracted using Euler's approximation and Equations (9), (10), (12) and (13). The function of this method is based on applying the above voltage vectors to Equations (7) to (13). Finally, the 8 different values according to voltage vector will be obtained on both the d- q axes of the synchronous reference frame for generating the output voltages. The function is involved of the absolute error between the reference and the predicted voltage stator in frame reference q and the absolute error among voltage reference and the predicted voltage stator in frame reference d. The cost function always is calculated for each of the 7 feasible switching statuses follows:

$$g = \left|v_{sp\_ref}^{q} - v_{sp}^{q}(sw)\right| + \left|v_{sp\_ref}^{d} - v_{sp}^{d}(sw)\right| \tag{16}$$

where SW is related to switching mode, which varies from 0 to 7.

The weight factor of the model predictive control cost function straightly affects performance of the controller and robustness under uncommon operating conditions such as model parameter inconformity. It is worth mentioning that the proposed MPVC is capable to control various major parameters with a single control law. For this target, due to the same nature of the two variables parameters voltages V_{SP}^{d} and V_{SP}^{q} of cost function, the unity weighing factor is selected that cases the normalizing the cost function. Consequently, due to the unnecessary for weight coefficients there is no required to use complex methods to tuning these coefficients.

In the MPVC method, a decision will be made according to the status of the switches in the inverter, which gives 8 switching modes, U_1, U_2, $U_{0and(7)}$ as illustrated in Figure 6. In which, cases (000) and (111) are in fact the same state and represent the zero voltage. According to the inverter switches, the value 1 is generated by the cost function to turn ON the upper switches of the inverter and also the value 0 is indicating the connection of the inverter for the lower. In this method, at each step, the generator output voltages are sampled and all the vectors shown in Figure 6 are applied to the stator of the control machine. First, the control machine stator current, then the BCDFIG rotor current, and finally the BCDFIG output voltages at the moment

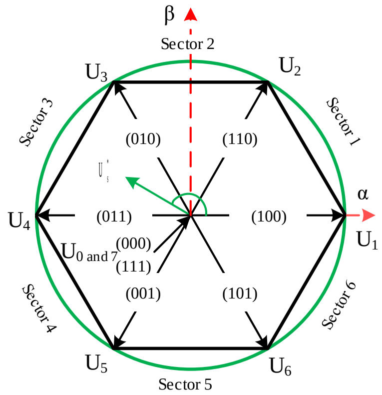


Figure 6. Voltage vectors used in the MPVC

(K+1) are predicted and compared with the generator output voltage references. Each voltage vector applied to the control machine stator that minimizes the objective function is selected in that step and applied to the control machine stator in next step. Since the generator output voltages are predicted at any given moment, in sudden electrical and mechanical changes of the system, the predictive control voltage method has a very high operating speed in maintaining the amplitude and frequency of the generator output voltages.

4. SIMULATION AND PRACTICAL IMPLEMENTATION

In order to demonstrate the effectiveness and performance of proposed method, the obtained equations, in pervious section, are performed in MATLAB/Simulink/M-File. The specifications of prototype BCDFIG used in this simulation are summarized in Table 1. The sampling time has been consideredin this simulation is 1μs. A 2.2 kW inductionmotor driven by a 2.5 kW inverter is used instead of a wind turbine to generate speed. A two–level inverter is provided the controllable energy for stator of CM, produced by the DSP TMS320F28335.

TABLE 1. Parametersused in simulation

Specifications	Power Machine	Control Machine
Stator resistance (Ω)	0.3332	1.8372
Rotor resistance (Ω)	0.337	2.4261
Stator leakage inductance (H)	0.6995	1.9268
Rotor leakage inductance (H)	0.6995	1.9268
Magnetic inductance (H)	20.81	58.43
Rated power (kW)	9.2	3
Number of poles	4	4

As shown in Figure 7, it is assumed that the mechanical speed of the generator shaft increases from 30 rpm to 300 rpm with increasing wind speed, and that the load step applied to the generator suddenly. These changes are shown in Figure 7.

According to specification of generator, the requirement speed of shaft of turbine should be over 300 rpm/min for achieving sustainable output voltage of generator. The test results are shown in Figure 7 with the rotorspeed maintained constant at 300 rpm/min. In this paper, the proposed MPVC strategy with the sampling time 1µs is applied for BCDFIG. The converter side of PM is provided 220vdc for inverter.

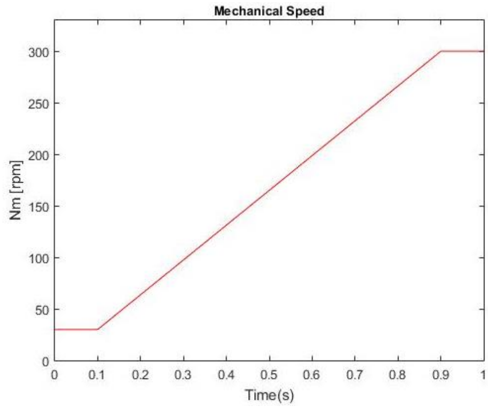
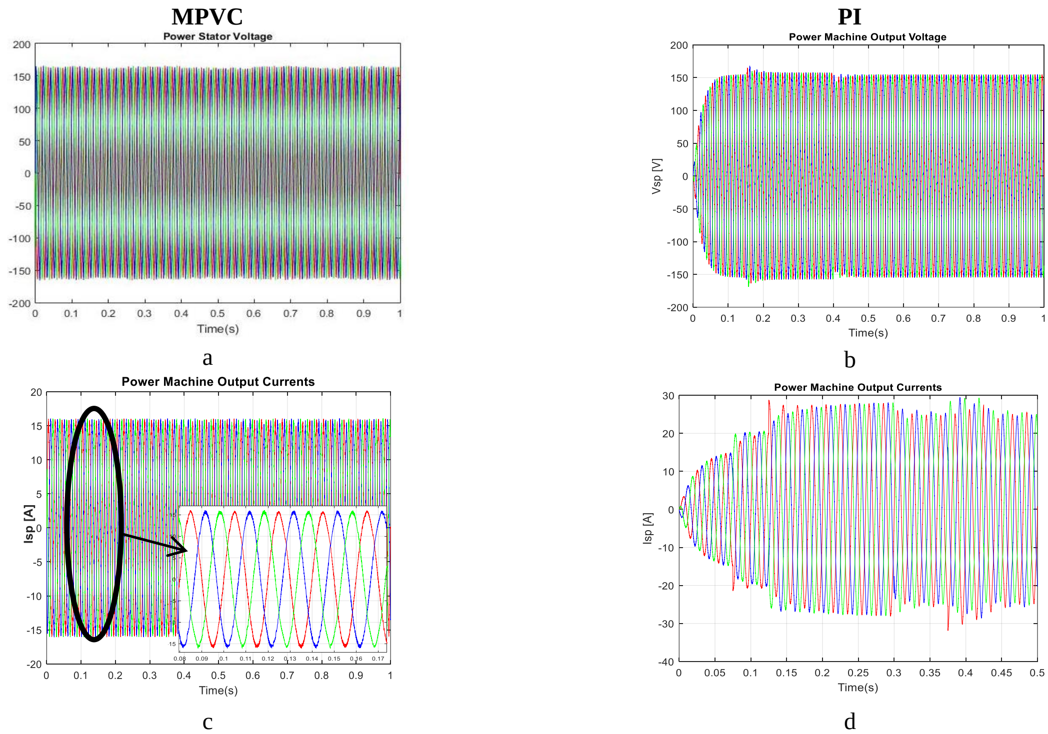


Figure 7. Changes in the mechanical speed of the BCDFIG shaft

4. 1. Controller Dynamic Performances The performance of the proposed MPVC for BCDFIG is compared with PI controller that has been proposed by Wu et al. [22]. The dynamic responses of BCDFIG for both methods under the same condition, against change load are illustrated in Figure 8. The nominal RMS voltage of stator PM is 110vac. However, the performance of the proposed control method is confirmed with precise regulation, minimum current distortions, very low ripples of voltage and current and fast dynamic response under variation load. In order to prove the ability of the proposed controller to stabilize the output voltage in case of over load and change the speed of the wind turbine, it seems that it is necessary to compare the performance of this controller with a conventional controller. The basis of this controller is based on sampling the output voltage and converting it to a d-q reference. The measured voltages are compared with their reference value and then PI controller adjusts the two voltage variables. The control coefficients for this PI controller are as follows: kpd=0.002, kid=0.00007, kpq=0.002, kiq=0.00007. Figure 8 shows the power stator voltage under PI controller. By applying the predictive control voltage method to the generator, the amplitude and frequency of the generator output voltages remain constant as the current changes at 0.4s the consumption load and increases the speed of the generator shaft. This proves the correctness and robustness of the control proposed method, as shown Figure 8a. It is visible that the overshoot



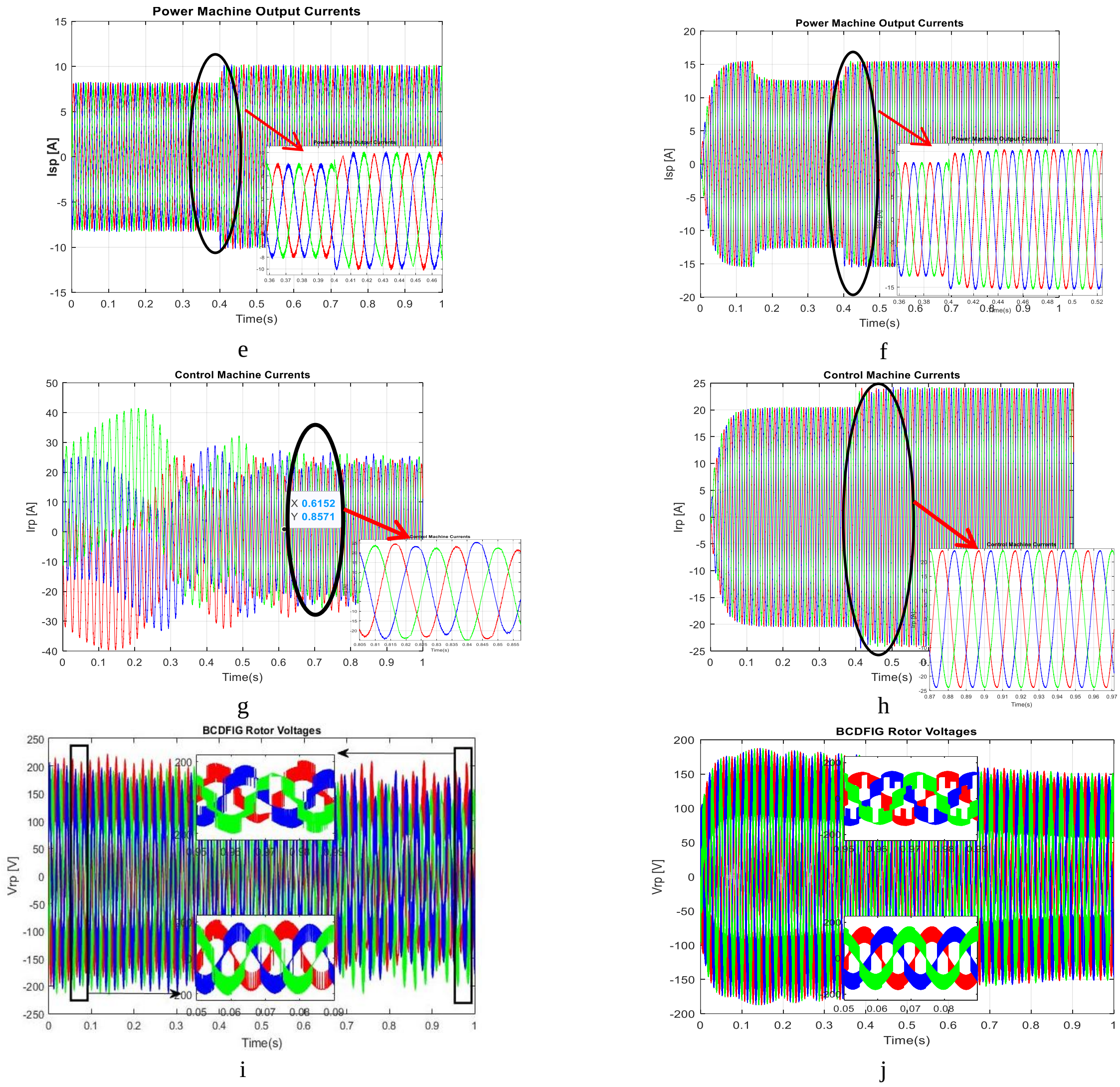


Figure 8. Comparison**;** steady-state performance of with proposed MPVCand PI strategies at rotor speed

or undershoot has not appeared against the PI method that has 3v undershoot voltage during changing load. For Figures 8c and 8d, the distortions of output current with PI method is high comparing with MPVC method due to its insufficient control bandwidth. As seen, the output currents of PM were become balanced (at 15 A) for MPVC at the step load from zero. As seen from Figures 8e and 8f, the BCDFIG with PI method is very slow at the zero step load. But the MPVC has fast reponse at the step load from zero to 8 A and then rised to 10 A. It takes to account that the PI controller does not have the ability to stabilize the output voltage in case of over load and change the speed of the wind turbine. Consequently, the MPVC strategy verifies a very fast dynamic performance during varing rotor slip and and step load compared to PI controller applied for BCDFIG.

The two-wire winding voltage of the power machine and control machine rotors, which was not available in previous studies due to the integration of the generator rotor, as shown in Figure 8i, with increasing mechanical speed of the generator shaft, the distortion created in the generator rotor increases.

4. 2. Experimental Results Test bench of BCDFIG prototype as presented in Figure 9. I is provided to validate the simulation results of theoretical proposed approach with the control method. The power set-up is consisted of two 4 poles DFIG machines that are connected in cascade configurations. Also, an induction machine with controllable speed shaft is coupled to the BCDFIG to provide initial speed. The back-to-back two-level converter is supplied the stator of CM and the local load is directly fed by stator of PM(110vac, 50 Hz) that the shaft speed of PM was rotated by induction machine at 300 rpm. Regarding to the advantages of digital signal processors (DSPs) such as very fast clock frequency, high frequency analog converters to digital converters (ADC) and the possibility high computational which allows using the intelligent control methods. Accordingly, the control system for both CCMS and CPMS is implemented with TMS320F28335 DSPs development board. The sampling frequency is selected 20 kHz and the predictive time for MPVC is chosen 10µs. The low pass filter with the cutting frequency at 20 kHz is applied to ADC for accuracy sampling in the output analog sampling. For evaluating the steady state performance of the proposed control strategy, the BCDFIG was carried out with different verification tests.

In the first study, the voltagestator of PM under full load operation is shown in Figure 10, that the zoomed voltage without any distortionis validated the quality of generated energy of PM. In order to evaluate the dynamic response of the proposed system, a step output load from 0.0 to 100% of load was conducted as shown in Figure 11. It is worth to be mentioned that fast transient response is fundamental requirement for standalone user such as drive, household consumption and industrial utilization applications to prevent damage to the devices. Therefore, the other study was investigated the dynamic response of BCDFIG in step load from 45 to 100% load (Figure 12) whereas at 5ms rising load is compensated, which validate the superior performance of the proposed method. At the same time it was subjected to the voltage change the CM, forcing the CM to generate the requirement voltage rotor of PM. As evidently appears from Figure 13. The MPVC algorithm is analyzed the

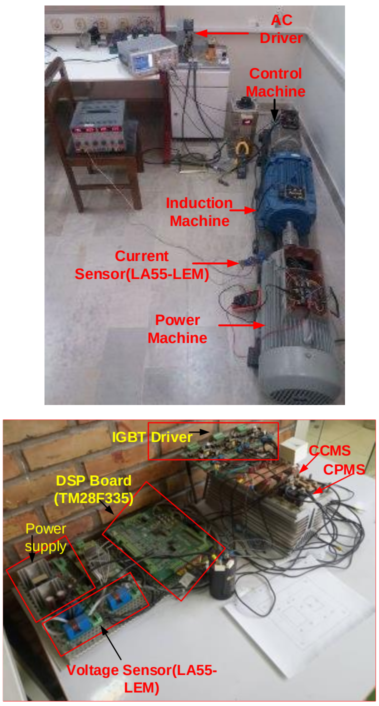


Figure 9. The set-up of the BCDFIG

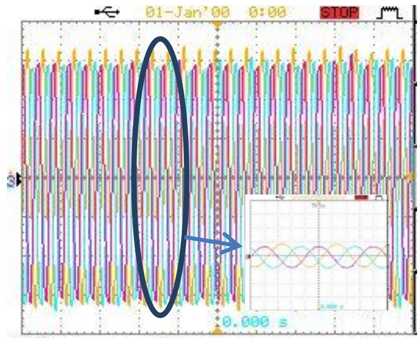


Figure 10. Experimental results under voltage stator of PM(50v/div)

sampled rotor current of CM which were estimated among the sampling period, and compares it with the reference current to introduce the Ir_{CM} error to near zero. The CCMS provided the voltage for the stator of CM very quickly at less than 15 ms.

In the next study, the validation of the performance during the accelerated the shaft speed is demonstrated. The shaft speed is raised from 300 to 900 rpm. It is worth mentioned that the ratio of the generated VArs of stator and rotor winding of PM depended on speed shaft which is directly effects the output power [23]. Under this condition, while the synchronous speed was increased speed from 300 to 900 rpm, the rotor current frequency

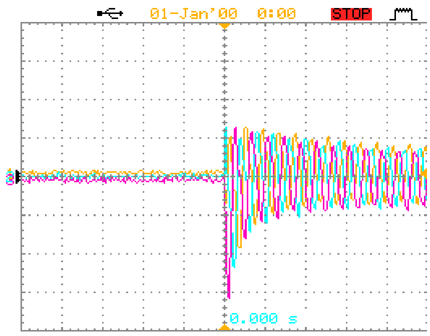


Figure 11. The stator current of PM for 100% step change of the output load(5 A/div)

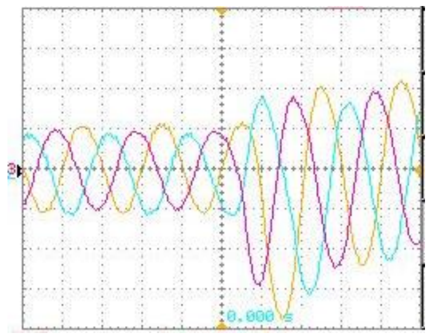


Figure 12. The stator current of PM under step output load from 45 to 100%(5 A/div)

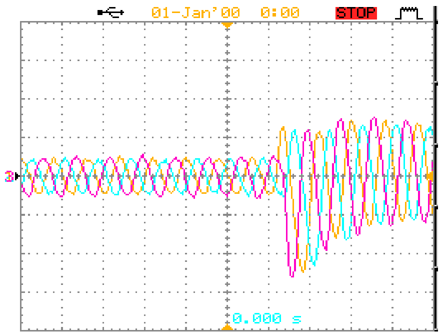


Figure 13. The stator voltage of CM under step output load from 45 to 100% (100V/div)

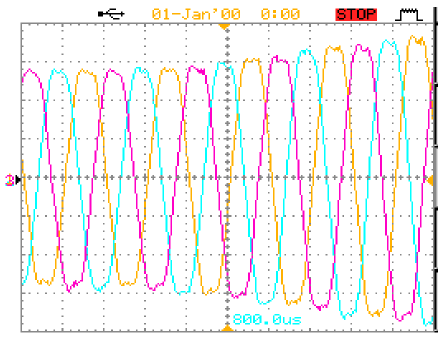


Figure 14. The stator voltage of CM under variable rotor speed (50 A/div)

of PM was decreased. Regarding to prediction of control parameters, the rotor and stator current of CM were predicted to compensate the stator voltage of CM. Due to exact compensation the reaching mininum of PM rotor current was prevented and keeping the constant output power. For $Vstator_{CM}$ shown in Figure 14, The CCMS is applied the $Vstator_{CM}$ compensation 180 vac due to varying the rotor slip. is depicted in Figure 14. Consequenty, The MPVC with high bandwidth exactly follows even small current errors with very high accuracy. But, other common control methods such as PI lead to considerable control errors due to bandwidth limitations. It can be observed from experimental results that the performance of MPVC is very fast and robust against speed and load variations. As shown in Table 2, the BCDFIG with MPVC efficiency is compared with other controller method that is about 93%.

The one factors of wind turbine is large inertia and speed variation at the moment. However, prediction of the very large variation of parameters in wind turbine is inevitable to maintain sustainable dynamic system. The predictive control method is well adapted to anticipate momentary change of parameters. The prediction method is best solution for following out the parameters to achieve optimum controller in order to smoother response of controller and improve dynamic performance of generator.

TABLE 2. Comparison of efficiency of Method controller

Controller	Efficiency (%)
LQG [27]	92
MPC with PTC [29]	90
PID [27]	87
SMC With DPC [30]	90
MPVC (Proposed)	93

5. CONCLUSION

In this paper, the predictive control voltage method is applied to a BCDFIG This study shows that this method has a fast and desirable performance in keeping the amplitude and frequency of the BCDFIG output voltages constant in stand-alone generation systems in sudden current changes in consumption load and mechanical changes in generator shaft speed. This proves the robustness and performance of the control method provided.

Contrary to popular control methods such as vector control, the proposed predictive control voltage method has the following advantages:

a. PI blocks and the trouble of selecting its coefficients were eliminated. In fact, in the vector method, with 8 PI coefficients, 8 appropriate and consistent choices had to be made to achieve the desired result. In this method, these troublesome blocks were removed.
b. No need for PWM in MPVC method. In this method, switching commands based on the cost function are performed. There is no need to generate a carrier wave and compare it to the reference value.
c. More balanced fluctuations in stable mode. In voltage predictive control methods, more accurate reference values are obtained due to predictor variables, resulting in more stable fluctuations in the steady state around the reference value.
d. An assessment of the efficiency between some other method controller and proposed MPVC scheme is presented in Table 2. This verified that BCDFIG with MPVC is efficient in terms of power capture and performance optimization.

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Persian Abstract

چکیده

هدف این مقاله ارائه یک مدل استراتژی کنترل ولتاژ پیش‌بینی کننده (MPVC) برای تثبیت دامنه و فرکانس ولتاژهای خروجی در یک ژنراتور القایی (BCDFIG) تحت تغییر بار و سرعت متغیر شافت ژنراتور در جایگاه است. حالت تنها BCDFIGs یک مدل خاص از BDFIG است که از دو ماشین القایی به نام ماشین کنترل و ماشین قدرت تشکیل شده است، به طوری که روتورهای آنها از نظر الکتریکی و مکانیکی بهم متصل می‌شوند. در این مقاله، برخلاف مطالعات قبلی، که روتور BCDFIG یکپارچه در نظرگرفته شده بود، روتور ژنراتور به عنوان مجموعه‌ای از دو روتور دو ماشین القایی جداگانه مورد تجزیه و تحلیل قرار می‌گیرد. همچنین، ولتاژهای خروجی ژنراتور با استفاده از مدل کنترل ولتاژ پیش‌بینی شده، در شرایط عملیاتی مختلف پیش‌بینی و تنظیم می‌شوند. به منظور تثبیت دامنه و فرکانس ولتاژهای خروجیBCDFIG، بردار ولتاژ مناسب تعیین می‌شود تا به استاتور ماشین کنترل اعمال شود. این سیستم تولیدی شبیه‌سازی شده و نتایج شبیه‌سازی صحت روش پیشنهادی را ثابت می‌کند. برای تأیید روش‌های پیشنهادی، نتایج تجربی در نمونه اولیه BCDFIG ارائه شده است. سرانجام، کنترل‌کننده پیشنهادی اثربخشی بهینه‌سازی بهتر جذب نیرو را تحت توربین بادی با سرعت متغیر به ارمغان می‌آورد.