Simple and Robust Direct-Model Predictive Current Control Technique for PMSGs in Variable-Speed Wind Turbines

Mohamed Abdelrahem, Zhenbin Zhang, Ralph Kennel
Institute for Electrical Drive Systems and Power Electronics
Technical University of Munich (TUM)
Munich, Germany
Corresponding author: mohamed.abdelrahem@tum.de

Hisham Eldeeb, Christoph Hackl
Research Group "Control of Renewable Energy Systems (CRES)"
Munich School of Engineering, TUM
Garching, Germany

***Abstract*—This paper presents a simple and robust direct-model predictive current control (DMPCC) scheme for surface-mounted permanent-magnet synchronous generators (PMSGs) in variable-speed wind turbines (VSWTs). The proposed DMPCC is based on computing the reference voltage vector (VV) directly from the demanded reference current using a deadbeat-like function. Then, the location of this reference VV is identified based on its angle. Finally, a certain cost function is evaluated for only three times to get the optimal voltage vector to be applied in the next sampling instant. However, the proposed DMPCC is a model-based control system, and accordingly, sensitive to parameter variations of the PMSG. To mitigate such limitation, a simple observer is designed to enhance the robustness of the proposed DMPCC scheme to variations of the PMSG parameters. The proposed DMPCC strategy has been experimentally implemented and its performance has been compared with that of the conventional DMPCC.**

***Index Terms*—Permanent-magnet synchronous generator, model predictive control, wind turbines, disturbance observer.**

I. INTRODUCTION

Compared with the doubly-fed induction generator [1], [2], the direct-drive permanent-magnet synchronous generator (PMSG) is more attractive, such as increasing the energy production, eliminating the gearbox, lowering maintenance cost, and enhancing the low voltage ride through (LVRT) capability [3]. Generally, permanent-magnet synchronous machines (PMSMs) are controlled according to the field-oriented control (FOC) principles based on proportional-integrator (PI) controllers [4], [5]. Those PI controllers give good steady-state control performance. However, their limited dynamic performance and linear nature are commonly referred to be their main drawbacks.

Currently, direct-model predictive control (DMPC), also called finite control set-model predictive control (FCS-MPC), is considered a promising and popular control scheme for power electronics and electrical drives because of its better transient response in comparison with the linear controllers and the absence of a modulator [6]–[13]. DMPC uses a finite-number of voltage vectors (VVs) and a discrete model to predict the future behavior of the system. Consequently, the voltage vector of the prediction which minimizes a pre-defined cost function is selected and applied in the next sampling interval. For 2-level power converters, 7 iterations for the current prediction and 7 evaluations of the cost function are required to obtain the optimal VV. Hence, a powerful digital signal processor (DSP) is essential to accommodate with the high computational load of the DMPC.

Recently, some methods have been presented to reduce this high computational load of the DMPC. In [14]–[17], a modified DMPC for reducing the calculation load has been proposed. The proposed strategy is based on calculating the reference voltage vector (VV) directly from the reference current using a deadbeat-like function and then evaluating the cost function for all the candidates VVs (7 times for 2-level power converter). This method has been modified in [18]–[20] by identifying the location of this reference VV, and accordingly, evaluating the cost function for only three times. However, only simulation results have been presented to validate the proposed method.

A well-known disadvantage of the model-based control schemes is its fragility against parameters uncertainties [21]. To mitigate this problem, an extended Kalman filter (EKF) is proposed in [22], [23] to estimate the machine parameters. An on-line estimation algorithm of the model parameters based on least-square method (LSM) is presented in [24]. However, the high computational load of these on-line estimation algorithms (i.e. EKF & LSM) is their main disadvantage. A robust DMPC strategy, which is independent of the model parameters, has been presented in [25]. This strategy uses the sampled current differences, instead of the machine model, to predict the current gradient under each switching action, and accordingly, the sensitivity to parameter variations is avoided. However, high-performance current sensors (i.e. higher cost) are required. In [26], adding of the last prediction errors of the previous switching state with a weighting factor to the predicted currents from the machine model is proposed to enhance the robustness of the FCS-MPC. However, tuning of the weighting factor is a time consuming process.

In this paper, a computationally efficient direct-model predictive current control (DMPCC) scheme for PMSGs is presented. The proposed DMPCC is based on the principles presented in [18], where the reference VV is directly calculated based on the reference current and the cost function is evaluated for only three times to obtain the optimal voltage vector. Furthermore, a simple observer is proposed to enhance the robustness of the proposed DMPCC against variations of the PMSG parameters. The proposed DMPCC and observer have been experimentally implemented/validated and its performance has been compared with that of the conventional DMPCC.

II. MODELING OF THE PMSG

The continuous-time model of the PMSG in the rotating reference frame (dq) can be written as follows [18], [27, Chap. 14]

$$\left.\begin{aligned} u_s^d &= R_{so} i_s^d + L_{so} \tfrac{d}{dt} i_s^d - \omega_r L_{so} i_s^q + \chi_s^d, \\ u_s^q &= R_{so} i_s^q + L_{so} \tfrac{d}{dt} i_s^q + \omega_r L_{so} i_s^d + \omega_r \psi_{pmo} + \chi_s^q, \end{aligned}\right\} \quad (1)$$

where u_s^d, u_s^q, i_s^d, i_s^q are the d- and q-axes components of the stator voltage and current of the PMSG, respectively. R_{so} and L_{so} are the nominal values of the stator resistance and inductance of the PMSG, respectively. $\omega_r = n_p \omega_m$ is the electrical angular speed of the rotor (n_p is pole pair number and ω_m is mechanical angular speed of the rotor) and ψ_{pmo} is the nominal value of the permanent-magnet flux linkage. χ_s^d and χ_s^q represent the summations of disturbances due to parameter variations and un-modeled uncertainties due to unmodeled dynamics. Both terms can be expressed as follows

$$\left.\begin{aligned} \chi_s^d &= \Delta R_s i_s^d + \Delta L_s \tfrac{d}{dt} i_s^d - \omega_r \Delta L_s i_s^q + \varepsilon_s^d, \\ \chi_s^q &= \Delta R_s i_s^q + \Delta L_s \tfrac{d}{dt} i_s^q + \omega_r \Delta L_s i_s^d + \omega_r \Delta\psi_{pm} + \varepsilon_s^q, \end{aligned}\right\} \quad (2)$$

where $R_s = R_{so} + \Delta R_s$, $L_s = L_{so} + \Delta L_s$, $\psi_{pm} = \psi_{pmo} + \Delta\psi_{pm}$, and ε_s^d, ε_s^q represent the un-modeled uncertainties for the d- and q-axis, respectively.

The DMPC relies on a discrete-time model of the PMSG to predict its future behavior for each switching vector. Applying the forward Euler method to the model in (1) and (2) gives the discrete model of the PMSG, which can be written as follows

$$\left.\begin{aligned} u_s^d[k] &= R_{so} i_s^d[k] + L_{so} \tfrac{i_s^d[k+1] - i_s^d[k]}{T_s} - \omega_r[k] L_{so} i_s^q[k] \\ &\quad + \chi_s^d[k], \\ u_s^q[k] &= R_{so} i_s^q[k] + L_{so} \tfrac{i_s^q[k+1] - i_s^q[k]}{T_s} + \omega_r[k] L_{so} i_s^d[k] \\ &\quad + \omega_r[k] \psi_{pmo} + \chi_s^q[k], \end{aligned}\right\} \quad (3)$$

$$\left.\begin{aligned} \chi_s^d[k] &= \Delta R_s i_s^d[k] + \Delta L_s \tfrac{i_s^d[k+1] - i_s^d[k]}{T_s} - \omega_r[k] \Delta L_s i_s^q[k] \\ &\quad + \varepsilon_s^d[k], \\ \chi_s^q[k] &= \Delta R_s i_s^q[k] + \Delta L_s \tfrac{i_s^q[k+1] - i_s^q[k]}{T_s} + \omega_r[k] \Delta L_s i_s^d[k] \\ &\quad + \omega_r[k] \Delta\psi_{pm} + \varepsilon_s^q[k], \end{aligned}\right\} \quad (4)$$

where k is the current sampling instant and T_s is the sampling time (i.e. $x[k] \approx x(kT_s)$ for any quantity above).

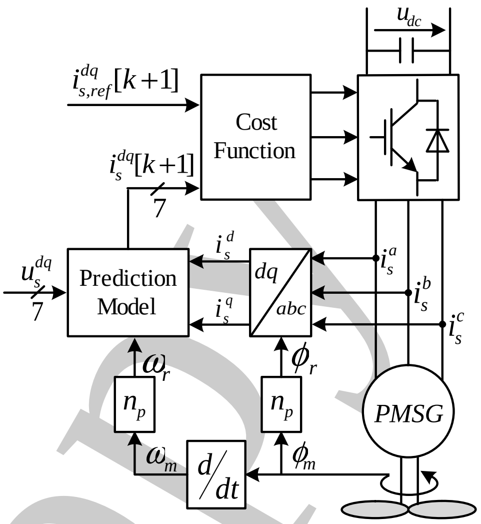


Fig. 1. Conventional DMPCC for PMSGs.

III. CONVENTIONAL DMPCC

The schematic diagram of the conventional DMPCC for PMSGs is shown in Fig. 1. Generally, for the conventional DMPC, the nominal parameters of the system are considered to predict its future performance [18]. Hence, rearranging (3) and neglecting $\chi_s^{dq}[k]$, the prediction model can be written as follows

$$\left.\begin{aligned} i_s^d[k+1] &= (1 - \tfrac{T_s R_{so}}{L_{so}}) i_s^d[k] + \omega_r[k] T_s i_s^q[k] + \tfrac{T_s}{L_{so}} u_s^d[k], \\ i_s^q[k+1] &= (1 - \tfrac{T_s R_{so}}{L_{so}}) i_s^q[k] - \omega_r[k] T_s i_s^d[k] - \tfrac{\omega_r T_s}{L_{so}} \psi_{pm} \\ &\quad + \tfrac{T_s}{L_{so}} u_s^d[k]. \end{aligned}\right\} \quad (5)$$

In this work, the cost function is defined by

$$g_c = \left| i_{s,ref}^d[k+1] - i_s^d[k+1] \right| + \left| i_{s,ref}^q[k+1] - i_s^q[k+1] \right|, \quad (6)$$

where $i_{s,ref}^d[k+1]$ and $i_{s,ref}^q[k+1]$ are the reference values of the $d-$ & $q-$axis currents.

Using the seven different voltage vectors (VVs) shown in Fig. 2 ($u_{s0}^{\alpha\beta}$–$u_{s6}^{\alpha\beta}$) of the two-level power converter and the prediction model in (5), seven different values of the currents can be predicted. Then, the cost function is evaluated for each VV and the VV, which its prediction minimizes the cost function (6), will be applied at the next sampling period.

The value of the q-axis reference current is computed according to the maximum power point tracking (MPPT) algorithm and the d-axis reference current is set to zero to achieve the maximum torque per ampere (MTPA) [18], [28].

IV. PROPOSED DMPCC

The concept of the conventional DMPCC is to select a VV $u_s^{dq}[k]$ which makes the predicted current $i_s^{dq}[k+1]$ close to its reference $i_{s,ref}^{dq}[k+1]$. Considering the predicted current in (5) and taking into account $\chi_s^{dq}[k]$, the reference VV $u_{s,ref}^{dq}[k]$ can

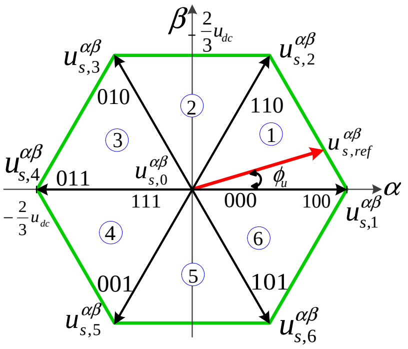


Fig. 2. Proposed sector distribution for 2-level power converter.

be directly calculated by replacing the current $i^{dq}_s[k+1]$ with the reference value $i^{dq}_{s,ref}[k+1]$ as follows

$$\left.\begin{aligned} u^d_{s,ref}[k] &= R_{so} i^d_s[k] + L_{so}\tfrac{i^d_{s,ref}[k+1]-i^d_s[k]}{T_s} \\ &\quad -\omega_r[k] L_{so} i^q_s[k] + \hat{\chi}^d_s[k], \\ u^q_{s,ref}[k] &= R_{so} i^q_s[k] + L_{so}\tfrac{i^q_{s,ref}[k+1]-i^q_s[k]}{T_s} \\ &\quad +\omega_r[k] L_{so} i^d_s[k] + \omega_r[k]\psi_{pmo} + \hat{\chi}^q_s[k], \end{aligned}\right\} \tag{7}$$

where $\hat{\chi}^d_s[k]$ and $\hat{\chi}^q_s[k]$ are the estimated values of the summation of disturbances due to parameter variations and un-modeled dynamics.

Then, this reference voltage is transformed to the stationary reference frame $\alpha\beta$ using the Park transformation. Therefore its location can be identified as shown in Fig. 2. Its angle is given by

$$\phi_u[k] = \mathrm{atan2}(u^\beta_{s,ref}[k], u^\alpha_{s,ref}[k]). \tag{8}$$

The auxiliary cost function can now be expressed as

$$g_p = \left|u^\alpha_{s,ref}[k] - u^\alpha_s[k]\right| + \left|u^\beta_{s,ref}[k] - u^\beta_s[k]\right|. \tag{9}$$

Based on the location of the reference VV $u^{\alpha\beta}_{s,ref}[k]$, the six sectors are defined, which are illustrated in in Fig. 2. For clarification, when $\phi_u[k] \in [0, \frac{\pi}{3}]$, then the reference VV is located in sector 1 and the only reasonable candidate VVs are $u^{\alpha\beta}_{s,0}$, $u^{\alpha\beta}_{s,1}$, and $u^{\alpha\beta}_{s,2}$. Hence, (9) is evaluated for only three times to obtain the optimal VV. The schematic diagram of the conventional DMPCC for PMSGs is shown in Fig. 3.

V. PROPOSED DISTURBANCE OBSERVER

The sensitivity of the proposed DMPCC technique to variations of the PMSG parameters and un-modeled dynamics can be avoided by employing a simple observer. The proposed observer is based on the time delay control approach [29]. To estimate the values of $\chi^d_s[k]$ and $\chi^q_s[k]$ in (3), it can be assumed that the values of $\chi^d_s[k]$ and $\chi^q_s[k]$ at the present sampling instant k are very close to those at a previous sampling instant $k-n$ as follows

$$\chi^d_s[k] \approx \chi^d_s[k-n] \quad \text{and} \quad \chi^q_s[k] \approx \chi^q_s[k-n], \tag{10}$$

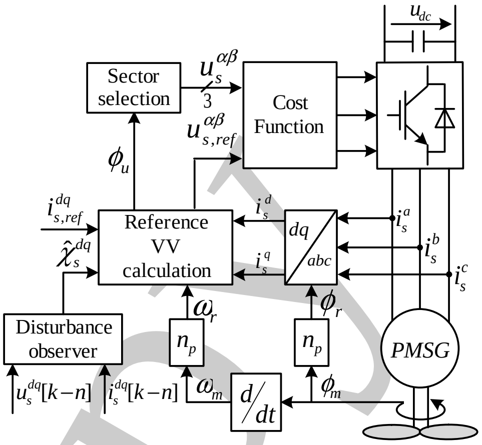


Fig. 3. Proposed DMPCC for PMSGs.

where n is a positive integer. Using this assumption and invoking (3), the values of $\chi^d_s[k]$ and $\chi^q_s[k]$ can be estimated as

$$\left.\begin{aligned} \hat{\chi}^d_s[k] &\approx \hat{\chi}^d_s[k-n] = u^d_{s,ref}[k-n] - \Big(R_{so} i^d_s[k-n] \\ &\quad + L_{so}\tfrac{i^d_s[k-n+1]-i^d_s[k-n]}{T_s} - \omega_r[k-n] L_{so} i^q_s[k-n]\Big) \\ \hat{\chi}^q_s[k] &\approx \hat{\chi}^q_s[k-n] = u^q_{s,ref}[k-n] - \Big(R_{so} i^q_s[k-n] \\ &\quad + L_{so}\tfrac{i^q_s[k-n+1]-i^q_s[k-n]}{T_s} + \omega_r[k-n] L_{so} i^d_s[k-n] \\ &\quad + \omega_r[k-n]\psi_{pmo}\Big) \end{aligned}\right\} \tag{11}$$

The proposed observer is simple and easy to implement. However, the main drawback of this observer is the required numerical differentiation of the measured current; thus, high frequency noise will be induced in the control loop, if not a low pass filter (LPF) is employed to filter the signals $\hat{\chi}^d_s[k]$ and $\hat{\chi}^q_s[k]$ and remove high frequency noise.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed DMPCC technique has been experimentally implemented and its performance has been compared with that of the conventional DMPCC. The setup consists of a 14.5 kW PMSG driven by a two-level voltage source converter (VSC). A 9.5 kW reluctance synchronous machine (RSM) driven by another two-level VSC is employed to emulate the variable-speed wind turbine dynamics and is controlled using a nonlinear current PI-based field-oriented control (FOC) technique [30]. The two machines (i.e. PMSG and RSM) are coupled through a torque sensor as illustrated in Fig. 4. The proposed DMPCC scheme for PMSG and the FOC system for RSM are implemented on a dSPACE DS1007 real-time platform with MATLAB/Simulink and Control Desk software. The sampling frequency is set to 11 kHz. The experimental setup is depicted in Fig. 4. The parameters of the PMSG are collected in Table I.

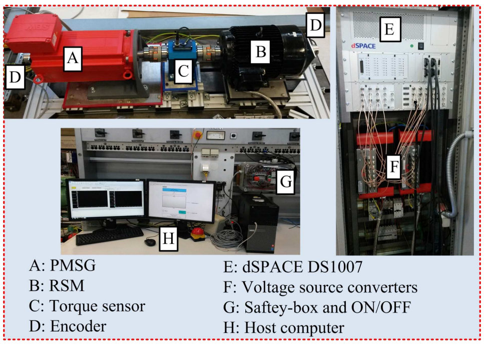


Fig. 4. Laboratory set-up to validate the proposed DMPCC.

TABLE I
PMSG PARAMETERS.

Name	Symbol	Value
Rated power	p_{rated}	14.5 kW
Rated stator line-line voltage	$u_{s,rated}$	400 V
DC-link voltage	u_{dc}	560 V
Rated mechanical angular speed	$\omega_{m,rated}$	157 rad/s
Stator resistance	R_s	0.15 Ω
Stator inductance	L_s	3.4 mH
Permanent-magnet flux linkage	ψ_{pm}	0.375 3 Wb
Pole pairs	n_p	3

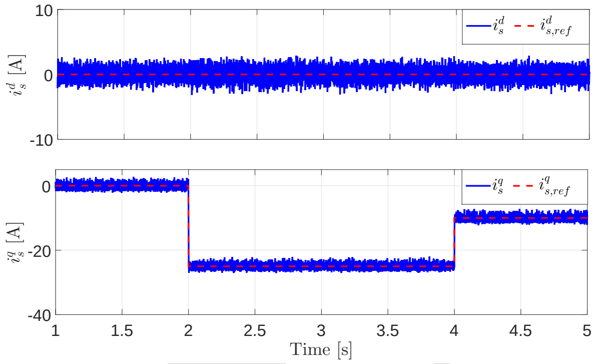
An incremental encoder with 2048 pulses per revolution (ppr) is used to measure the rotor position of the PMSG, which is fed to dSPACE using a DS3002 incremental encoder board. Three current sensors and one voltage sensor are used to measure the stator currents of the PMSG and the DC-link voltage, respectively. The measured currents and voltage are handed over to dSPACE through a DS2004 analog to digital converter (A/D) board. For the design of the proposed disturbance observer, in this work $n = 1$ was selected.

Fig. 5 shows the performance of the proposed DMPCC and the conventional one during step changes in the reference q-axis current $i^q_{s,ref}$ of the PMSG. At the time instants $t = 2\,\mathrm{s}$ and $t = 4\,\mathrm{s}$, step changes in the reference q-axis current $i^q_{s,ref}$ of the PMSG from $0\,\mathrm{A}$ to $-25\,\mathrm{A}$ and then to $-10\,\mathrm{A}$ have been applied. The mechanical speed of the rotor ω_m is set to $100\,\mathrm{rad/s}$ by the RSM control system. It can be observed that the dynamic performance of the proposed DMPCC (Fig. 5a) is similar to that of the conventional DMPCC (Fig. 5b). However, the proposed DMPCC requires approximately 10 µs execution time, while, the conventional DMPCC requires approximately 27 µs execution time. Hence, the computational load is reduced to $\frac{10}{27} \cdot 100\% = 37\%$ (i.e., a reduction by 63%!). Furthermore, the steady-state performance of the proposed DMPCC is better than that of the conventional one. The steady-state error (SSE) using the proposed DMPCC is zero, while, a non-zero SSE is observed using the conventional DMPCC. The reasons for this non-zero SSE are: (i) Parameter uncertainties and un-modeled dynamics, and (ii) the lack of integral control action [31].

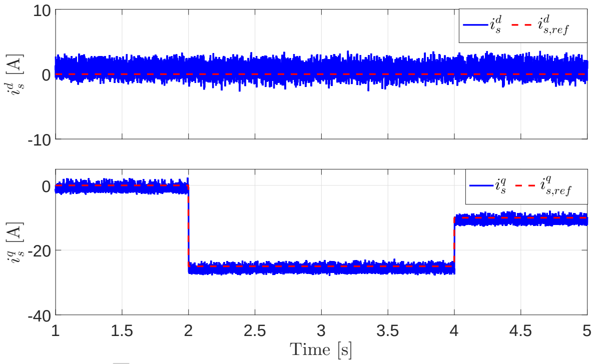
The robustness of the proposed DMPCC to variations of the PMSG parameters is investigated and compared with that of the conventional one. Fig. 6 illustrates the performance of the proposed DMPCC and the conventional one for $\pm 50\%$ software step changes in the stator resistance R_s of the PMSG. The mechanical speed of the rotor ω_m is set to $80\,\mathrm{rad/s}$ by the RSM control system and the reference q-axis current $i^q_{s,ref}$ of the PMSG is set to $-15\,\mathrm{A}$. It can be seen from this figure that the proposed DMPCC demonstrates better performance than that of the conventional one.

Moreover, the performance of the proposed DMPCC is investigated under variations of the stator inductance L_s of the PMSG. At the time instants $t = 1\,\mathrm{s}$ and $t = 3\,\mathrm{s}$, $+50\%$ and -50% increase/decrease in the stator inductance L_s of the PMSG have been applied. The mechanical speed of the rotor ω_m is set to $120\,\mathrm{rad/s}$ by the RSM control system and the reference q-axis current $i^q_{s,ref}$ of the PMSG is set to $-10\,\mathrm{A}$. According to Fig. 7, the performance of the proposed DMPC is better than that of the conventional one. In contrast to the conventional one, only very small ripples appear in the currents i^d_s and i^q_s due to the inductance variation, but, the SSE is zero. In case of the conventional DMPCC, the q-axis current i^q_s significantly deviates from its reference value $i^q_{s,ref}$ due to the variations of the stator inductance L_s. Furthermore, higher ripples appear in the currents i^d_s and i^q_s.

Finally, the performance of proposed DMPCC is tested under uncertainties in the permanent-magnet flux linkage ψ_{pm}. Fig. 8 illustrates the performance of the proposed DMPCC and the conventional one for $\pm 50\%$ software step changes

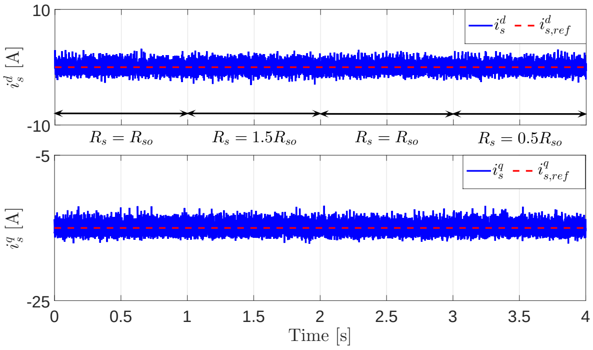


(a) Proposed DMPCC.

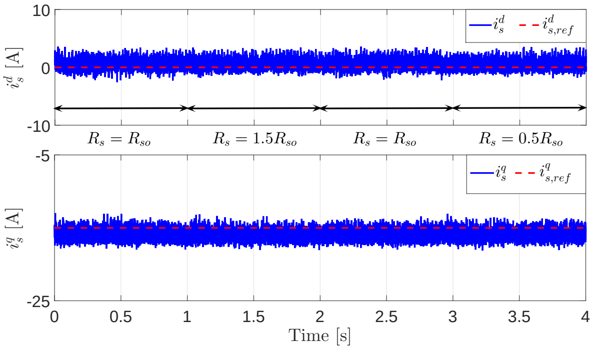


(b) Conventional DMPCC.

Fig. 5. Experimental results at step changes in the q-axis current of the PMSG.

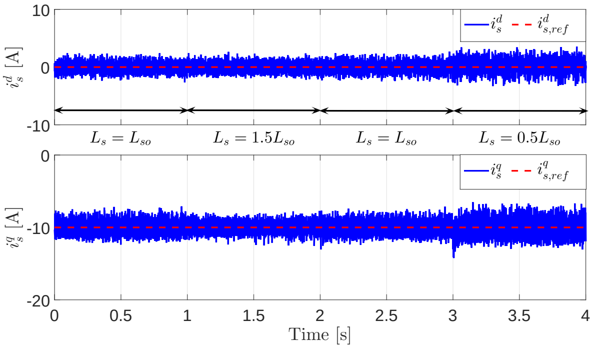


(a) Proposed DMPCC.

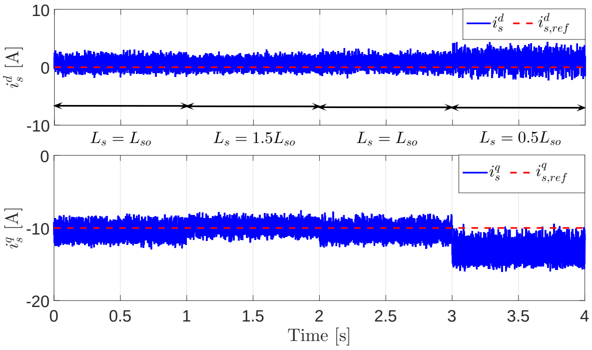


(b) Conventional DMPCC.

Fig. 6. Experimental results at step changes in the stator resistance R_s of the PMSG.



(a) Proposed DMPCC.



(b) Conventional DMPCC.

Fig. 7. Experimental results at step changes in the stator inductance L_s of the PMSG.

in the permanent-magnet flux linkage ψ_{pm}. The mechanical speed of the rotor ω_m is set to $90\,\mathrm{rad/s}$ by the RSM control system and the reference q-axis current $i_{s,ref}^q$ of the PMSG is set to $-20\,\mathrm{A}$. It can be observed that the proposed DMPCC is robust to variations of the permanent-magnet flux linkage ψ_{pm}. Thanks to the proposed disturbance observer, only small ripples appeared in the currents i_s^d and i_s^q (see Fig. 8a). In contrast to the proposed DMPCC, the performance of the conventional DMPC is significantly deteriorated (see Fig. 8b).

VII. CONCLUSION

In this paper, a simple and robust direct model predictive current control (DMPCC) for permanent-magnet synchronous generators (PMSGs) in variable-speed wind turbines has been proposed. The proposed DMPCC is based on computing the reference voltage vector (VV) directly from the demanded reference currents. Then, according to the location of this reference VV, an auxiliary cost function is evaluated for only three times to obtain the optimal switching vector. Furthermore, to enhance the robustness of the proposed DMPCC against variations of machine parameters and un-modeled dynamics, a simple disturbance observer has been presented in this work. The proposed DMPCC is experimentally implemented and its performance has been compared with that of the conventional DMPCC. The results have shown that the proposed DMPCC gives a similar dynamic performance as the conventional one, but with significantly reduced computational burden. Furthermore, steady-state response and the robustness of the proposed DMPCC are better than those of the conventional DMPCC.

ACKNOWLEDGMENT

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REFERENCES

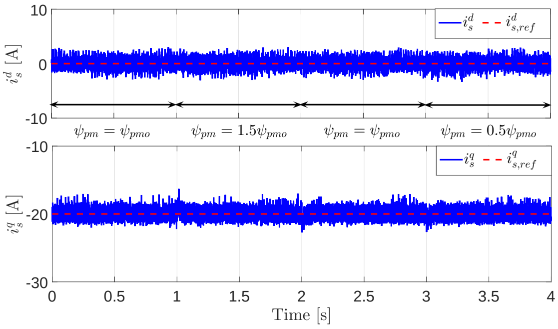
[1] M. Abdelrahem, C. Hackl, and R. Kennel, "Sensorless Control of Doubly-Fed Induction Generators in Variable-Speed Wind Turbine Systems", *in Proceedings of the* 5^{th} *International Conference on Clean Electrical Power (ICCEP)*, Taormina, Italy, 16-18 June 2015, pp. 406-413.

[2] M. Abdelrahem, R. Kennel, "Direct-Model Predictive Control for Fault Ride-Through Capability Enhancement of DFIG", *in proceedings of International Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management (PCIM)*, 16-18 May 2017, Nuremberg, Germany, pp. 1917-1924.

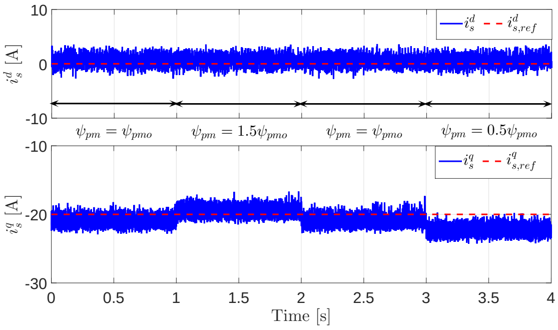
[3] M. Abdelrahem, R. Kennel, "Fault-Ride through Strategy for Permanent-Magnet Synchronous Generators in Variable-Speed Wind Turbines", *Energies*, vol. 9, no. 12, pp. 1-15, 2016.

[4] M. Abdelrahem, C. Hackl, R. Kennel, "Finite Position Set-Phase Locked Loop for Sensorless Control of Direct-Driven Permanent-Magnet Synchronous Generators", *IEEE Transactions on Power Electronics*, doi: 10.1109/TPEL.2017.2705245 (early access), pp. 1-9, 2017.

[5] M. Abdelrahem, C. Hackl, R. Kennel, "Implementation and experimental investigation of a sensorless field-oriented control scheme for permanent-magnet synchronous generators", *Electrical Engineering*, Doi:10.1007/s00202-017-0554-y (early access), pp. 1-8, 2017.



(a) Proposed DMPCC.



(b) Conventional DMPCC.

Fig. 8. Experimental results at step changes in the permanent-magnet flux linkage ψ_{pm} of the PMSG.

[6] P. Cortes, M. Kazmierkowski, R. Kennel, D. Quevedo, J. Rodriguez, “Predictive Control in Power Electronics and Drives”, *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 12 ,pp. 4312–4324, Dec. 2008.

[7] S. Vazquez, J. Leon, L. Franquelo, J. Rodriguez, H. Young, A. Marquez, P. Zanchetta, “Model Predictive Control: A Review of Its Applications in Power Electronics”, *IEEE Industrial Electronics Magazine*, Vol. 8, No. 1, pp. 16–31, March 2014.

[8] H. Young, M. Perez, J. Rodriguez, H. Abu-Rub, “Assessing Finite-Control-Set Model Predictive Control: A Comparison with a Linear Current Controller in Two-Level Voltage Source Inverters”, *IEEE Industrial Electronics Magazine*, vol. 8, no. 1, pp. 44–52, March 2014.

[9] M. Abdelrahem, C. Hackl, and R. Kennel, “Model Predictive Control of Permanent Magnet Synchronous Generators in Variable-Speed Wind Turbine Systems”, *in Proceedings of Power and Energy Student Summit (PESS 2016)*, Aachen, Germany, 19-20 January 2016.

[10] Z. Zhang, C. Hackl, M. Abdelrahem, and R. Kennel, “Voltage Sensorless Direct Model Predictive Control of 3L-NPC Back-to-Back Power Converter PMSG Wind Turbine Systems with Fast Dynamics”, *in Proceedings of Power and Energy Student Summit (PESS 2016)*, Aachen, Germany, 19-20 January 2016.

[11] M. H. Mobarak, M. Abdelrahem, N. Stati and R. Kennel, “Model predictive control for low-voltage ride-through capability improvement of variable-speed wind energy conversion systems”, *in proceedings of IEEE International Symposium on Industrial Electronics (INDEL)*, Banja Luka, 2016, pp. 1-6.

[12] M. Abdelrahem, M. H. Mobarak, and R. Kennel, “Model Predictive Control for Low-Voltage Ride Through Capability Enhancement of DFIGs in Variable-Speed Wind Turbine Systems”, *in proceedings of IEEE 9^{th} International Conference on Electrical and Computer Engineering (ICECE 2016)*, 20-22 December 2016, Dhaka, Bangladesh, pp. 70-73.

[13] M. Abdelrahem, C. Hackl, R. Kennel, “Encoderless Model Predictive Control of Doubly-Fed Induction Generators in Variable-Speed Wind Turbine Systems”, *in Proceedings of The Science of Making Torque from Wind (TORQUE 2016) Conference*, Munich, 5–7 October, pp. 1-10, 2016.

[14] S. Kwak, S. Yoo, J. Park, “Finite control set predictive control based on Lyapunov function for three-phase voltage source inverters”, *IET Power Electronics*, Vol. 7, No. 11, pp. 2726–2732, Nov. 2014.

[15] M. Akter, S. Mekhilef, N. Tan, H. Akagi, “Modified Model Predictive Control of a Bidirectional AC–DC Converter Based on Lyapunov Function for Energy Storage Systems”, *IEEE Transactions on Industrial Electronics*, Vol. 63, No. 2, pp. 704–715, Feb. 2016.

[16] Z. Zhang and R. Kennel, and C. Hackl, “Computationally efficient Direct Model Predictive Control for three-level NPC back-to-back converter PMSG wind turbine systems”, *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pp. 1045–1050, 2016.

[17] Z. Zhang and C. Hackl, and R. Kennel, “Computationally Efficient DMPC for Three-level NPC Back-to-Back Converters in Wind Turbine Systems With PMSG”, *IEEE Transactions on Power Electronics*, doi 10.1109/TPEL.2016.2637081 (early access), 2016

[18] M. Abdelrahem, C. Hackl, R. Kennel, “Simplified Model Predictive Current Control without Mechanical Sensors for Variable-Speed Wind Energy Conversion Systems”, *Electrical Engineering Journal*, vol. 99, no. 1, pp 367-377, March 2017.

[19] M. Abdelrahem, R. Kennel, “Efficient Direct Model Predictive Control for Doubly-Fed Induction Generators”, *Electric Power Components and Systems*, pp 1-14, doi: 10.1080/15325008.2017.1289572, March 2017.

[20] K. A. Islam, M. Abdelrahem, and R. Kennel, “Efficient finite control set-model predictive control for grid-connected photovoltaic inverters”, *in proceedings of IEEE International Symposium on Industrial Electronics (INDEL)*, Banja Luka, 2016, pp. 1-6.

[21] H. Young, M. Perez, and J. Rodriguez, “Analysis of Finite-Control-Set Model Predictive Current Control With Model Parameter Mismatch in a Three-Phase Inverter”, *IEEE Transactions on Industrial Electronics*, vol. 63, no. 5, pp. 3100-3107, May 2016.

[22] N. Stati, M. Abdelrahem, M. H. Mobarak, and R. Kennel, “Finite control set-model predictive control with on-line parameter estimation for variable-speed wind energy conversion systems”, *in proceedings of IEEE International Symposium on Industrial Electronics (INDEL)*, Banja Luka, 2016, pp. 1-6.

[23] M. Abdelrahem, C. Hackl, and R. Kennel, “Application of Extended Kalman Filter to Parameter Estimation of Doubly-Fed Induction Generators in Variable-Speed Wind Turbine Systems”, *in Proceedings of the 5^{th} International Conference on Clean Electrical Power (ICCEP)*, Taormina, Italy, 16-18 June 2015, pp. 226–233.

[24] S. Kwak, U. Moon, and J. Park, “Predictive-Control-Based Direct Power Control With an Adaptive Parameter Identification Technique for Improved AFE Performance”, *IEEE Transactions on Power Electronics*, vol. 29, no. 11, pp. 6178-6187, Nov. 2014.

[25] C. K. Lin, T. H. Liu, J. t. Yu, L. C. Fu. and C. F. Hsiao, “Model-Free Predictive Current Control for Interior Permanent-Magnet Synchronous Motor Drives Based on Current Difference Detection Technique”, *IEEE Transactions on Industrial Electronics*, vol. 61, no. 2, pp. 667-681, Feb. 2014.

[26] M. Siami, D. A. Khaburi, A. Abbaszadeh, and J. Rodriguez, “Robustness Improvement of Predictive Current Control Using Prediction Error Correction for Permanent-Magnet Synchronous Machines”, *IEEE Transactions on Industrial Electronics*, vol. 63, no. 6, pp. 3458-3466, June 2016.

[27] C.M. Hackl, “Non-identifier based adaptive control in mechatronics: Theory and application”, Springer International Publishing, 2017 (doi: 10.1007/978-3-319-55036-7).

[28] H. Eldeeb, C.M. Hackl, J. Kullick and L. Horlbeck, “A unified theory for optimal feedforward torque control of anisotropic synchronous machines”, International Journal of Control, 2017 (doi: 10.1080/00207179.2017.1338359).

[29] Kyeong-Hwa Kim and Myung-Joong Youn, “A simple and robust digital current control technique of a PM synchronous motor using time delay control approach”, *IEEE Transactions on Power Electronics*, vol. 16, no. 1, pp. 72-82, Jan 2001.

[30] C. Hackl, M. Kamper, J. Kullick, and J. Mitchel, “Current control of reluctance synchronous machines with online adjustment of the controller parameters”, *in Proceedings of the 2016 IEEE International Symposium on Industrial Electronics (ISIE 2016)*, Santa Clara, USA, pp. 153–160, 2016.

[31] C. M. Hackl, “MPC with analytical solution and integral error feedback for LTI MIMO systems and its application to current control of grid-connected power converters with LCL-filter”, *in Proceedings of the 2015 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE)*, Valparaiso, pp. 61-66, 2015.