This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

New adaptive control strategies for open-end winding permanent magnet synchronous generator(OEW-PMSG) for wind power generation

PLEASE CITE THE PUBLISHED VERSION

<https://doi.org/10.1049/icp.2021.1106>

PUBLISHER

Institution of Engineering and Technology

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This paper was accepted for publication in The 10th International Conference on Power Electronics, Machines and Drives (PEMD 2020) and the definitive published version is available at
<https://doi.org/10.1049/icp.2021.1106>.

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Xing, Ning, Shubo Hu, Zhengyu Lin, Zheng Tan, Wenping Cao, and Shady Gadoue. 2021. "New Adaptive Control Strategies for Open-end Winding Permanent Magnet Synchronous Generator(oew-pmsg) for Wind Power Generation". Loughborough University. <https://hdl.handle.net/2134/16438308.v1>.

NEW ADAPTIVE CONTROL STRATEGIES FOR OPEN-END WINDING PERMANENT MAGNET SYNCHRONOUS GENERATOR(OEW-PMSG) FOR WIND POWER GENERATION

Ning Xing¹, Shubo Hu², Zhengyu Lin³, Zheng Tan⁴, Wenping Cao⁵, Shady Gadoue⁶

¹Aston University, Birmingham, UK

²Dalian University of Technology, Dalian, China

³Loughborough University, Loughborough, UK

⁴State Grid Corporation of China, Beijing, China

⁵Aston University, Birmingham, UK

⁶Aston University, Birmingham, UK

* xingn@aston.ac.uk

Keywords: DEADBEAT PREDICTIVE CURRENT CONTROL, MODEL REFERENCE ADAPTIVE CONTROL, MODEL PREDICTIVE CONTROL, OPEN-END WINDING PERMANENT MAGNET SYNCHRONOUS GENERATOR, SLIDING MODE CONTROL

Abstract

A wind turbine system with a new open-end-winding permanent magnet synchronous generator (OEW-PMSG) is studied in this paper, with a focus on torque ripple minimisation of the OEW-PMSG. The problem of torque ripple minimisation of OEW-PMSGs is addressed. Generally, the q -axis current injection method is employed to suppress the torque ripple. However, the third flux linkage parameters will be affected by high temperature when the machine is operating. In order to solve this problem, two sensorless adaptive control methods are presented in the following paper. The first method is based on adaptive sliding mode control and deadbeat-based predictive current control. The second method is based on model reference adaptive control with deadbeat predictive control. In these two control systems, a zero-sequence back-EMF observer (ZCBO) is used to estimate the zero-sequence back-EMF and zero-sequence current simultaneously and continuously. Meanwhile, the zero-sequence voltage which exists in the zero-sequence path and interferes the ZCBO's performance is considered. The performance of two control strategies is evaluated in MATLAB/SIMULINK environment.

1 Introduction

Renewable energy is key to establishing future low-carbon economy. Wind energy industry is rapidly growing as wind is only renewable sources of energy which can be utilised in large quantity economically, after hydro energy. In the last three decades, commercial wind turbines have increased in power and size, which have reached 10 MW [1]. The function of wind energy conversion systems (WECS) is to convert the mechanical energy which is captured by the turbine into the electrical energy, and which is fed into the power grid via power electronic converters. Generally, a WECS consists of a wind turbine, an electrical generator, several converters and the grid. Regarding the generators, doubly fed induction generators (DFIGs) are widely used for medium and large wind turbines, as they offer several advantages such as variable speed operation, four-quadrant reactive and active power capabilities [2]. Compared with the synchronous generators with full-rated converters, DFIG-based systems have lower power electronics losses and lower capital costs [3]. However, they need regular maintenance, especially on the slip rings and the gearbox [3]. The use of permanent magnet synchronous generators (PMSGs) in a direct drive topology eliminates the gearbox and slip rings. They have higher efficiency, power density, and high reliability. An open-end-

winding PMSG (OEW-PMSG) is chosen in the WECS in this paper. OEW-PMSGs are typically used in traction drives such as electrical vehicles and aerospace applications. However, they haven't been found in use in wind turbine applications.

In the literature [7], to suppress the torque ripple of the OEW-PMSG, a q -axis current injection method is developed. This method uses zero-sequence back-EMF to counteract the torque ripple. And the zero-sequence back-EMF is obtained by measured zero-sequence current (ZSC) and third zero-sequence back-EMF. The third zero-sequence back-EMF is computed by the third flux linkage parameter, measured electrical angular, and measured electrical rotor angle. But, the third flux linkage parameter is estimated by off-line measurement, which is not accurate enough due to the offline error. Additionally, during the machine's operation, high temperature in magnet affects the third flux linkage variation. Theoretically, these disturbances can lead to inaccuracy in the injected q -axis current [6]. To solve this problem and improve the reliability of OEW-PMSG, two sensorless adaptive control methods are presented in this paper. These two methodologies are based on adaptive Sliding Mode Control (SMC) using Deadbeat-based Predictive Current Control (DPCC) and Model Reference Adaptive Control (MRAC) with deadbeat (DB) predictive control. In the meantime, a zero-sequence

back-EMF observer (ZCBO) is proposed, which can simultaneously and continuously estimate the zero-sequence back-EMF and ZSC in different conditions [6]. Then the estimated current and back-EMF can decrease the disturbances as mentioned above and compensate for one-step control delay. Besides, zero-sequence voltage (ZSV) is also considered in this study. Because of the dead time of the inverter, ZSV still exists in the zero-sequence path although the central hexagon modulation is applied in the PCC. The existence of ZSV affects the accurate performance of ZCBO. Therefore, the consideration of ZSV is innovative for this research.

2. Structure of open-end-winding PMSG (OEW-PMSG)

PMSGs have their pros and cons. Their excitation is free, but magnets are expensive. In order to minimise torque ripple and obtain a sinusoidal back-EMF, a Multiphysics approach is necessary when designing machines. Torque ripple is generally produced by the interaction of rotor electromagnetic properties and the stator current magnetomotive forces (MMF) [4]. Depending on different structures of PMSGs, three forms of torque ripple are needed to study. The first one is a result of interaction between stator MMF (mutual torque) and the rotor flux, the second one is based on the interaction between the rotor reluctance (reluctance torque) and the stator MMF, and the third one is commutation torque [4]. For OEW-PMSGs, an adaptive control method to suppress their torque ripple has been attempted previously by some researchers [5], but the performance is varied.

Structurally, an OEW-PMSG has six terminals of the stator windings, and two ends of every stator phase winding which are available to be connected to power converters [6]. Figure 2.1 shows the configuration of the wind energy conversion system structure used in this research. A diode full-bridge rectifier is connected to the terminal of each phase set separately. This topology is a cost-effective and straightforward way to provide unidirectional power flow from the OEW-PMSG to the grid-tied inverter. In the second converter stage, the dc-dc boost converters elevate the voltage of the generator and feed into the DC link. In the last converter stage, a medium-voltage NPC inverter is used to connect to the grid through a three-phase transformer.

Figure 2.2 shows the diagram of the zero-sequence path of OEW-PMSG, and Figure 2.3 shows the diagram of the ZCBO.

2.1 Wind energy conversion system with open-end winding PMSG

2.2 Zero-sequence path of OEW-PMSG

2.3 Diagram of the zero-sequence back-EMF observer

3. Methodology

As a control method which is characterized with good static current tracking accuracy, fixed switching frequency, less computation burden, and fast current dynamic response, the deadbeat-based predictive current control (DPCC) is utilized in the first SMC methodology. In the proposed model, a sliding mode speed controller is used in the speed loop, and the discrete deadbeat-based predictive current controller is employed for the current regulation. The proposed scheme is presented in Figure 3.1. Ideally, the proposed control strategy can achieve precise steady-state performance and fast dynamic response. In order to converge the estimated parameters to an adaptive slide mode surface, designing a reliable adaptive sliding mode function is very important for the whole control system [5].

In the proposed methodology, a new adaptive sliding mode function is designed to upgrade the performance of SMC. Meanwhile, the Lyapunov theorem is used in SMC to ensure the convergence of it. The Lyapunov function V is presented as equation (1), S_0 is the adaptive sliding mode surface. According to the principle of Lyapunov stability, when the

4.1 The waveforms of wind generator active power in SMC-MPC

4.2 The waveforms of wind generator T_e and T_m in SMC-MPC

4.3 The waveform of stator d-q voltage in SMC-MPC

4.4 The waveform of three-phase output current in SMC-MPC

4.5 The waveform of electromagnetic torque T_e in SMC-MPC

4.6 The waveform of line current in SMC-MPC

4.7 The waveform of line to line voltage V_{ab} in SMC-MPC

Then, the simulation results of Model Reference Adaptive Control (MRAC) with deadbeat (DB) predictive control which is based on OEW-PMSG show as follows:

4.8 The waveform of line to line voltage V_{ab} in MRAC-MPC

4.9 The waveform of line current in MRAC-MPC

4.10 The waveform of electromagnetic torque T_e in MRAC-MPC

4.11 The waveform of three-phase output current in MRAC-MPC

4.12 The waveform of stator d-q voltage in MRAC-MPC

4.13 The waveforms of wind generator T_e and T_m in MRAC-MPC

4.14 The waveforms of wind generator active power in MRAC-MPC

In the second control strategy (MRAS with deadbeat predictive controller for OEW-PMSM), the power reaches at 6123 W when the wind speed is 12 m/s. And in first control strategy (Sliding mode control with predictive current control with ZCBO for OEW-PMSM), the power reaches at 6793 W when the wind speed is 152 m/s. After a comparison between them, the second method is more stable and more efficient. Therefore, improving the control performance and enhancing the efficiency of the first method could be future work.

4 Conclusion

This paper has presented two sensorless adaptive control methods for wind turbine generating system with an open-end winding PMSG. The control and performance of the proposed strategies is evaluated by simulation results. From the results, the second proposed system (Model Reference Adaptive Control with deadbeat predictive control) is proven to be stable and reliable. However, when producing the same active power of the first strategy, the first proposed system (Sliding Mode Control using Deadbeat-based Predictive Current Control) needs a high wind speed. Therefore, continuing to develop the first control method will be the next step of this study.

5 Acknowledgements

None

6 References

- [1]. Prathap. P and Muralidharan. V, "Open-End-Winding PMSG for Wind Energy Conversion System with Dual Boost NPC Converter", International Journal for Research in Applied Science & Engineering Technology, Volume 2 Issue V, May 2015.
- [2]. Müller. S, Deicke. M, and R.W. De Doncker, "Doubly fed induction generator systems," IEEE Industry Applications Magazine, vol. 8, n°3, pp. 26-33, May-June 2002.
- [3]. Benelghali. S, Benbouzid. M, Charpentier. J, "Comparison of PMSG and DFIG for Marine Current Turbine Applications", <https://hal.archives-ouvertes.fr/hal-00532656>, HAL ID: hal-00532656, 4th Nov 2010.
- [4]. Parsa. L, Hao. L, and Toliyat. H. A, "Optimization of Average and Cogging Torque in 3-Phase IPM Motor Drives",

Proceedings of the IEEE Industry Applications Conference 37th IAS Annual Meeting, Pittsburgh 2002.

[5]. Yuan. X, Zhang. C and Zhang. S, "Torque Ripple Suppression for Open-end Winding Permanent-Magnet Synchronous Machine Drives with Predictive Current Control", IEEE Transactions on Industrial Electronics, DOI 10.1109/TIE.2019.2907506, March 2019.

[6]. Yoo. H. J, Nguyen. T. T and Kim. H. M, "MPC with Constant Switching Frequency for Inverter-Based Distributed Generations in Microgrid Using Gradient Descent", Energies 2019, 12(6), 1156, 25 March 2019.

[7]. Nian. H and Hu. W, "Torque Ripple Suppression Method with Reduced Switching Frequency for Open-Winding PMSM Drives with Common DC BUS," IEEE Transactions on Industrial Electronics, DOI: 10.1109/TIE.2018.2833803, May. 2018.

[8]. Abdelrahem. M, Hackl. C and Kennel. R, "A Robust Encoderless Predictive Current Control Using Novel MRAS Observer for Surface-mounted Permanent Magnet Synchronous Generators", PCIM Europe 2017.

[9]. Matthias. P and Erik. S, "Sensorless Model Predictive Direct Current Control Using Novel Second Order PLL-Observer for PMSM Drive Systems," IEEE Transactions on Industrial Electronics, Vol.99, pp.1, 2010.

[10]. Islam. K. A, Abdelrahem. M, and Kennel. R, "Efficient Finite Control Set-model Predictive Control for Grid-connected Photovoltaic Inverters", IEEE International Symposium on Industrial Electronics (INDEL), Banja Luka, pp. 1-6, 2016.

[11]. Morel. F, et al., "A Comparative Study of Predictive Current Control Schemes for a Permanent-magnet Synchronous Machine Drive", IEEE Trans, Ind. Electron., Vol. 56, pp. 2715-2728. 2009.

[12]. Stumper. J. F, Hagenmeyer. V, Kuehl. S, and Kennel. R, "Dead-beat Control for Electrical Drives: A Robust and Performance Design Based on Differential Flatness", IEEE Trans. Power Electron, Vol. 30, No. 8. 4585-4596, 2015.