International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 7, No. 2, June 2016, pp. 498~508
ISSN: 2088-8694

Control of DFIG Stator Voltage on Autonomous Micro Hydro Power Plant

Feri Yusivar, Nanda Avianto Wicaksono, Aries Subiantoro, Ridwan Gunawan
Department of Electrical Engineering, University of Indonesia, Jakarta, Indonesia

Article Info

Article history:

Received Dec 28, 2015
Revised Mar 19, 2016
Accepted Apr 1, 2016

Keyword:

Autonomous power plant
DFIG
Micro hydro power plant
Off-grid configuration
PMSG
Variable angular speed

ABSTRACT

An autonomous micro hydro power plant was proposed to utilize the small hydro power potency as a run-of-river. It consisted of a PMSG, a DFIG, and a converter and should be operated in the off-grid configuration. In a previous research, the DFIG stator voltages couldn't be controlled. In this paper, the novel control algorithm that is able to maintain the DFIG stator voltages of the autonomous micro hydro power plant in the off-grid configuration is proposed. The control algorithm was proposed to use the actual DFIG stator voltages and currents as feedback signals. The controller was tested by varying three input signals, i.e. the DC-link voltage, the DFIG stator voltage reference, and the external stator load which simulated the off-grid configuration. The result of the simulation showed that the DFIG stator voltages could be controlled and were always in accordance with the reference.

Corresponding Author:

Feri Yusivar,
Department of Electrical Engineering,
University of Indonesia,
Kampus UI Depok, Jakarta, 16424, Indonesia.
Email: yusivar@ee.ui.ac.id

1. INTRODUCTION

Two types of generators frequently used in hydro power plant applications are a synchronous generator and a squirrel cage induction generator. Both types are operated at a constant rotor speed. The generated power is controlled by adjusting flow rate by varying the degree of the flow gates. The implementation by using the flow gates needs an operator and/or a gate controller which is expensive. These configurations don't suit to locations which is remote and far from cities with low electricity consumption and small population. The hydro power plant should have a simple configuration and a low maintenance but should still have a high reliability.

To utilize the small hydro power potency as a run-of-river, the micro hydro power plant must be able to be operated in the varying angular speed without a mechanical gate control. It could be connected to the varying isolated load without an auxiliary source or which was called the off-grid connection. The simplest configuration that could be chosen was by using a permanent magnet synchronous generator (PMSG) and a converter, but this configuration is expensive.

In the wind turbine application, the alternative generator type that could be used in the varying angular speed is a doubly fed induction generator (DFIG). Belkacem *et al*. [1] and Nora *et al.* [2] controlled the generated active power by using the q-axis rotor current as a feedback signal and the generated reactive power by using the d-axis rotor current as a feedback signal. Medhav *et al.* added the stator voltage controller by using the d-axis rotor current as a feedback signal [3]. Murthy *et al.* controlled the generated active and reactive power by using the stator fluxes and the slip speed as feedback signals [4]. These researches used the DFIG in an on-grid configuration.

The autonomous micro hydro power plant that was connected to the off-grid with the varying angular speed was proposed. It consisted of a PMSG, a DFIG, and a back to back converter. The capacity of the PMSG and the converter was a quarter of the rated power, so it could reduce the cost [5]. This autonomous configuration was shown in Figure1.

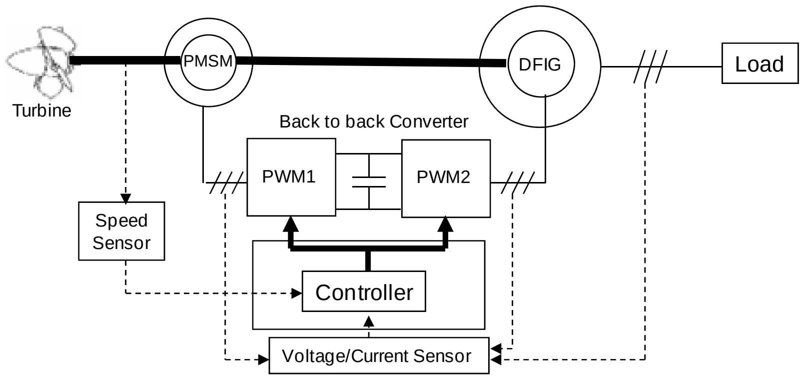

Figure 1. The configuration of the autonomous small/micro hydro power plant

The autonomous micro hydro power plant was proposed by Ansel *et al*. [5]. Ansel *et al*.'s model and controller were tested by giving the constant DFIG stator voltage reference. If the DFIG stator terminal was connected to the external stator load and the DFIG stator voltage reference was varied, the DFIG stator voltage couldn't be controlled in accordance with the reference. It was caused by two factors. First, the Ansel *et al*.'s model assumed that the DFIG stator currents were the disturbances (see Figure 2) and omitted the relation in the Ohm's law between the DFIG stator voltages, the DFIG stator currents, and the external stator load. Second, the Ansel *et al*.'s controller used the DFIG stator voltages as feedback signals (see Figure 2). To control the DFIG stator voltages, the Ansel *et al*. model must be added wuth a DFIG's external stator load and the Ansel *et al*. controller must be modified.

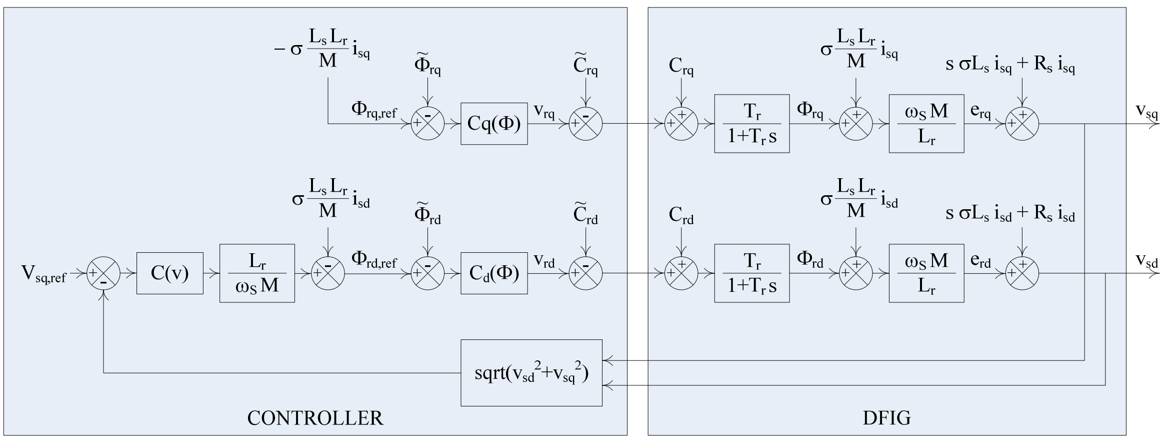

Figure 2. The Ansel *et al*.'s model and controller [5]

To maintain the DFIG stator voltages, this paper proposed the modified control algorithm. The DFIG rotor voltages were controlled by using the actual DFIG stator voltages and currents as feedback signals. The algorithm was also evaluated by using a varying external stator load that simulated the off-grid configuration.

This research continued the PMSG controller in the autonomous micro hydro plant model that was developed by Yusivar *et al*. The Yusivar *et al.*'s PMSM controller assumed the DFIG rotor as the load resistance of the PWM1 (see Figure 1). The load resistance that could be handled by the PMSG was between

1,000 and 10,000 ohm. At the water velocity that was greater than or equal to 1.5 m/s, the DC-link voltage that could be generated by PMSG was in range between 20 and 100 V [6].

2. RESEARCH METHOD

2.1. DFIG Model

Electrical model of DFIG was expressed by equations (1) – (8).

$$v_{sd} = R_s i_{sd} + \frac{d\emptyset_{sd}}{dt} - \omega_s \emptyset_{sq} \quad (1)$$

$$v_{sq} = R_s i_{sq} + \frac{d\emptyset_{sq}}{dt} + \omega_s \emptyset_{sd} \quad (2)$$

$$v_{rd} = R_r i_{rd} + \frac{d\emptyset_{rd}}{dt} - (\omega_s - p\omega_r)\emptyset_{rq} \quad (3)$$

$$v_{rq} = R_r i_{rq} + \frac{d\emptyset_{rq}}{dt} + (\omega_s - p\omega_r)\emptyset_{rd} \quad (4)$$

$$\emptyset_{sd} = L_s i_{sd} + M i_{rd} \quad (5)$$

$$\emptyset_{sq} = L_s i_{sq} + M i_{rq} \quad (6)$$

$$\emptyset_{rd} = L_r i_{rd} + M i_{sd} \quad (7)$$

$$\emptyset_{rq} = L_r i_{rq} + M i_{sq} \quad (8)$$

In these equations: v_{sd} and v_{sq} were stator voltages in dq-axis, i_{sd} and i_{sq} were stator currents in dq-axis, ϕ_{sd} and ϕ_{sd} were stator flux in dq-axis, v_{rd} and v_{rq} were rotor voltages in dq-axis, i_{rd} and i_{rq} were rotor currents in dq-axis, ϕ_{rd} and ϕ_{rd} were rotor flux in dq-axis, ω_s was an angular speed of electrical stator, ω_r was a rotor speed.

2.2. Ansel *et al.*'s Model and Controller

In [5], Ansel *et al.* assumed that the DFIG stator currents as disturbances which depended on the DFIG stator voltages v_s and neglected the external stator load R_L. Both conditions didn't represent the off-grid configuration.

To control the DFIG stator voltage, Ansel *et al.* used three correctors $C_q(\phi_{rd})$, $C_d(\phi_{rq})$, and $C(v_s)$. The corrector $C_d(\phi_{rd})$ manipulated the DFIG rotor voltage in d-axis (v_{rd}) that referred to the error between the DFIG rotor flux references in d-axis ($\phi_{rd,ref}$) and the actual DFIG rotor flux in d-axis (ϕ_{rd}). The corrector $C_q(\phi_{rq})$ adjusted the DFIG rotor voltage in q-axis (v_{rq}) that referred to the error between the DFIG rotor flux reference in q-axis ($\phi_{rq,ref}$) and the actual DFIG rotor flux in q-axis (ϕ_{rq}). The corrector $C(v_s)$ regulated the DFIG stator voltage correction (e_{vs}) that referred to the error between the DFIG stator voltage reference ($v_{s,ref}$) and the actual DFIG stator voltage (v_s). The DFIG rotor flux references ($\phi_{rd,ref}$ and $\phi_{rq,ref}$) and the variables C_{rd} and C_{rq} were given by equations (9)-(12). The variables C_{rd} and C_{rq} represented the sum of the drop voltage which was caused the stator currents and the nonlinear-cross-coupling between dq-axis components. The diagram block of the Ansel *et al.*'s Model and Controller was shown in Figure [5].

$$\emptyset_{rd,ref} = -\sigma \frac{L_s L_r}{M} i_{sq} \quad (9)$$

$$\emptyset_{rq.ref} = \frac{L_r}{\omega_s M} e_{vs} - \sigma \frac{L_s L_r}{M} i_{sd} \quad (10)$$

$$C_{rd} = \frac{M R_r}{L_r} i_{sd} + (\omega_s - p\omega_\mathrm{m})\emptyset_{rq} \quad (11)$$

$$C_{rq} = \frac{MR_r}{L_r} i_{sq} + (\omega_s - p\omega_{\mathrm{m}})\emptyset_{rd} \tag{12}$$

2.3. External Stator Load

The off-grid configuration was simulated by connecting the external stator load R_L to the DFIG stator terminal as shown in Figure 3 in this research project. Consequently, the changing stator load R_L would affect to the DFIG stator voltages v_s and the DFIG stator currents i_s. The relation between the external stator load, the DFIG stator voltages and the DFIG stator currents referred to the Ohm's law in (13).

$$v_s = -i_s R_L \tag{13}$$

By using (13), the dq-axis stator voltages in (1) and (2) were substituted by (14) and (15).

$$v_{sd} = -i_{sd} R'_L \tag{14}$$

$$v_{sq} = -i_{sq} R'_L \tag{15}$$

So, the equations (1) and (2) of the DFIG model would be written as:

$$0 = R'_L i_{sd} + R_s i_{sd} + \frac{d\emptyset_{sd}}{dt} - \omega_s \emptyset_{sq} \tag{16}$$

$$0 = R'_L i_{sq} + R_s i_{sq} + \frac{d\emptyset_{sq}}{dt} + \omega_s \emptyset_{sd} \tag{17}$$

By using of the external stator load R_L, it changed the signal type of the DFIG stator currents. Before using the external stator load R_L, the DFIG stator currents was input signals. After using the external stator load R_L, the DFIG stator currents became output signals of the DFIG model.

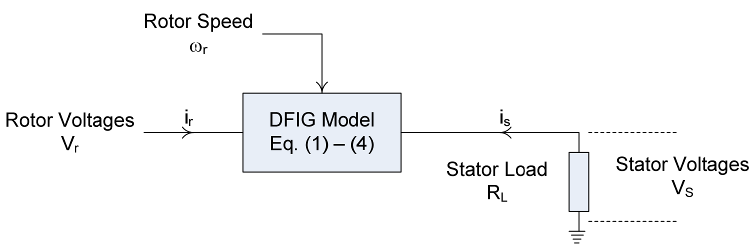

Figure 3. The DFIG model with the stator load R_L

2.4. Proposed Control Algorithm

The proposed DFIG stator voltages control concept was shown in Figure 4. The DFIG stator voltages were controlled by adjusting the DFIG rotor voltages. The DFIG rotor voltages were adjusted by two PI controllers. The DFIG rotor voltage in d-axis were adjusted by the PI controller in d-axis that referred to the difference between the DFIG rotor flux reference in d-axis and the actual DFIG stator current in q-axis. On the other hand, the DFIG rotor voltage in q-axis were manipulated by the PI controller in q-axis that referred to the difference between the DFIG rotor flux reference in q-axis and the actual DFIG stator current in d-axis (see Figure 5).

To eliminate a nonlinear-cross-coupling between dq-axis components, the decouple equations were added into the PI controllers output, so the DFIG could be sighted as a linear system (see Figure 4 and Figure 5).

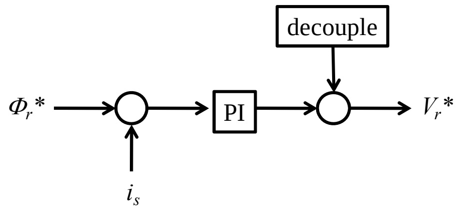

Figure 4. The stator voltage control concept

The DFIG stator voltages controller used the different methods to manipulate the DFIG rotor fluxes between q-axis and d-axis. The DFIG rotor flux in q-axis was maintained by aligning the vector resultant of the DFIG stator fluxes to the d-axis of the rotating reference frame. To align the stator flux to the d-axis, the controller maintained that the stator flux in q-axis was equal to zero ($\Phi_{sq}=0$) and the stator flux in d-axis was equal to the magnitude of the DFIG stator fluxes resultant ($\Phi_{sd} = \Phi_s$). By substituting $\Phi_{sq}=0$, the equations (6) and (8) of the DFIG model would be written as:

$$i_{rq} = -\frac{L_s}{M} i_{sq} \tag{18}$$

$$\emptyset_{rq} = -\frac{\sigma L_s L_r}{M} i_{sq} \tag{19}$$

So, the alignment of the DFIG stator flux to the d-axis of the rotating reference frame was always maintained by setting the rotor flux reference in q-axis that referred to the equation (20).

$$\emptyset_{rq}^* = -\frac{\sigma L_s L_r}{M} i_{sq} \tag{20}$$

The DFIG rotor flux reference in d-axis was adjusted by a PI controller that referred to the error between with the DFIG stator voltage reference and the actual DFIG stator voltage. The detail DFIG stator voltages controller by using the DFIG stator voltages and currents as feedback signals was shown in Figure 5.

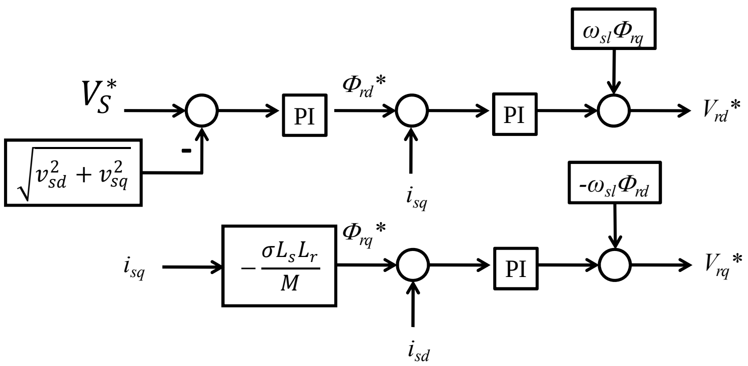

Figure 5. The stator voltages control referred to the rotor fluxes by using the stator currents as feedback

2.5. Software Simulation

The mathematics model of DFIG-PMSG in an autonomous micro hydro power plant was written in the C MEX S-Functions and was simulated by using MATLAB/Simulink. The implementation of the autonomous micro hydro power plant model was shown in Figure 6.

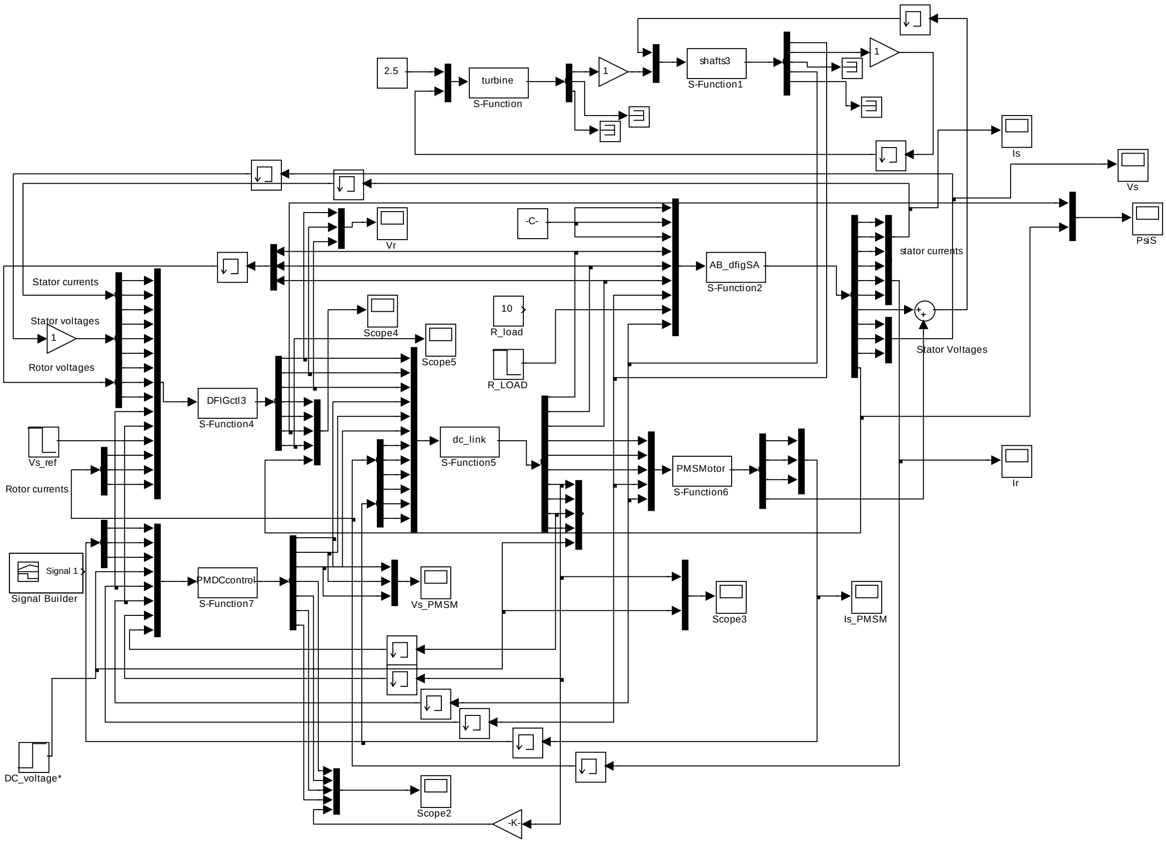

Figure 6. The implementation of DFIG-PMSG in autonomous micro hydropower

2.6. Test Scenario

The test scenario of the system was done by varying three input signals, i.e. the DC-link voltage (V_{DClink}), the DFIG stator voltage reference (V_{S_DFIG}), and the external stator load (R_L). The DC-link voltage (V_{DClink}) given was 0 V between 0 and 4 sec. and then 100 V after 4 sec. The DFIG stator voltage reference (V_{S_DFIG}) given was constant signal 0 V between 0 and 5 sec., then 100 V between 5 and 8 sec., and 50 V after 8 sec. The stator load reference (R_L) given was 30 ohm between 0 and 7 sec. and then 20 ohm after 7 sec. The timing diagram of the three input signals was shown in Figure 7.

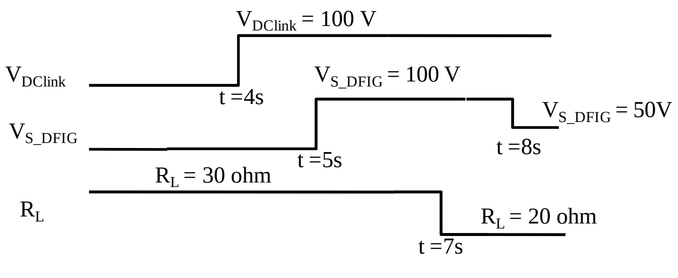

Figure 7. The timing diagram of the three input signals

3. RESULTS AND ANALYSIS

3.1. Ansel *et al.*'s Model and Controller

In the research [5], the Ansel *et al.*'s model omitted the relation in the Ohm's law between the DFIG stator voltages, the DFIG stator currents, and the external stator load. The DFIG stator currents were resulted from dividing the power reference by the DFIG stator voltage. This model and controller were merely tested by giving the constant DFIG stator voltage reference of 230 V.

The DFIG stator voltage couldn't be controlled in accordance with the reference if the DFIG stator terminal was connected to the external stator load and the DFIG stator voltage reference was varied as shown in the test scenario in Figure 7. By using the test scenario, the simulation showed that the DFIG stator voltage was uncontrollable and increased up to 300 V starting at 4 s although the DFIG stator voltages reference was still at 0V (see zone A in Figure 8). Starting at 4.5s, the response of the DFIG stator voltages became unstable (see zone B in Figure 8).

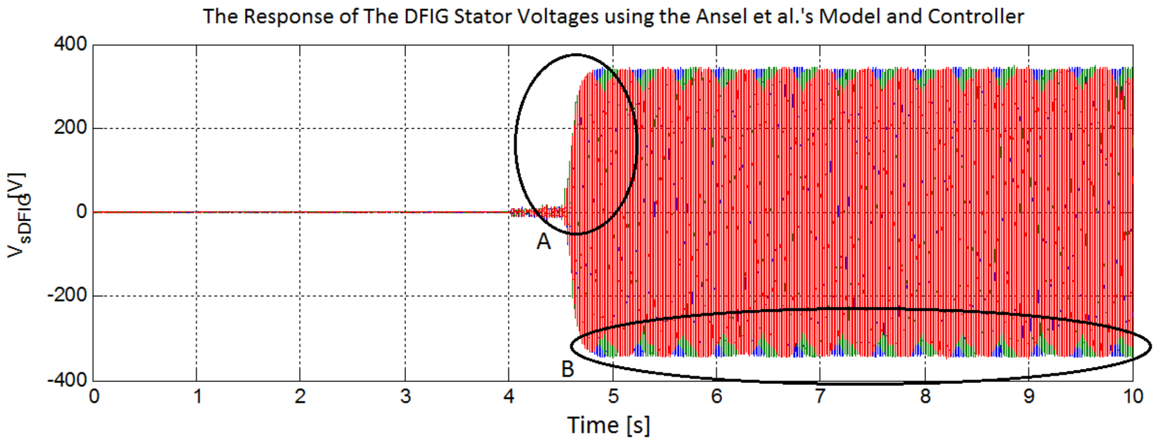

Figure 8. The response of the DFIG stator voltages using the Ansel *et al*.'s model and controler

3.2. Proposed Control Algorithm

By using the same test scenario, the simulation result showed that the proposed control algorithm could maintain the DFIG stator voltage in accordance with the reference. The response of the DFIG stator voltages by using the proposed control algorithm was shown in Figure 9. Until 5s, the DFIG stator voltages were still at 0V. Starting at 5s, the DFIG stator voltages of 100V were generated. Starting at 7s, the DFIG stator voltages could be maintained at constant 100 V although the external stator load was changed from 30 to 20 ohm at 7s. Starting at 8s, the DFIG stator voltages could follow the changing of the reference from 100V to 50V. The DFIG stator voltages were always in accordance with the reference.

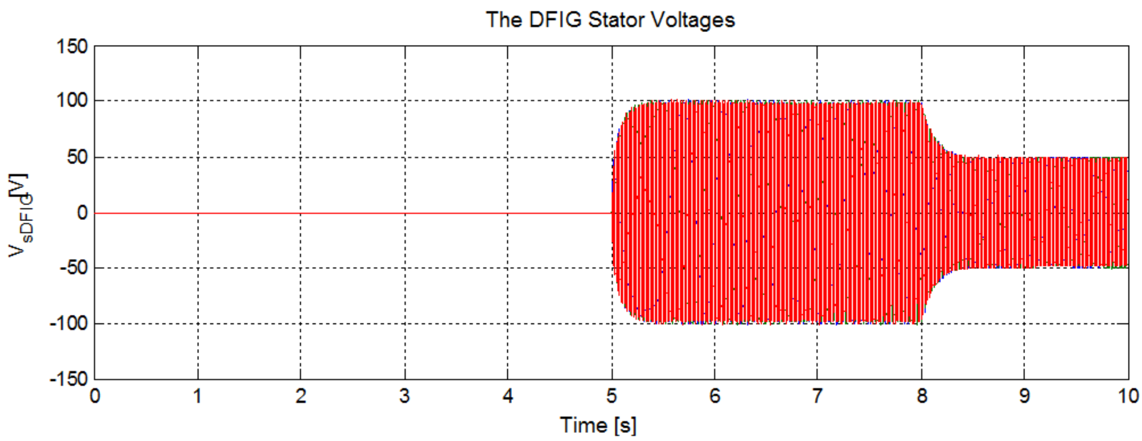

Figure 9. The response of the DFIG stator voltages by using the proposed control algorithm

By using the proposed control algorithm, the DFIG stator currents could also go along with the changing of the stator voltages and the stator load. The response of the DFIG stator currents was shown in Figure 10. The DFIG stator current was still at 0A until 5s. Starting at 5s, the DFIG stator currents could go along with the changes of the DFIG stator voltage reference from 0V to 100V. Starting at 7s, the DFIG stator currents could go along with the changes of the external stator load from 30 ohm to 20 ohm at 7s. Starting at 8s, the DFIG stator currents could also go along with the changes of the reference from 100V to 50V.

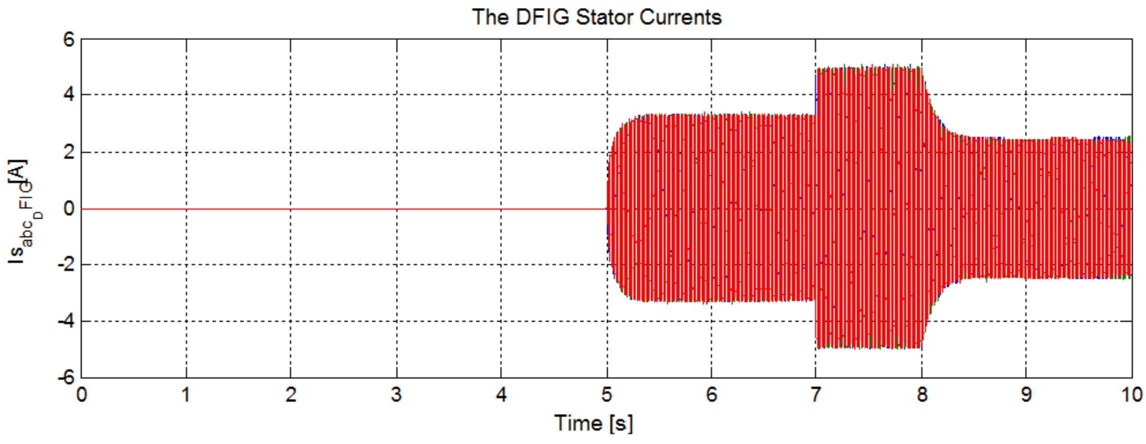

Figure 10. The response of the DFIG stator currents

Figure 11 shows that the DFIG generated power could suit to the changes of the stator voltages and the stator currents. It indicates that the DFIG generated power could be controlled. For further research, the DFIG generated power could be limited by using the maximum stator currents at the constant stator voltages.

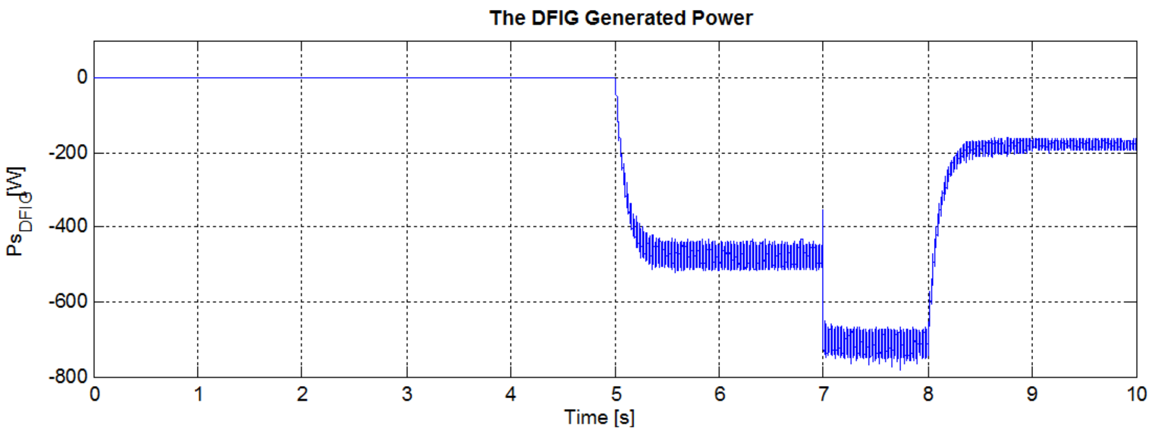

Figure 11. The response of the DFIG generated power

In speed sensorless application, the estimated angle of the stator flux had to match with the the stator flux orientation. Figure 12 shows that the estimated angle of the stator flux could follow the changes of the stator flux orientation. At the end, Figure 13 and Figure 14 show the response of the DFIG rotor voltages and currents.

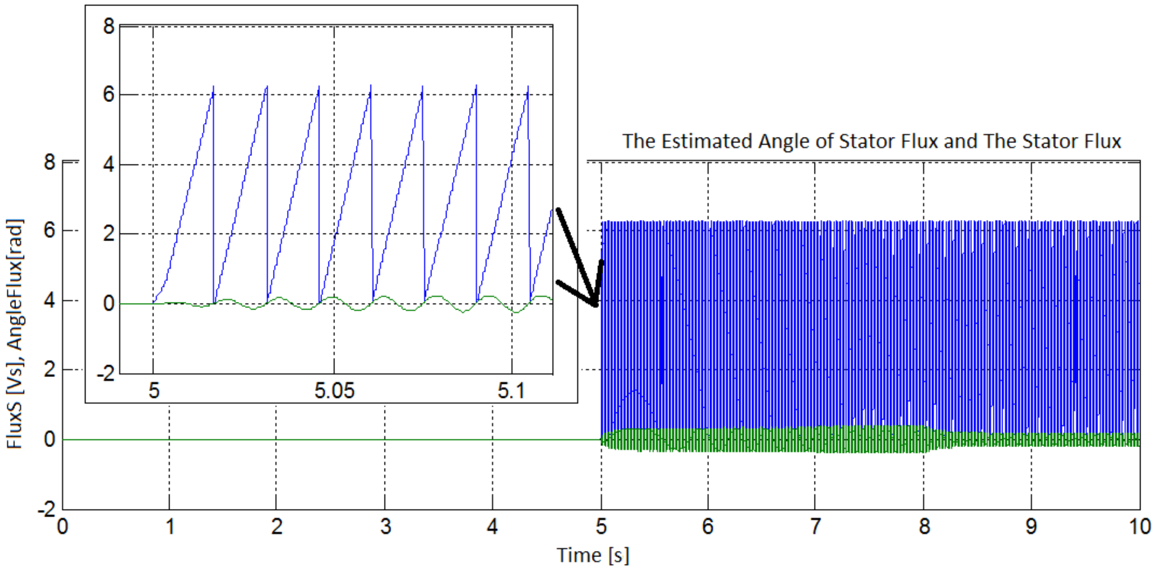

Figure 12. The response of the estimated angle of stator flux and the response of the stator flux

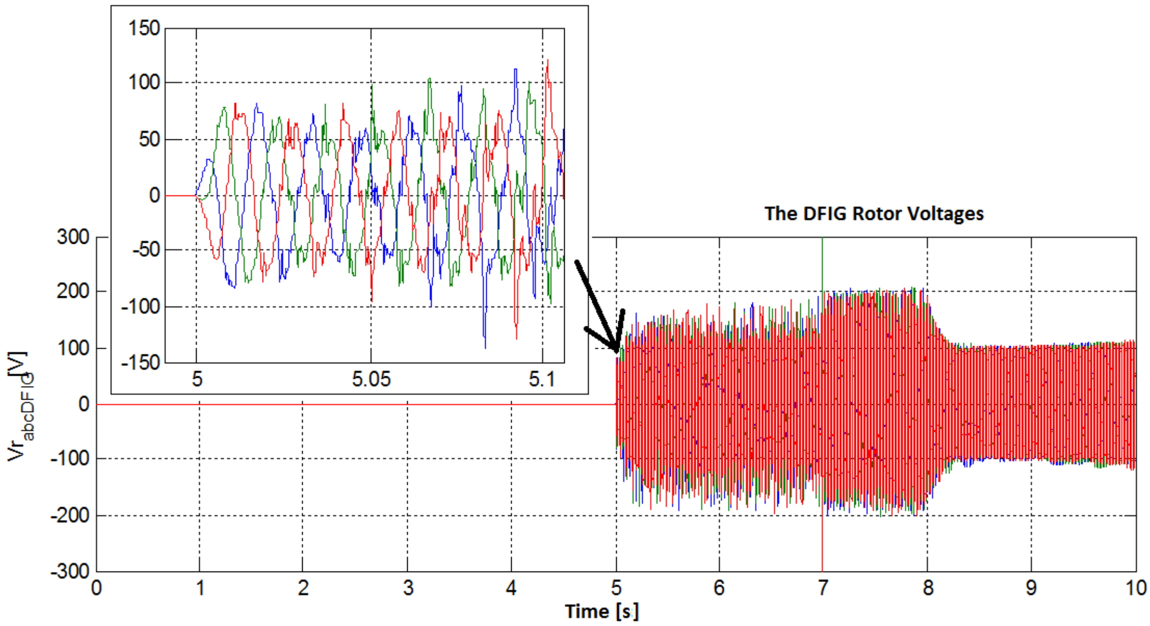

Figure 13. The response of the DFIG rotor voltages

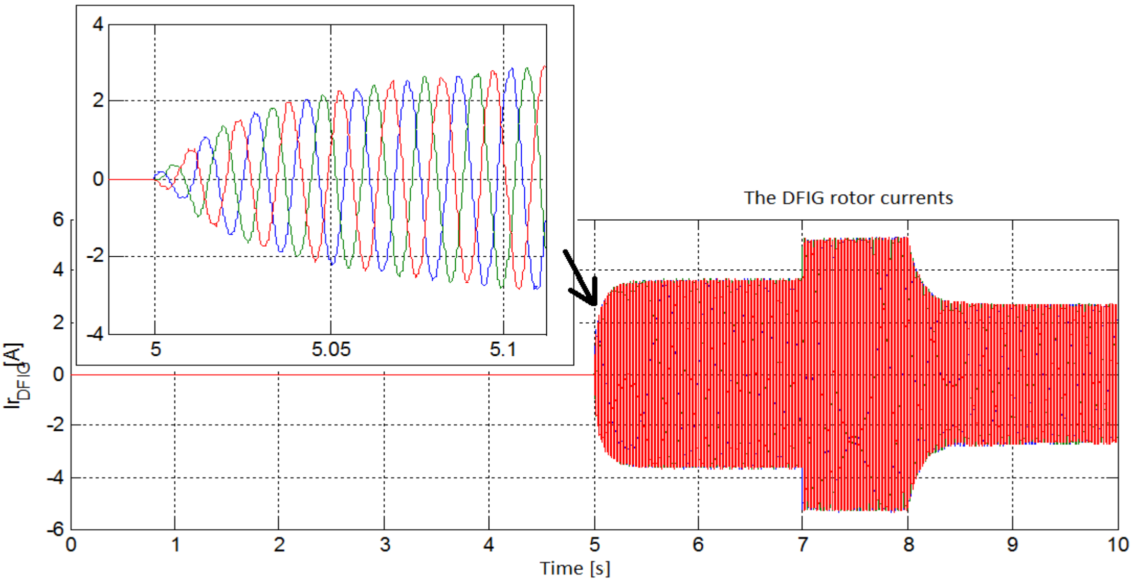

Figure 14. The response of the DFIG rotor currents

4. CONCLUSION

The authors were able to develop the control algorithm which could maintain the DFIG stator voltages of the autonomous micro hydro power plant in the off-grid configuration. The proposed control algorithm could maintain the DFIG rotor voltages by using the actual DFIG stator voltages and currents as feedback signals. The controller was tested by varying three input signals i.e. the DC-link voltage and the DFIG stator voltage reference, and the external stator load which simulated the off-grid configuration. The result of the simulation showed that the DFIG stator voltages could be maintained by the proposed control algorithm and were always in accordance with the reference.

ACKNOWLEDGEMENTS

This research was supported by Ministry of Research, Technology and Higher Education, Republic of Indonesia and University of Indonesia (2335/UN2.R12/HKP.05.00/2015).

REFERENCES

[1] Belabbas Belkacem, Tayeb Allaoui, Mohamed Tadjine, and Ahmed Safa, “Hybrid Fuzzy Sliding Mode Control of a DFIG Integrated into the Network”, *International Journal of Power Electronics and Drive System*, vol. 3-4, pp. 351-364, 2013.

[2] Zerzouri Nora and Labar Hocine, “Active and Reactive Power Control of a Doubly Fed Induction Generator”, *International Journal of Power Electronics and Drive System*, vol. 5-2, pp. 244-251, 2014.

[3] G. Venu Madhav and Y. P. Obulesu, “A Fuzzy Logic Control Strategy for Doubly Fed Induction Generator for Improved Performance under Faulty Operating Conditions”, *International Journal of Power Electronics and Drive System*, vol. 4-4, pp. 419-429, 2014.

[4] K. Viswanadha S Murthy, M. Kirankumar, and G.R.K. Murthy. “A Performance Comparison of DFIG using Power Transfer Matrix and Direct Power Control Techniques”, *International Journal of Power Electronics and Drive System*, vol. 5-2, pp. 176-184, 2014.

[5] A. Ansel and B. Robyns, “Modelling and simulation of an autonomous variable speed micro hydropower station”, *Mathematics and Computers in Simulation*, vol. 71, pp. 320–332, 2006.

[6] F. Yusivar, M. Shanizal, A. Subiantoro, and R. Gunawan, “Stability Analysis of DC-link Voltage Control on Autonomous Micro Hydro Power Plant System”, *International Journal of Power Electronics and Drive System*, vol. 4-4, pp. 499-507, 2014.

[7] S. Nababan, E. Muljadi, and F. Blaabjerg, “An overview of power topologies for micro-hydro turbines”, in *the 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG) 2012,* pp. 737–744, 2012.

[8] M. Andreica, S. Bacha, D. Roye, I. Exteberria-Otadui, and I. Munteanu, “Micro-hydro water current turbine control for grid connected or islanding operation”, in *IEEE Power Electronics Specialists Conference (PESC) 2008*, pp. 957–962, 2008.

[9] S. Breban, B. Robyns, and M.M. Radulescu, "Islanding detection methods for a micro-hydro power station - Simulation and experimental results", in *the 8th International Symposium on Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, ELECTROMOTION*, pp. 1-6, 2009.
[10] L.G. Scherer and R.F. de Camargo, "Control of micro hydro power stations using nonlinear model of hydraulic turbine applied on microgrid systems", in *Brazilian Power Electronics Conference (COBEP)*, pp. 812–818, 2011.
[11] L.G. Scherer and R.F. de Camargo, "Frequency and voltage control of micro hydro power stations based on hydraulic turbine's linear model applied on induction generators", in *Brazilian Power Electronics Conference (COBEP)*, pp. 546–552, 2011.
[12] Guocheng Wang, Qingzhi Zhai, and Jianhua Yang, "Voltage control of cage induction generator in micro hydro based on variable excitation", in *International Conference on Electrical Machines and Systems (ICEMS) 2011*, pp. 1–3, 2011.
[13] Yang Sheng and V. Ajjarapu, "Sensorless Control of the Doubly-Fed Induction Generator for Wind Energy Generations Using a Speed-Adaptive Full-Order Flux Observer", in *Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition (APEC) 2009*, pp. 1951–1957, 2009.
[14] Keyuan Huang, Guofu Chen, Shoudao Huang, and Luoqiang Cai. "Experimental evaluation of sensorless control for doubly-fed induction wind power generator", in *International Conference on Electrical Machines and Systems (ICEM) 2009*, pp. 1-6, 2009.
[15] M. Andreica, S. Bacha, D. Roye, I. Munteanu, A.I. Bratcu, and J. Guiraud., "Cross-flow Water Turbines Control Under Grid Disturbances", in *IEEE Bucharest Power Tech Conference Romania*, 2009.

BIOGRAPHIES OF AUTHORS

Feri Yusivar was born in Bandung, Indonesia. He received his bachelor degree in Electrical Engineering at University of Indonesia in 1992, and completed his Doctor degree in 2003 at Waseda University, Japan. He is currently the Head of Control Laboratory in Electrical Engineering at University of Indonesia. His research interests are in control system, electrical drive, power electronics, and renewable energy.

Nanda Avianto Wicaksono was born in Jakarta, Indonesia. He received his bachelor and master degrees in Electrical Engineering at Institute Technology of Bandung, Indonesia in 1998 and 2002. He is currently the student in Electrical Engineering at University of Indonesia and the researcher in Research and Development Agency, Ministry of Energy and Mineral Resources, Republic of Indonesia. His research interests are in control system, electrical drive, power electronics, and renewable energy.

Aries Subiantoro was born in Jakarta, Indonesia. He received his Bachelor degree in Electrical Engineering at University of Indonesia in 1995, and completed his Doctor degree in 2013 at University of Indonesia. His research interests are in model and simulation, intelligent control system, and model predictive control system.

Ridwan Gunawan was born in Jakarta, Indonesia. He received his Bachelor degree in Electrical Engineering at University of Indonesia in 1978, and completed his Doctor degree in 2006 at University of Indonesia. His research interests are in power system, electrical drive system, and power electronics system.