Sensorless MPPT Technique for PMSG Micro Wind Turbines based on State-Flow

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***Abstract*— The field of small scale distributed wind energy generation features noticeable concern regarding the utilization of direct driven permanent magnet synchronous generators (PMSGs). The quality of the output power from a wind turbine generator is mainly dependent on how the maximum power point is tracked. Classical hill-climbing maximum power point tracking (MPPT) techniques exhibit inherit oscillation/settling time trade-off. Wind MPPT process can be considered as an event driven problem. This paper proposes a Stat-Flow based Hill Climbing Searching (HCS) wind MPPT as a competitive technique. The presented technique features simplified implementation, more degree-of-freedom, controllable event timing. Those features contribute to enhance the MPPT process by minimizing the steady-state power oscillations and improve the transient performance. Rigorous simulations are carried out to examine the proposed technique under various wind speeds and power levels to validate the technique's effectiveness.**

Keywords*— *Wind Turbine, Permanent Magnet Synchronous Generator, DC/DC converter, MPPT, P&O method, State-Flow.

I. Introduction

Recently, renewable energy systems are attracting great attention due to environmental problems such as: greenhouse gases, acid rain and air pollution that takes place as a reason of fossil fuel consumption. Therefore, wind power can be a competitor to convention fossil fuel, as it is cheaper compared to other renewable power generation systems, non-polluting and provides sustainable electrical energy supply to world development.

Small scale wind turbines driving PMSG is getting more interest recently in the market as PMSGs are often directly coupled to the turbine eliminating the need of gearbox thus loses and maintenance of the gearbox are avoided. In addition PMSG are self-excited, more efficient, light weight and feature high power density machine [1].

Wind turbines modes of operation can be classified as variable speed and fixed speed. However, variable speed operation offers more efficiency and control flexibility [2]. Since the output power of wind energy conversion system varies with respect to the wind speed and due to the nonlinear characteristics of the wind turbine, it is challenging to track the maximum power point (MPP) of a wind turbine for wide range of wind speed variations. The maximum power point techniques used for wind turbine system are commonly classified into three main control methods namely: Tip Speed Ratio (TSR) control, Power Signal Feedback (PSF) control and Hill Climbing Searching (HCS) control [3-8]. Those techniques varied compared to each other from several aspects like machine parameters' dependency, power oscillation, complexity and settling time. As the MPPT can be considered as event-driven process, in this paper a simple HCS control method based State-Flow is introduced to track the maximum power of a small scale stand-alone PMSG wind turbine at various wind speed operating conditions. The paper is organized as follows: section-II provides the wind turbine system modelling and analysis, while section-III presents the proposed State-flow based MPPT algorithm. The simulation results are presented in section-IV. Finally, a conclusion is given in section-V.

II. Wind Turbine Modelling and Analysis

Typical wind energy conversion system (WECS) includes a wind turbine coupled with an electrical generator that is connected to the load through a power electronic converters and a controller that guarantees the transfer of the maximum power generated to the load as shown in figure 1[3].

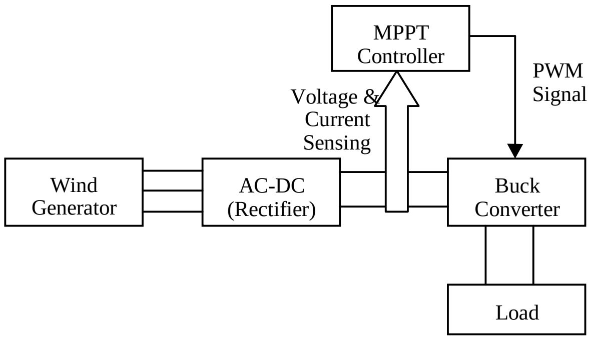


Figure 1: Wind energy conversion system block diagram

A. Wind Turbine Characteristics

A wind turbine converts kinetic energy of the wind into electrical energy through the coupled generator. The wind power is known to be proportional to the cube of the wind speed and can be expressed as.

$$\boldsymbol{P_w = \frac{1}{2}\rho A v_w^3} \qquad (1)$$

Where, $\boldsymbol{\rho}$ is the air density

$\boldsymbol{A}$ is the swept area of the blades

However, the wind turbine can capture only a fraction of this power depending on its power coefficient (c_p) that is a function of the tip speed ratio (λ) and the blade pitch angle ($\boldsymbol{\beta}$). Thus the mechanical power extracted from wind by the wind turbine is:

$$P_m = \frac{1}{2} c_p(\beta, \lambda) \rho A v_w^3 \qquad (2)$$

The tip speed ratio (λ) is the ratio between the rotor speed and the wind speed (v_w), thus it is given as.

$$\lambda = \frac{R \times w_m}{v_w} \qquad (3)$$

Where, $\boldsymbol{R}$ is the radius of blade. The wind turbine shaft torque can be calculated from the power and expressed in the torque coefficient c_T as follow:

$$T_m = \frac{P_m}{w_m} = \frac{1}{2} \rho \pi R^3 v_w^2 c_T \qquad (4)$$

$$c_T = \frac{c_p}{\lambda} \qquad (5)$$

From equations (2) and (3) and referring to figure 2 [9], it is clear that when the wind speed changes the rotor speed and the power captured by the wind turbine will change. Thus for each wind speed there exists a specific turbine speed that gives a maximum output power when the blade pitch angle is fixed at zero ($\boldsymbol{\beta} = 0$).

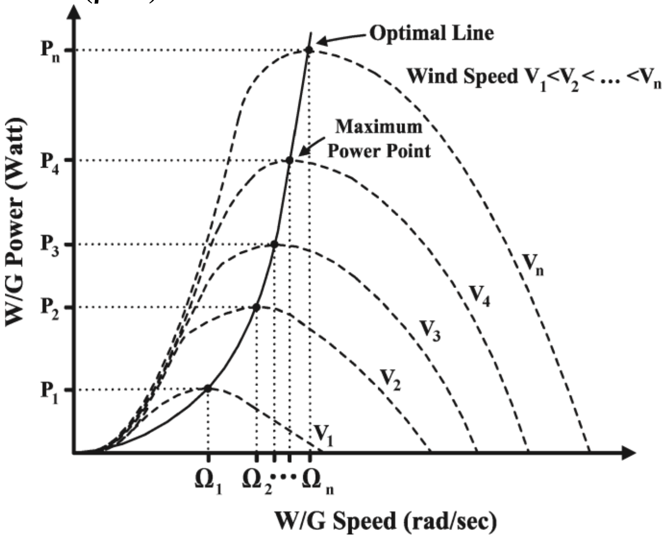


Figure 2: PMSG power curves at various wind speeds.

B. PMSG Modelling

Several types of generators such as induction generators (squirrel cage, wound rotor with slip control and doubly fed) and synchronous generator are used for wind turbine systems. However, variable speed direct driven multi-pole PMSG turbines have been considered as high performance drive system for typical WECSs due to the offered reliable, self-excited, low wear and tear, compact, efficient, low noise performance.

The sinusoidal model of the PMSG assumes that both the flux established by the permanent magnets in the stator and the electromotive forces are sinusoidal. From each phase equivalent circuit of the PMSG the voltage equations can be expressed as [10]:

$$\frac{V_s i_q}{\sqrt{i_q^2 + i_d^2}} = -R_s i_q - L_q s i_q - \omega_e L_q i_d + \omega_e \phi_m \qquad (6)$$

$$\frac{V_s i_d}{\sqrt{i_q^2 + i_d^2}} = -R_s i_d - L_d s i_d - \omega_e L_d i_q \qquad (7)$$

Where, $\mathbf{V_s}$ is the magnitude of phase voltage

$\boldsymbol{i_d}$, $\boldsymbol{i_q}$ are the d and q axis generate currents

$\boldsymbol{R_s}$ is the stator internal resistance

$\boldsymbol{L_d}$, $\boldsymbol{L_q}$, are the d and q axis stator inductance

$\boldsymbol{w_e}$ is the rotor angular velocity

$\boldsymbol{\Phi_m}$ magnetic flux

Since the power generated from the PMSG is converted into DC power through the diode bridge rectifier connected to it. Hence, the DC current (I_{dc}) and voltage (V_{dc}) are expressed as:

$$I_{dc} = \frac{\pi}{2\sqrt{3}} \sqrt{i_q^2 + i_d^2} \qquad (8)$$

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_s \qquad (9)$$

Starting from the fact that PMSG output currents and voltages are proportional to the torque and rotor speed, thus perturbing the output voltage will cause varying in the generator rotor speed and consequently varies the output power. The method to follow the optimal mechanical number of revolutions to reach maximum power generation is known as MPPT control.

C. Buck DC/DC converter

The buck converter is known to be a step-down converter where the ratio between its input voltage (v_i) and the output voltage (v_o) is controlled by the duty cycle (d) of the IGBT switch. The schematic of Buck DC/DC converter is shown in figure 3 [11].

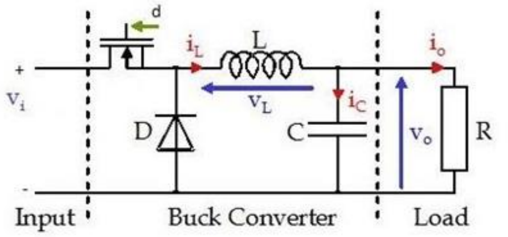


Figure 3: The Buck DC/DC converter schematic.

Under the assumption that the buck converter is working in continuous current mode, the converter input–output voltage relationship can be represented by the following averaged relation:

$$d = \frac{v_o}{v_i} \qquad (10)$$

The selection of capacitor and inductor size is a major part in designing a buck converter that is mainly affected by the selection of the switching frequency (f_s). At higher switching frequencies, the value of required inductor is reduced to produce continuous current and smaller capacitor size to limit output ripple. The minimum inductor value (L_{min}) is determined as:

$$L_{min} = \frac{v_o(v_i - v_o)}{\Delta i_L \times f_s \times v_i} \qquad (11)$$

Where Δi_L is the inductor ripple current calculated as in equation 12 while i_o is the maximum output current.

$$\Delta i_L = 0.2 \times i_o \qquad (12)$$

For the buck converter to operate at CCM, the inductance value has to be 25% greater than L_{min} [12] as in equation 13.

$$L = 1.25 \times L_{min} \qquad (13)$$

The pulsating current produced by the switching action is smoothed by the capacitive filter where the capacitance value is determined by equation 14, as v_r is the ripple voltage [13].

$$C = \frac{\Delta i_L}{8 \times f_s \times v_r} \qquad (14)$$

D. *MPPT Algorithm*

The amount of power output from a wind turbine generator is mainly depending upon the efficiency in which the maximum power point is tracked by the MPPT controller. Several comparative studies of different control strategies for MPPT were proposed in literature [14-17] at which all MPPT algorithms are concerned in how to automatically obtain the reference rotor speeds at maximum output power under various wind speeds.

Among these algorithms, the hill-climbing searching algorithm is widely used, which doesn't require any previous knowledge of wind turbine and generator characteristics [18]. Flowchart of the hill-climbing algorithm is illustrated in figure. 4, which operates by varying the duty cycle of the buck converter. Thus varying the output voltage of the wind generator, and observe the resulting power to increase or decrease the duty cycle in the next cycle. If the increase of duty cycle produces an increase of the power, then the direction of the perturbation signal is the same as the previous cycle. Contrary, if the perturbation duty cycle produces a decrease of the power, then the direction of perturbation signal is the opposite from the previous cycle.

III. PROPOSED STATE-FLOW BASED MPPT

Since the chosen of appropriate converter with highly efficient design was important with proposing a MPP tracker, as the applied algorithm adjust the duty ratio automatically on the event of any wind speed variation. So the proposed algorithm in this paper based on State-Flow is considered to be a challenging design tool that works with Simulink to model and simulate reactive systems [20].

Stat-Flow is proposed as competitive MPPT technique, as shown in figure 5, featuring simplified implementation, more degree-of freedom, and controllable event timing. Those features are expected to enhance MPPT tracking by minimizing the steady-state power oscillations and improve the transient performance. The proposed algorithm has been simulated using MATLAB/SIMULINK® Software package.

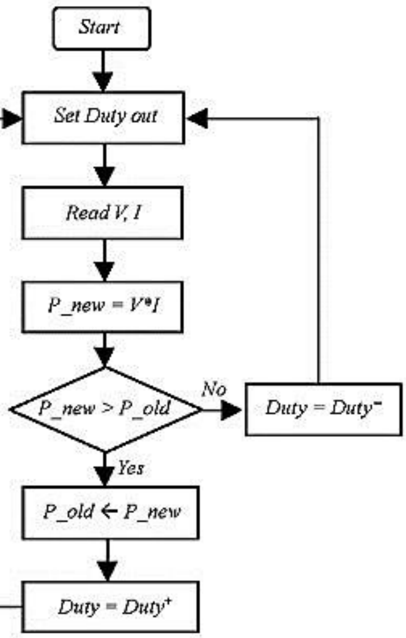


Figure 4: P&O algorithm [16].

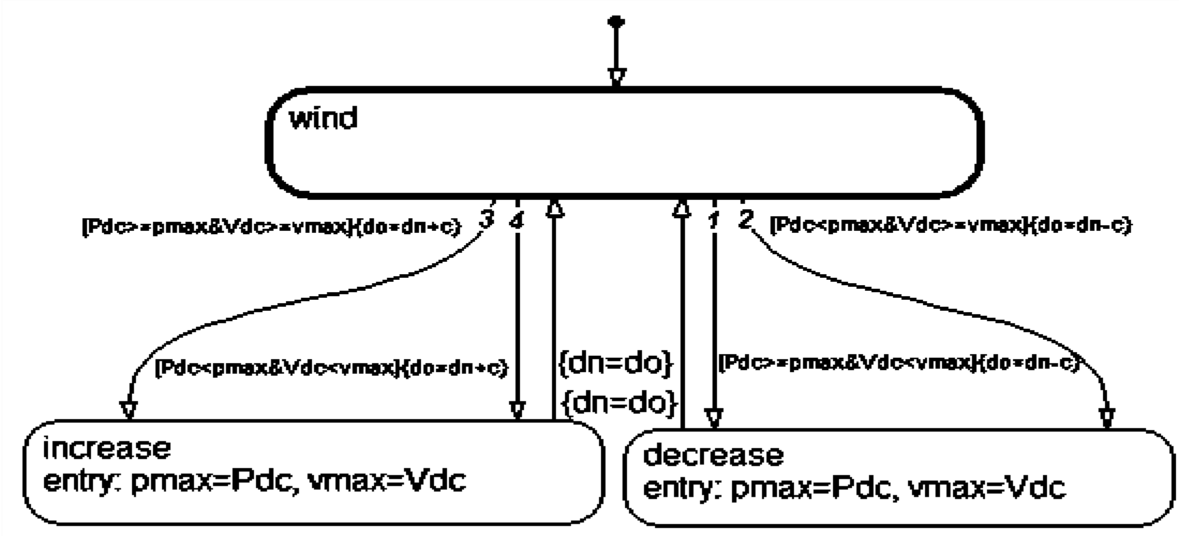


Figure 5: Proposed State-Flow based Wind MPPT technique

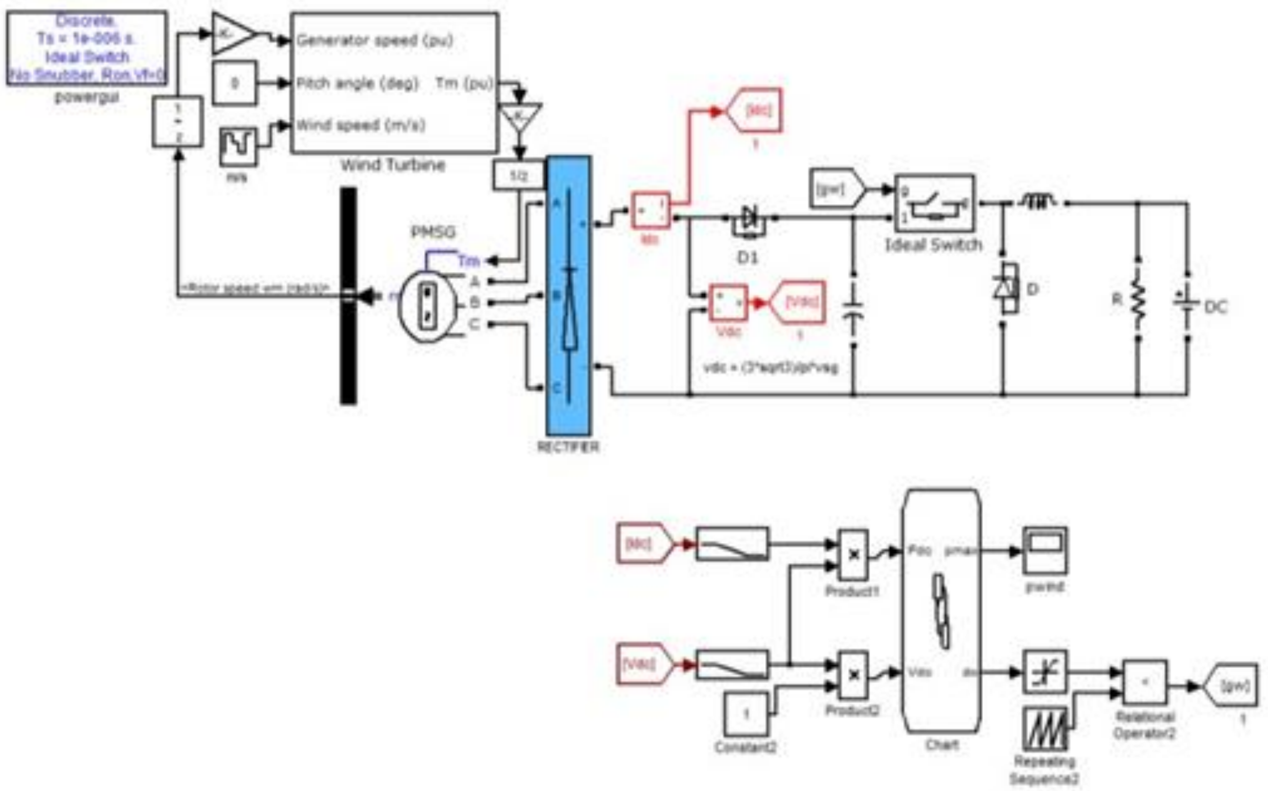


Figure 6: WECS utilizing the proposed State-Flow based MPPT technique MATLAB/SIMULINK® simulation diagram

IV. Simulation Results

The WECS under investigation is simulated utilizing the proposed State-Flow MPPT technique using MATLAB/SIMULINK software package. The model is illustrated in figure 6. The parameters of the simulated PMSG are listed in Table 1 while its Power-Generator speed characteristics are shown in figure 7.

The start-up operation in addition to the steady-state performance for the system under investigation is illustrated in figure 8. At a wind speed of 12m/s, the PMSG attains its rated power of 600W in 0.8s as shown in figure 8(a).

During steady-state operation, the PMSG based WECS adopting the proposed Sate-Flow based MPPT technique offers minimal power oscillations, nearly 3.3%, as shown in figure 8(b).

For performance assessment under sudden change of wind speeds, the system is simulated when the wind velocity suddenly drops from 12m/s to 10m/s as illustrated in figure 9. Under the proposed MPPT technique, the turbine successfully attains the new maximum power that corresponds to the current wind velocity as shown in figure 9(a).

The smooth under-shoot-free output power change is illustrated by zooming during the period of wind speed variation (from 2 to 2.3s) as shown in figure 9(b).

Table 1: Wind Turbine & PMSG Characteristics

System Output Rated Power	600 W
Rated Wind Speed	12 m/s
Start-up Wind Speed	2 m/s
Rotor Diameter	1.85 m
Number of Blades	3
Rated Voltage	48 V
Rated Current	12 A

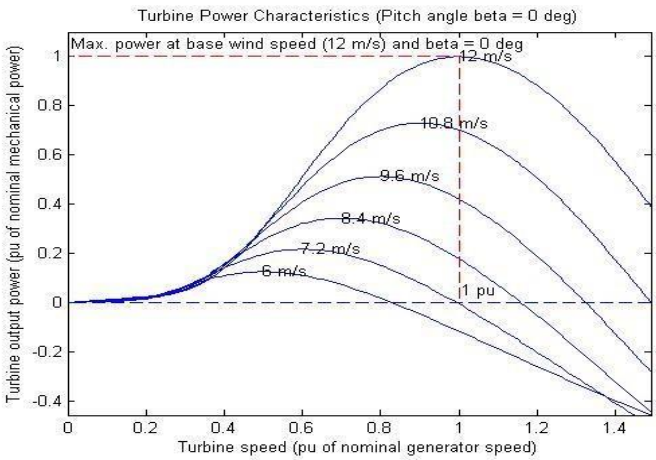
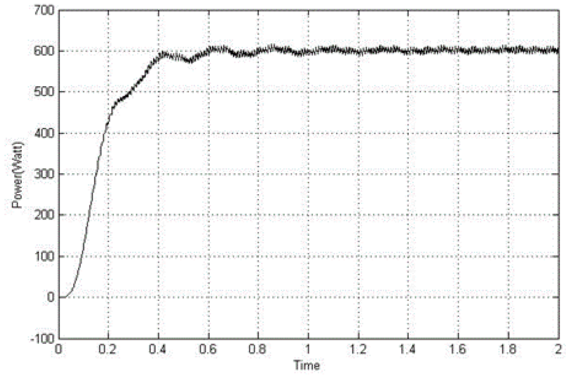
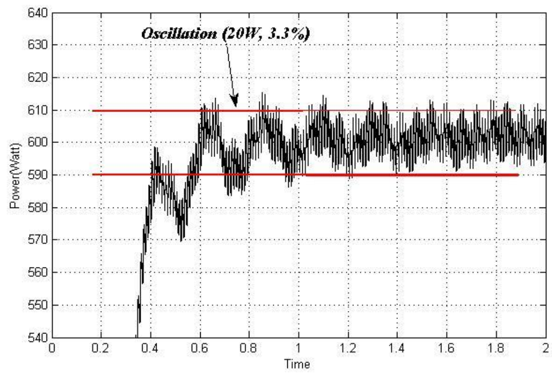


Figure 7: Simulated PMSG characteristics

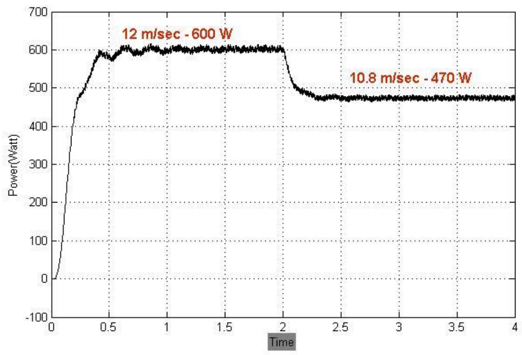


(a)

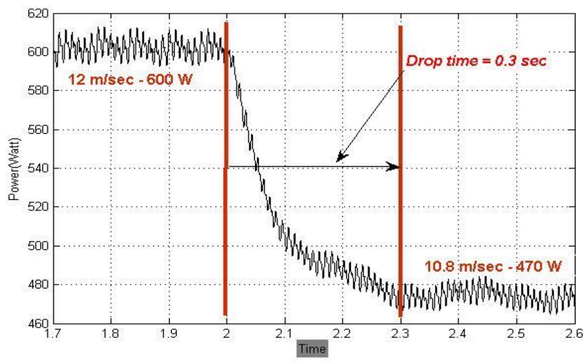


(b)

Figure 8: Simulation results for the investigated WECS adopting the proposed State-Flow MPPT technique: (a) start-up operation and (b) zoom on steady-state



(a)



(b)

Figure 9: WECS output power under sudden wind speed decrease

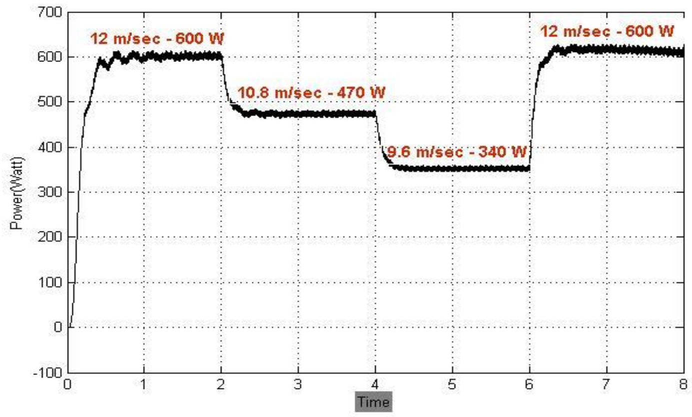


Figure 10: Simulation for 4 different speeds

Figure 10 shows the enhanced performance of the WECS adopting the proposed State-Flow based MPPT technique under varying wind velocities. Minimal oscillations in addition to fast tracking of the optimal maximum power prove the proposed MPPT technique's enhanced performance.

V. CONCLUSION

An enhanced performance wind MPPT technique is proposed in this paper for PMSG wind turbines. The presented technique is based on State-Flow as the MPPT operation can be considered as an event-driven process. As the proposed technique features two degrees of freedom, simulation results reveal improved performance, better tracking, machine-parameters independency and minimal power oscillations.

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REFERENCES

[1]. G. Chun, P. Ganeshkumar, A. Ahmed and J. Park 'Design of MPPT Controller for Small Scale Wind Power System with PMSG', 15th International Conference on Electrical Machines and Systems (ICEMS), 2012

[2]. Mirza Mohd.Shadab 'Performance Analysis of Permenant Synchronous Advanced Technology & Engineering Reseach (IJATER), May 2012.

[3]. Aryuanto Soetedjo, Abraham Lomi, Widodo Puji Mulayanto, 'Modeling of Wind Energy System with MPPT Control' International Conference on Electrical Engineering and Informatics, Bandung, Indonesia 17-19 July 2011.

[4]. A. J. Mahdi, W. H. Tang, and Q. H. Wu 'Novel Perturbation and Observation Algorithms for Variable- Speed Wind Turbine Generator Systems' IEEE Power and Energy Society General Meeting, 2012.

[5]. C.-T. Pan and Y.-L. Juan, 'A novel sensorless MPPT controller for a high-efficiency microscale wind power generation system', IEEE Trans. Energy Conversion, vol. 25, no. 1, pp. 207–216, Mar. 2010.

[6]. Q. Huang and Z. Pan, 'Sensorless control of permanent magnet synchronous generator in direct-drive wind power system' in Proc. 2011

Int. Conf. Electr. Mach. Syst., ICEMS'11, Beijing, China, Aug. 20–23, 2011, pp. 1–5.

[7]. Haque M.E, Negnevitsky M., Muttaqi K.M. 'A novel control strategy for variable-speed wind turbine with a permenant-magnet synchronous generator', IEEE Trans. Ind. Appl. 2010, 46, 331-339.

[8]. Kazemi, S.M.R.; Goto, H.; Guo, H.J,; Ichinokura, O. 'A novel algorithm for fast and efficient speed-sensorless maximum power point tracking in wind energy conversion systems', IEEE Trans. Ind. Electron. 2011.

[9]. Eftichios Koutroulis and Kostas Kalaitzakis, 'Design of a Maximum Power Tracking System for Wind-Energy- Conversion Applications', IEEE Transaction on Industrial Electronics, VOL. 53, NO. 2, APRIL 2006.

[10]. He XU, Jing HUI, Dinghui WU, Wenxu YAN. 'Implementation of MPPT for PMSG-Based Small- Scale Wind Turbine' 4th IEEE Conference on Industrial Electronics and Applications, 2009. ICIEA 2009.

[11]. In-Hwan Oh. 'A soft switching synchronous buck converter for zero voltage switching (ZVS) in Light and Full load conditions', IEEE xplore, 978-1-4244-1874- 9/08, pp.1460-1464, 2008.

[12]. N. J. A. B. Mohd, 'Photovoltaic Charge Controller', Bachelor Degree Electrical & Electronics Engineering, Universiti Malaysia Pahang 2009.

[13]. N.H. Abdul Rahman, A.M. Omar, E.H. Mat Saat, 'A Modification of Variable Step Size INC MPPT in PV System', IEEE 7th International Power Engineering and Optimization Conference (PEOCO2013), Langkawi, Malaysia. June 2013.

[14]. Natalia Angela Orlando, Marco Liserre, Rosa Anna Mastromauro, and Antonio Dell Aquila, 'A Survey of Control Issues in PMSG-Based Small Wind-Turbine Systems', IEEE Transaction on Industrial Informatics, VOL. 9, NO. 3, AUGUST 2013

[15]. A.Mirecki, X.Roboam, F.Richardeau, 'Comparative Study of Maximum Power Strategy in Wind Turbines', 07803, pp.993-998,2004.

[16]. G.D.Moor, H.J.Beukes, 'Maximum Power Point Trackers For Wind Turbines', 35th Annual IEEE Power Electronics Specialists Conference, pp.2044-2049, 2004.

[17]. Jogendra Singh Thongam and Mohand Ouhrouche, 'MPPT Control Methods in Wind Energy Conversion Systems' Fundamental and Advanced Topics in Wind Power, 'www.intechopen.com.

[18]. W. Xiao, W. Dunford, P. Palmer, and A. Capel, "Application of centered differentiation and steepest descent to maximum power point tracking," IEEE Transactions on Industrial Electronics, vol. 54, no. 5, pp. 2539 – 2549, Oct. 2007.

[19]. J. A. Jiang, T.L. Huang, Y.T. Hsiao, C.H. Chen, "Maximum Power Tracking for Photovoltaic Power Systems", Tamkang Journal of Science and Engineering, Vol. 8, No.2, pp. 147-153, 2005.

[20]. Rana Ahmed, A. Namaane and N. K. M'Sirdi, "Improvement in Perturb and Observe Method Using State Flow Approach" Energy Procedia Volume 42, 2013, Pages 614–623, Mediterranean Green Energy Forum 2013: Proceedings of an International Conference MGEF-13