2017 Nineteenth International Middle East Power Systems Conference (MEPCON), Menoufia University, Egypt, 19-21 December 2017.

Second Order Adaptive Notch Filter Based Wind Power Smoothing Using Flywheel Energy Storage System

A. A. Abu El-Naga, M. I. Marei and H. S. K. El-Goharey
Electrical Power and Machines Department
Faculty of Engineering, Ain Shams University
Cairo, Egypt
Abdallah.Alaa@eng.asu.edu.eg

***Abstract*—Smoothing wind power is a vital process to allow increasing wind integration into the grid. This paper proposes a control strategy to smooth wind power by using flywheel energy storage system (FESS) driven by permanent magnet synchronous machine (PMSM). A back-to-back converter is used to connect the flywheel system with the grid. The converter functions are to control the charging/discharging process of the flywheel, to keep the DC link voltage at constant predetermined value, and to control the reactive power exchanged with the grid. The second order adaptive notch filter (SOANF) is proposed to estimate the flywheel power reference by filtering the wind power. The dynamic performance of the proposed control strategy is studied using PSCAD/EMTDC software. The simulation results proved the success of the proposed control in smoothing wind power. They also show acceptable behavior of the proposed filtering technique and the strength of the proposed control strategy.**

***Index Terms*--Adaptive notch filter, back to back converter, Flywheel, PMSM.**

I. INTRODUCTION

Wind energy is one of the most important renewable sources as it has high potential in many sites compared to other renewable sources. Its importance has been increased as many countries need to reduce their fossil fuel consumption and to reduce the greenhouse gas emissions [1], [2]. However, wind power is directly proportion to the cube of the wind speed and since the wind speed is intermittent and has high fluctuations; the output power from wind energy has rapid short and long period's fluctuations. Short period fluctuations in the output power can cause problems in the system stability and can cause frequency error. These problems are significant in small grids such as microgrids [3].

Many methods have been used to reduce the problems arising from wind power generation. Variable speed wind turbine is one of the methods that can reduce the wind output fluctuations by using blade angle control. This method reduces the torque peaks for the gearbox and the shaft and hence reduces the output power fluctuations. However, mechanical stress on the turbine blade increases in case of short term fluctuations. Generally, energy storage devices are used for controlling the power flow from the wind generators to the grid. Energy storage devices will reduce the power fluctuation injected to the grid and can be used to provide ancillary services [4], [5]. There are many types of energy storage devices such as batteries, super-conducting magnetic energy storage systems (SMESs), super-capacitors (SC), and flywheel energy storage systems (FESSs) [6], [7]. FESSs are well adapted to mitigate short term fluctuation arises from wind generation. Besides, FESS have many merits as they have long life time, high efficiency, high power density, and can operate in large range of different temperatures [7]-[9]. Power smoothing ensures higher power quality for the injected power to the grid which is essential for the increased penetration wing energy systems.

Flywheel control studies can be divided into two levels: high level and low level control. Low level control is responsible for controlling the flywheel machine to operate as a motor or a generator by managing the instantaneous current of the machine. The main focus in this level is on flux weakening strategies to operate flywheel at high speed using sensorless control methods to reduce the cost and weight of the system, increasing the machine efficiency, and enhancing the machine dynamic response. In [8], the flywheel is activated by using an induction machine that has been controlled using direct flux oriented control (DFOC) and with integrated flux weakening control strategy. In [10], the flywheel is driven by reluctance synchronous machine controlled by using single pulse mode and flux weakening strategy to run the machine above its base speed. Reference [11] has proposed a sensorless vector control to drive the induction machine, where an adaptive observer is modeled to track the flywheel rotational speed. In [12], an immune sensorless control for a dual air gap axial permanent magnet machine is discussed. The sensorless control is achieved by using stator flux observer. The harmonic losses in the rotor of the synchronous reluctance machine have been studied, then control technique and filter design are investigated to reduce these losses in [13]. Different controllers such as PI, PID, fuzzy control, and adaptive neural fuzzy are used to control the machine current [14], [6].

On the other hand, many papers have dealt with the high level control to determine the power reference for the flywheel in order to smooth the output power fed to grid. In [15], the power reference for the flywheel is determined by filtering the wind output power using high pass filter. While in [16]-[18], a fuzzy logic control has been used to manage the power injected to the grid taking into account the filtered values for output wind power and the flywheel state of charge. Hence, the flywheel is always exchanging power. In

978-1-5386-0990-3/17/$31.00 ©2017 IEEE

[19], an enhanced power smoothing strategy for the wind power is presented using a backlash block with low pass filter. Although filtering the wind signal is the basic block of the supervisory control, the aforementioned papers didn't investigate different filtering methods to enhance the smoothing power reference.

This paper presents a new filtering method for tracking the flywheel power reference signal in order to smooth the injected power to the grid. The paper is organized as following. First, the dynamic models for both the flywheel and PMSM are described in section II. The control for the back to back converter and the proposed adaptive filtering method is described in section III. The simulation results are analyzed in section IV. Finally, the paper conclusions is stated in section V.

II. THE SYSTEM MODEL

Figure 1 presents the proposed flywheel energy storage system for power smoothing of wind energy system. The wind energy system consists of wind turbine, PMSM, and a wind side converter which is controlled to extract the maximum wind power. The complete model and control of the wind energy system is explained in [20]. The flywheel energy storage system consists of flywheel storage device, PMSM, and FW side converter. The wind and flywheel energy systems are coupled to the DC link of the grid side converter. The dynamic model of the flywheel energy storage system is described in the following subsection.

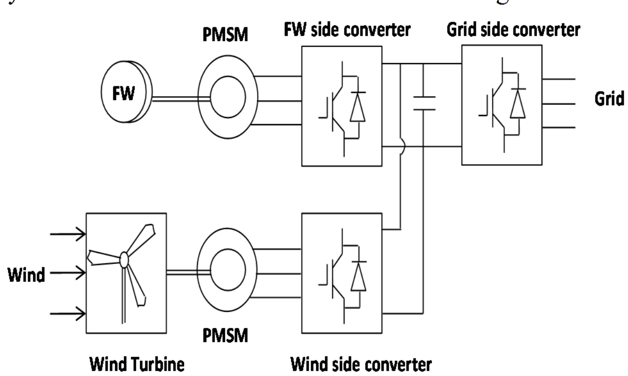


Figure 1.Block diagram of the proposed system.

A. The Flywheel model

The flywheel is a mechanical storage device in which its storage energy capability can be determined from its moment of inertia and its rotational speed. The maximum energy storage of the flywheel is determined from:

$$E_{max} = \frac{1}{2} J_{Fw} (\omega_{max}{}^2 - \omega_{min}{}^2) \quad (1)$$

where E_{max} is the maximum flywheel energy storage capacity, J_{Fw} is the flywheel moment of inertia, ω_{max} is the maximum flywheel angular speed, and ω_{min} is the minimum flywheel angular speed which is usually $\frac{1}{3}\omega_{max}$ to keep the capability of the machine to absorb or inject the required power [21]. Since the flywheel is a rotating mass which is coupled directly to the PMSM, thus its dynamic model can be integrated with the PMSM model by adding their inertias and their damping coefficient together in the electromechanical equation as follows:

$$T_e - T_L = J_{eq} \frac{d\omega_r}{dt} + B_{eq}\omega_r \quad (2)$$

where T_e is the electromagnetic torque of the PMSM, T_L is the mechanical load torque; J_{eq} is the equivalent moment of inertia of both the flywheel J_{Fw} and the PMSM J_{PMSM}, B_{eq} is the equivalent damping coefficient of both the flywheel B_{FW} and the PMSM B_{PMSM}, and ω_r is the PMSM rotor angular speed.

B. The PMSM Model

The PMSM is modeled in the d-q rotor frame. The stator voltage is given by

$$V_{sd} = R_s i_{sd} + L_{sd} \frac{di_{sd}}{dt} - \omega_e L_{sq} i_{sq} \quad (3)$$

$$V_{sq} = R_s i_{sq} + L_{sq} \frac{di_{sq}}{dt} + \omega_e L_{sd} i_{sd} + \omega_e \psi_m \quad (4)$$

where V_{sd} and V_{sq} are the stator voltage in d-axis and q-axis, respectively, i_{sd} and i_{sq} are the stator current in the d-axis and q-axis, respectively, ω_e is the PMSM electrical angular speed, R_s is the stator resistance, L_{sd} is the direct stator inductance, and L_{sq} is the quadrature stator inductance. The voltage in the d-q axis is calculated by transforming the three phase voltage using Park's transformation, while the electromagnetic torque is given by

$$T_e = \frac{3}{2} P \left[\psi_m + \left(L_{sd} - L_{sq}\right) i_{sd}\right] i_{sq} \quad (5)$$

where P is the number of pole pairs of the PMSM.

C. Back to Back Converter

The speed of the flywheel is variable according to its state of charge. Therefore, the voltage of the PMSM is varying in both amplitude and frequency. A back to back converter is used to connect the PMSM with the grid and to control the flywheel charging and discharging process. During charging process, the power flows from the grid to the PMSM which acts as motor. Hence, the speed and the stored energy of the flywheel increase; while in discharging process the power flows from the PMSM, which acts as a generator, to the grid. As a result, the speed and the stored energy of the flywheel decrease. The back to back converter consists of two converters with a common dc link.

III. THE PROPOSED CONTROL SYSTEM

The functions of the flywheel are achieved by controlling both the flywheel side converter and the grid side converter.

A. Grid side converter control

A vector control strategy is used for the grid side converter. The active and the reactive power are controlled separately by using current in the d-q frame as shown in Fig. 2. The active component is used to keep the dc link voltage at set value. A PI controller is used to process the error between

V_{dcref} and V_{dc} and its output is the quadrature current component, while the reactive component is used to control the reactive power injected to the grid. The direct current component is set at zero to minimize the inverter rating by injecting zero reactive power. The d-q current reference is transformed to three-phase components using park's transformation with the aid of phase locked loop (PLL). Finally, the inverter gate signal is determined by using hysteresis current control.

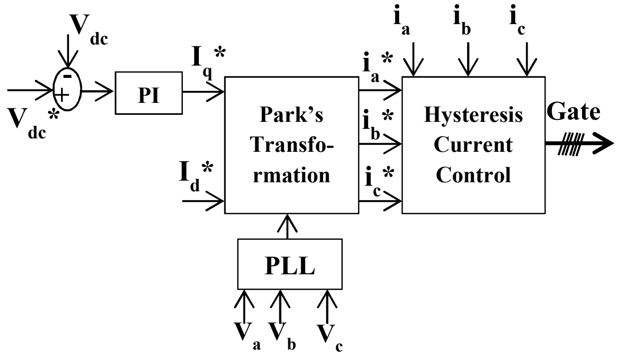


Figure 2.Grid side converter control block diagram.

B. The control of the flywheel side converter

The flywheel converter is responsible for the charging/discharging operation in order to smooth wind variation. The PMSM reference power is determined to absorb the wind fluctuations which could be determined directly by filtering the wind power. The second order adaptive notch filter (SOANF) is proposed for this task. The flywheel side converter is controlled by using vector control as shown in Fig. 3. A PI controller is used to regulate the output power from the PMSM track at its reference P_{ref}. The output of this PI controller is the quadrature current component while the direct current component is set to zero to achieve maximum torque per ampere control. The d-q current reference is transformed to three-phase currents by using park's transformation. The rotor angle of the PMSM is determined from

$$\theta_r = \theta_{ri} + \frac{d\omega_r}{dt} \tag{6}$$

where θ_r is the rotor angle and θ_{ri} is the initial rotor angle. The hysteresis current control is used to determine the flywheel side converter gate signals.

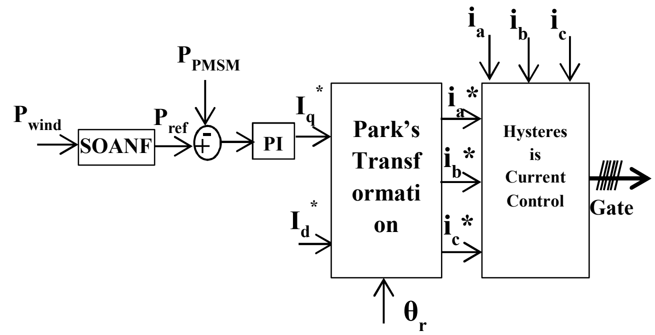


Figure 3.Flywheel side converter control block diagram.

C. The Second Order Adaptive Notch Filter (SOANF)

The SOANF, shown in Fig. 4, is a band bath filter in which the cut-off frequency is estimated using frequency locked loop (FLL) [22], [23]. It has higher immunity to the DC component than ANF. It has three design parameters K1, K2 and ϒ. In general, K1 determines the filter bandwidth. As K1 decreases, the bandwidth of the filter becomes narrower. The conversion speed of the FLL is controlled by ϒ, where increasing ϒ results in fast reaching of the estimated cut-off frequency. However, K2 should be increased to reduce the oscillation. To allow the flywheel system to absorb most of wind fluctuations, K1 is chosen to be large to insure that *Pref* include all the wind fluctuations.

IV. SIMULATION RESULTS

The paper investigates the dynamic behavior of the proposed control system for the FESS to smooth the output power from the wind energy system. The system is simulated using PSCAD/EMTDC program. The wind speed profile used in this study is portrayed in Fig. 5. The wind turbine is controlled to extract the maximum power as shown in Fig. 6. It is obvious that the output wind power has high fluctuations which have bad effect on the power system. Therefore, the

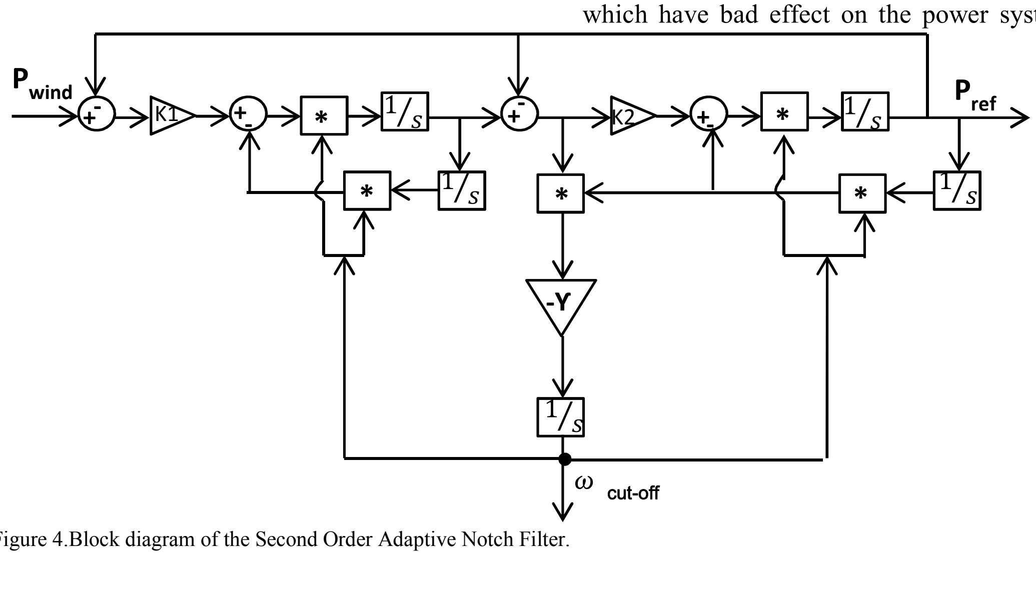


Figure 4.Block diagram of the Second Order Adaptive Notch Filter.

flywheel should be controlled to absorb these fluctuations. The reference power signal for the flywheel is illustrated in Fig. 7. The regulated grid power, portrayed in Fig. 6, clarifies the success of the proposed filter to set a smoothed reference for grid power with low fluctuations.

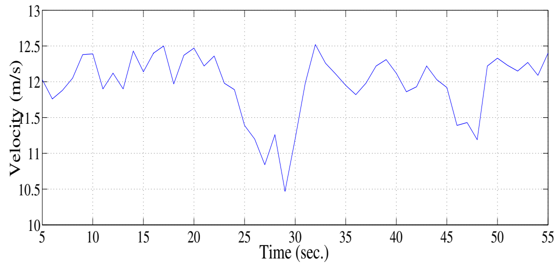


Figure 5.Wind speed profile.

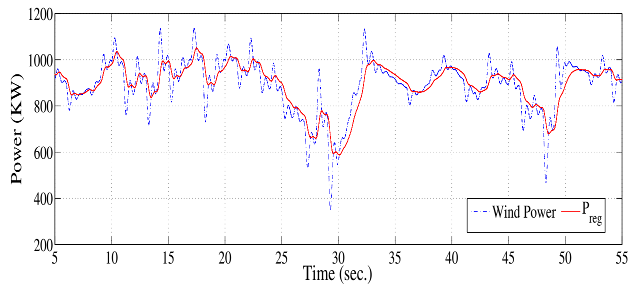


Figure 6.The output power from the wind turbine and the reference signal for regulated grid power.

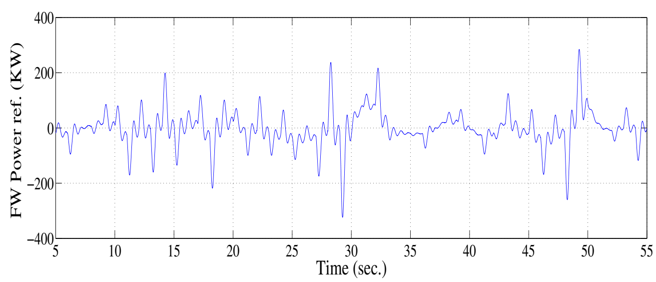


Figure 7.Flywheel power reference.

Figure 8 illustrates the dynamic behavior of the control system of the machine side converter. Fig. 8(a) shows i_q* which is responsible for controlling the flywheel active power. It is clear that i_q* has the same shape of the flywheel power reference presented in Fig. 7. In addition, i_q follows i_q* and i_d is kept which indicate the fast response of the proposed current control. Fig. 8(b) portrays the electromagnetic torque of the PMSM coupled with the flywheel which has the same shape of i_q as expected from (8). Fig. 8(c) demonstrates the flywheel power which tracks the flywheel power reference with good dynamic response and negligible overshoot.

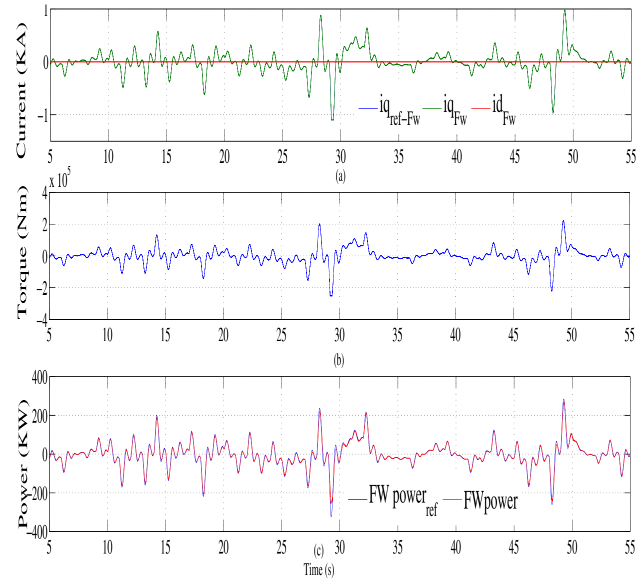
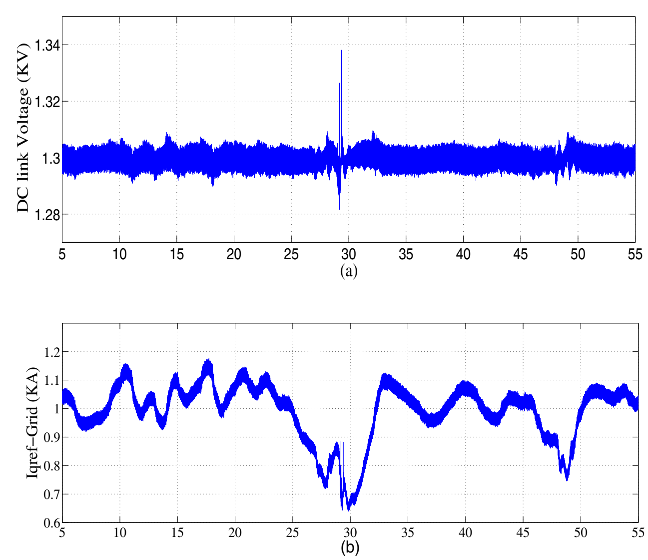


Figure 8.Flywheel side converter dynamic response.

Figure 9 exhibits the dynamic behavior of the grid side converter which is responsible for controlling the DC link voltage. Fig. 9(a) indicates that the grid side converter is tightly regulating the DC link voltage at the desired value, 1.3 KV, with small ripples. At t=29s, when a large power exchange is illustrated, the control succeeds to keep the DC link voltage regulation with a negligible overshoot. Fig. 9(b) explores the q-component reference of the grid current which is responsible for keeping the DC link at the desired value. Fig. 9(c) illustrates the output power for the grid which is smoothed. The power fed to the grid is slightly less than the regulated power due to the losses in the converter and the DC link. Fig. 9(d) displays the phase current of the grid side converter which depends on the quadrature current component. The quadrature current component is the envelope of the phase current magnitude.



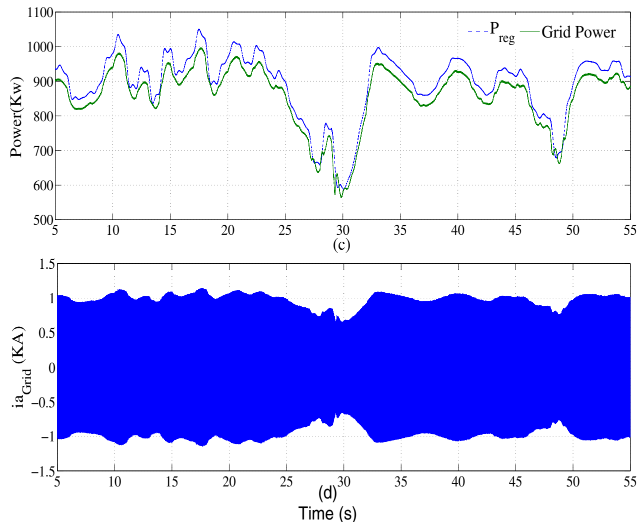


Figure 9.Grid side converter dynamic response.

Figure 10(a) portrays the three-phase current waveforms of the grid which are sinusoidal and has low harmonic content. In addition, it proves the immunity of the control system against injecting neutral current to the grid. Figure 10(b) illustrates the current and voltage waveforms of the grid which are in-phase. This action indicates zero reactive power exchanged with the grid as desired from the control.

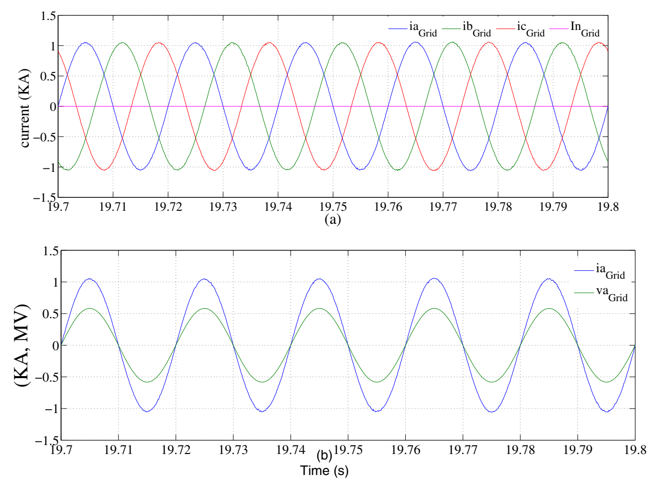


Figure10.Grid current wave forms.

V. CONCLUSIONS

In this paper, the flywheel energy storage system is integrated with the wind energy system to smooth the injected power into the grid. The SOANF is proposed to estimate the regulated grid power. Consequently, the flywheel reference power is set for the flywheel converter. Vector control method based on PI controllers is used for both current controlled machine and grid side converters. The control method is examined using PSCAD/EMTDC program. The results proof the accurate dynamic performance of both the machine and grid side converters control. The proposed filter is succeeded in tracking the flywheel reference power which results in smoothed grid power with low fluctuations.

REFERENCES

[1] Jay Squalli," Renewable energy, coal as a base load power source, and greenhouse gas emissions: Evidence from U.S. state-level data," Energy ELSEVIER, vol. 127, pp. 479–488. May 2017

[2] Farzana Islam, Ahmed Al-Durra, S. M. Muyeen, "Smoothing of Wind Farm Output by Prediction and Supervisory-Control-Unit-Based FESS," IEEE Transactions on Sustainable Energy, vol. 4, Issue 4, October 2013.

[3] Nuruddin Hama, Weerawoot Kanokbannakorn, and Siriroj Sirisukprasert," An evaluation of voltage variation and flicker severity in micro grid," 2017 Electrical Engineering Congress (iEECON), International Conf.

[4] R. Cárdenas, R. Peña, G. Asher, and J. Clare," Using a Sensorless Vector Controlled Induction Machine Driving a Flywheel," IEEE Transactions on Energy Conversion, vol. 19, no. 1, pp. 206-216, March 2004.

[5] Hany M. Hasanien, "A Set-Membership Affine Projection Algorithm-Based Adaptive-Controlled SMES Units for Wind Farms Output Power Smoothing," IEEE Transactions on Sustainable Energy, vol. 5, no. 4, pp. 1226–233 October 2014.

[6] Talha Ahmed Taj, Hany M. Hasanien, Abdulrahman I. Alolah, and Syed M. Muyeen," Transient stability enhancement of a grid-connected wind farm using an adaptive neuro-fuzzy controlled-flywheel energy storage system," IET Renewable Power Generation, vol. 9, Issue 7, pp. 792–800, September 2015.

[7] G.O. Suvire, and P.E. Mercado," Combined control of a distribution static synchronous compensator/flywheel energy storage system for wind energy applications," IET Generation, Transmission & Distribution, vol. 6, Issue 6, pp. 483–492, June 2012.

[8] G. Cimuca, S. Breban, Mircea M. Radulescu, C. Saudemont, and B. Robyns," Design and Control Strategies of an Induction-Machine-Based Flywheel Energy Storage System Associated to a Variable-Speed Wind Generator," IEEE Transactions on Energy Conversion, vol. 25, no. 2, pp. 526–534, June 2010.

[9] Nair S. Gayathri, NilanjanSenroy, and Indra N. Kar," Smoothing of wind power using flywheel energy storage system," IET Renewable Power Generation, vol. 11, Issue 3, pp. 289–298, February 2017.

[10] R. Cárdenas, R. Peña, M. Pérez, J. Clare, G. Asher, and P. Wheeler," Power Smoothing Using a Flywheel Driven by a Switched Reluctance Machine," IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1086–1093, August 2006.

[11] R. Cárdenas, R. Peña, G. M. Asher, J. Clare, and R. Blasco-Giménez," Control Strategies for Power Smoothing Using a Flywheel Driven by a Sensorless Vector-Controlled Induction Machine Operating in a Wide Speed Range," IEEE Transactions on Industrial Electronics, vol. 51, no. 3, pp. 603–614, June 2004.

[12] T. Duy Nguyen, and G. Foo," Sensorless control of a dual-airgap axial flux permanent magnet machine for flywheel energy storage system," IET Electric Power Applications, vol. 7, Issue 2, pp. 140–149, February 2013.

[13] J. Park, C. Kalev, and Heath F. Hofmann," Analysis and Reduction of Time Harmonic Rotor Loss in Solid-Rotor Synchronous Reluctance Drive," IEEE Transactions on Power Electronics, vol. 23, no. 2, pp. 985–992, March 2008.

[14] F.Bouchafaa, I.Hamzaoui, and A.Talha," Control the Flywheel Storage System by Fuzzy Logic Associated with the Wind Generator," International Journal of Renewable Energy Research-IJRER, vol.2, no.4, pp. 723–729, 2012.

[15] F. Hardan, J. A. M. Bleijs, R. Jones, and P. Bromly," BI-Directional Power Control for Flywheel Energy Storage System with Vector-Controlled Induction Machine Drive," 1998 IET Power Electronics and Variable Speed Drives Seventh International Conf. , pp. 477–482.

[16] L. Leclercq, B. Robyns, and J.-Michel Grave," Control based on fuzzy logic of a flywheel energy storage system associated with wind and diesel generators," ELSEVIER Mathematics and Computers in Simulation, vol. 63, pp. 271-280, November 2003.

[17] Gabriel O. Cimuca, C. Saudemont, B. Robyns, and Mircea M. Radulescu," Control and Performance Evaluation of a Flywheel Energy-Storage System Associated to a Variable-Speed Wind Generator," IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1074–1085, August 2006.

[18] X. Sun, K. Koh, B. Yu, and M. Matsui," Fuzzy-Logic-Based V/f Control of an Induction Motor for a DC Grid Power-Leveling System Using Flywheel Energy Storage Equipment," IEEE Transactions on Industrial Electronics, vol. 56, no. 8, pp. 3161–3168, August 2009.

[19] G.O. Suvire, and P.E Mercado, "Active power control of a flywheel energy storage system for wind energy applications," IET Renewable Power Generation, vol. 6, Issue 1, pp. 9–16, January 2012.

[20] M. I. Marei and H. S. K. El-Goharey, "Modeling and Dynamic Analysis of Gearless Variable-Speed Permanent Magnet Synchronous Generator Based Wind Energy Conversion System," International Conf. on Renewable Energies and Power Quality (ICREPQ'12) Santiago de Compostela (Spain), vol. 10, March 2012.

[21] Md. Rafiqul Islam Sheikh, Energy Storage, India: Sciyo, 2010, pp. 20-41

[22] Z. Xin, R. Zhao, P. Mattavelli, P. Chiang Loh, and F. Blaabjerg," Re-Investigation of Generalized Integrator Based Filters from a First-Order-System Perspective," IEEE Access, vol. 4, pp. 7131 – 7144, October 2016.

[23] R. S. R. Chilipi, N. Al Sayari, K. Al Hosani, and Abul R. Beig," Adaptive Notch Filter Based Multipurpose Control Scheme for Grid-Interfaced Three-Phase Four-Wire DG Inverter," IEEE Transactions on Industry Applications, vol., Issue 99,pp. 1-8, March 2017.