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Adaptively controlled SMES unit for stabilization of power oscillations due to grid connected wind power generator

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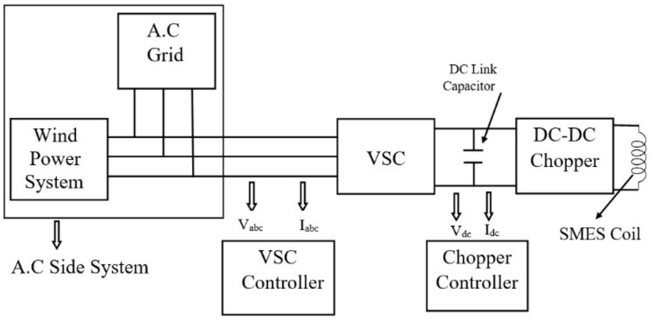
Article

ABSTRACT



In this report, an Adaptively controlled Superconducting magnetic energy storage (SMES) unit is used for stabilizing the power oscillations in an electric grid connected with a wind power generator. This study concentrates on the modelling of horizontal axis wind turbine connected to an asynchronous induction generator. This report presents average models of V.S.C and two quadrant type-D dc-dc chopper, for controlling working of the SMES unit. The control techniques for V.S.C, dc-dc chopper as well as adaptive controller are presented. The duty-cycle of dc-dc chopper is controlled by the adaptive controller. The power oscillations in the grid (occurring due to change in wind velocity), are then compared, for the system without any SMES unit, system with adaptive controlled SMES unit and system with proportional integral controlled SMES unit.

Keywords: Superconducting magnetic energy storage (S.M.E.S); Voltage source converter (V.S.C); proportional integral (P.I) controller

INTRODUCTION

The requirement for certain electrical power producers to move from conventional power plants to renewable energy sources power plants, such as wind energy conversion systems, is brought on by the depletion of fossil fuels. Since the amount of wind power collected by wind energy power plants is related to the cube of wind velocity, wind power changes with variations in wind velocity according to erratic weather conditions. This wind power variations, ultimately leads to power fluctuations in the grid, to which wind power generator is connected. This wind power variations due to uncertain weather conditions needs to be analyzed and mitigated.[1]

Energy storage devices that are frequently employed include battery systems, energy capacitor systems, flywheel systems, and super conducting magnetic energy systems.[2] The most widely used energy storage device is battery, but it has several drawbacks associated with it such as limited lifetime, environmental issues and current and voltage restrictions. With the advent in power electronics, SMES system has received interest in applications like improvement of power quality, voltage stability and reactive power control, enhancement of dynamic stability etc. Some of the merits of SMES system are large storage efficiency, unlimited charging and discharging periods and a very smooth and quick response i.e., power of the order of megawatts can be converted in few milliseconds.[3]

SMES systems' expensive cost is one of its primary downsides, however with the advancement of power electronics, this is expected to alter soon. In this report, SMES unit is used for stabilizing power oscillations in the grid, due to change in the wind speed. SMES is merely a sizable coil that a cryogenic keeps at a predetermined low temperature. When dc current travels through it, It can absorb or provide both active and reactive power as needed by the power system and retains magnetic energy.[4]

According to this study, a dc-dc chopper and voltage source converter, which are joined together by a dc link capacitor, acts as a controlling interface between the SMES coil and the AC side system.[5-10] Using a cascaded control system, the voltage source converter (VSC) and a two-quadrant type-D dc-dc chopper govern the operation of the SMES unit. To transmit active and reactive

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power between the Grid and the SMES unit, two different controllers are used to give the reference control signals for the VSC and the dc-dc chopper. This keeps the DC-Link voltage across the capacitor at its desired, constant value. Controlled by the adaptive/PI controller is the dc-dc chopper's duty cycle, which in turn controls how the SMES coil is charged and discharged. In this research, average models of V.S.C. and dc-dc chopper are used instead of conventional models composed of IGBTs.[11]

In these average models there is no actual connections between the grid-connected wind power generator and the SMES unit, instead they are connected via equations linking them. The advantage of using these average models (with no IGBT's) is that there is no harmonics involved, less losses and a faster and more accurate response for larger sample time.

H.M.Hasanien et.al.[1] have reported the control strategy of the controller used for controlling the pulses of the IGBT's of the VSC and dc-dc chopper. Their publication also emphasizes on the modelling of the horizontal axis wind turbine.

An adaptive controller and a PI controller in this study are used to control the SMES unit. PI controller despite of being robust and having wide stability margin, is sensitive to parameter variations and for different operating conditions, its performance degrade. The performance of an adaptive controller, however, is better than a PI controller's and is unaffected by varying operating conditions.

W. Yao et. al.[2] have discussed the adaptive power oscillation damping scheme for the SMES device to enhance the dynamic stability of the power system. The generalized predictive control and model identification approaches are used to design the adaptive controller.[3] M.D.Mufti et.al.[4] have discussed the design of the adaptive controller and the structure of the linear discrete-time model for stabiliser design in his publication. Additionally, it discusses the least squares identification procedure and the performance index that must be reduced in order to estimate the model parameter from input-output data recorded by the system.

This report emphasizes on the modeling of horizontal axis wind turbine,[1] modeling of average voltage source converter, working of controller of average VSC,[1] average model of type D dc-dc chopper, working and design of adaptive controller.[4] This paper compares the outcomes of the grid power oscillations in the system with and without utilizing SMES, with SMES controlled by PI logic, and with SMES controlled by Adaptive logic.[12]

WIND TURBINE MODELLING[1]

The equation of the power generated by wind is given as:

$$P_W = C_p(\lambda,\beta) * \frac{1}{2} * \rho * A * \upsilon^3$$

Where ρ is the air density, A is the area swept by the rotor blades, υ is the wind velocity, Cp is called power coefficient whose maximum theoretical value is equal to Cp=0.593 according to BETZ'S limit, λ is tip speed ratio given by

$$\lambda = \frac{\omega_m * R}{\upsilon}$$

Where R is the radius of rotor and ω_m is the rotor angular velocity, β is blade pitch angle

$$C_p = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda_i$$

$$\lambda_i = \frac{1}{\lambda + 0.08 * \beta} - \frac{0.0350}{\beta^3 + 1}$$

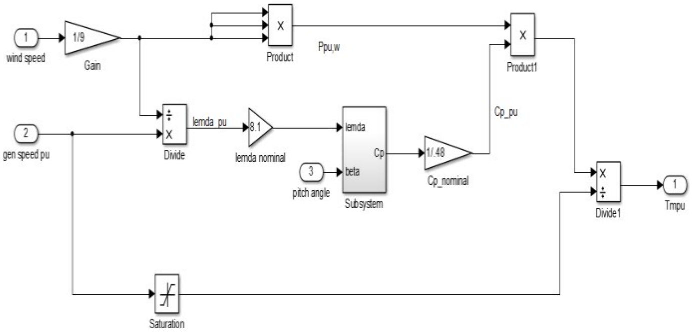

Figure 1: Simulation model of wind turbine[1]

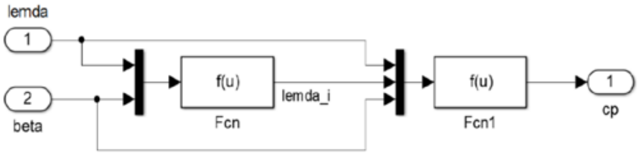

Figure 2: Simulation model for Calculation of Cp[1]

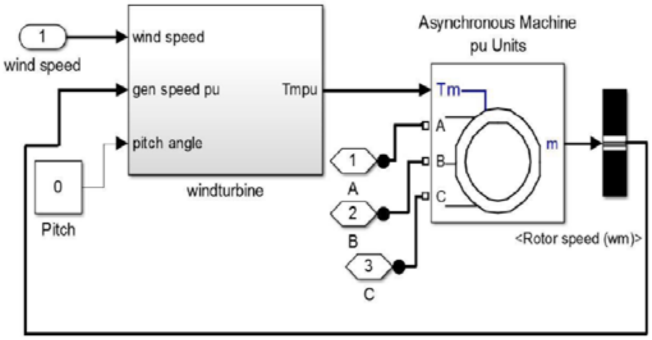

Figure 3: Simulation model of wind turbine connected to Induction Generator

AVERAGE VOLTAGE SOURCE CONVERTER

Figure 7 depicts the interconnection of the VSC with the A.C side system (comprising of wind power system and the electric A.C grid) and the dc-dc chopper connected to the SMES coil. In conventional VSC, the cascaded control strategy is used to generate pulses for the IGBTs of VSC using PWM technique. But in this report average model of VSC is used instead of conventional VSC as shown in figure 5. In Average VSC model there is no requirement of actual IGBT's, and hence no need to generate pulses using PWM technique. Also, in this model there is no actual connection between the VSC (connected to wind generator and grid) and the SMES coil connected to dc-dc chopper as shown in figure 4. Since this model works directly as per relating equations, it can be simulated for larger sample time, comparatively faster than conventional VSC with IGBT's. This model is used for simulation purpose, for making simulation of large power system network faster.[13-15]

Average VSC model is constructed using the following equations:

$$P = (Vab * Ia) – (Vbc * Ic) = Vdc * Idc$$

$$Idc = (Vab * Ia) – (Vbc * Ic)/ Vdc$$

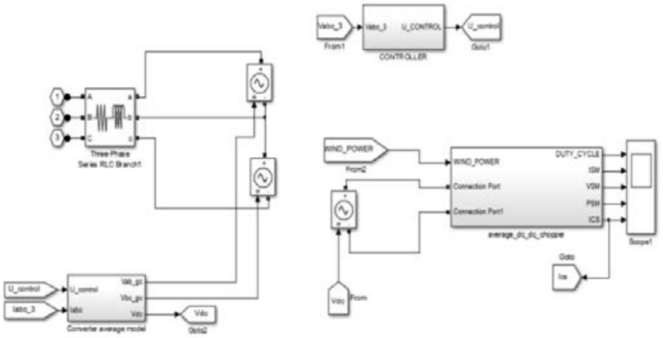

Figure 4: Simulation model showing indirect connections between average VSC, SMES unit and wind power generator connected to grid.

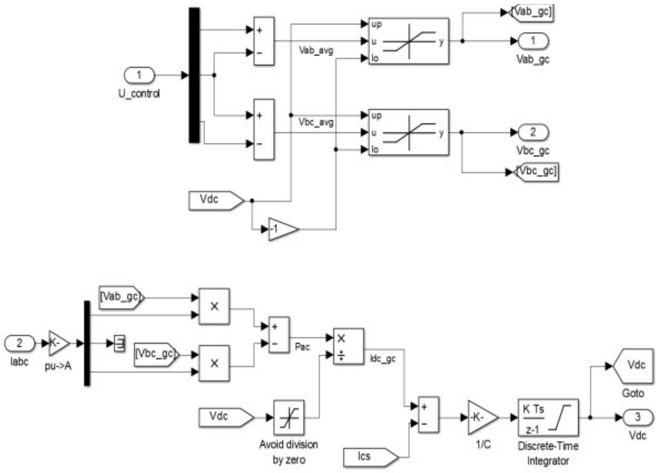

Figure 5: Simulation model of Average VSC

WORKING OF CONTROLLER OF AVERAGE VSC

The average VSC acts both as a rectifier and inverter to allow flow of power between the SMES unit and A.C side system (comprising of wind power generator connected to grid) by ensuring a desired constant dc-link capacitor voltage.[16]

The PLL(3ph) block is used to track the frequency and phase of a three-phase sinusoidal voltage signal on the grid side and apply the phase so obtained, to abc to dq converter as well as dq to abc converter. The three-phase grid side current signal is converted to a dq0 rotating frame (park transform) to give Id and Iq components. The error between dc-link voltage (Vdc) and the reference voltage (Vdc_ref) is the input to the PI controller, which outputs Id ref. The error between Id and Id_ref and between Iq and Iq_ref, given to two different PI controllers, gives controlling voltage signals in dq0 form, which when converted to abc form, gives the control signal for the average VSC. Working of the controller is shown in figure 6.

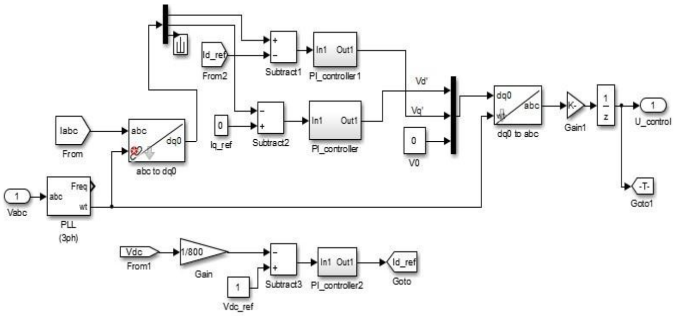

Figure 6: Simulation model of the controller for Average VSC

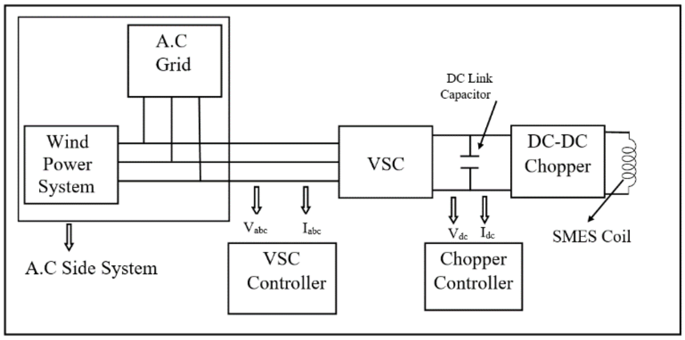

Figure 7: Block diagram of the overall system.

AVERAGE MODEL OF TYPE D DC-DC

CHOPPER CONNECTED TO SMES

The dc-dc chopper's duty cycle manages how the SMES coil is charged and discharged. The proposed adaptive/PI controller receives the wind power error (i.e., wind power deviation) as an input and uses it to modulate the duty cycle of the dc-dc chopper. Power will now flow from the grid to the SMES if the duty cycle is more than 0.5, whereas if the duty cycle is less than 0.5, power will flow from the SMES to the grid. The type-D dc-dc chopper utilized in this research is an average model without any IGBTs. Figure 8 displays the block diagram for the typical model.

The output voltage and input current for type D dc-dc chopper is given by equations:

$$Vo = (2D-1) * Vin$$

$$Ics = (2D-1) * Io$$

Where; Vin = Vdc = DC-link Voltage; Vo = voltage across SMES coil; Io =Ism= current in the SMES coil; D = duty cycle of chopper; Ics = current from dc link capacitor.

In this type of chopper output current is always positive, while output voltage can be both positive as well as negative for Ton > Toff and Ton < Toff respectively.

For D>0.5; charging (SMES)

D=0.5; neither charging nor discharging(SMES)

D< 0.5; discharging(SMES)

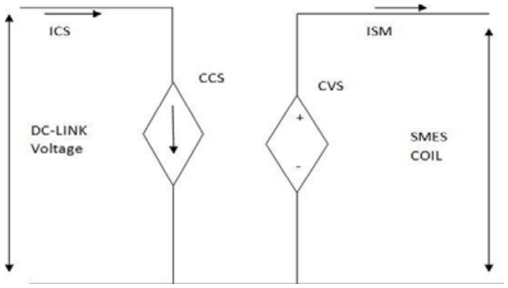

Figure 8: Diagram for Average model of type D dc-dc chopper

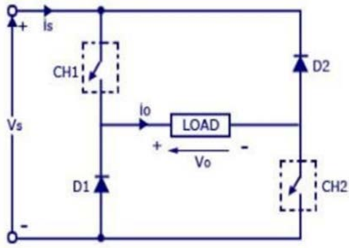

Figure 9: Conventional type D dc-dc chopper

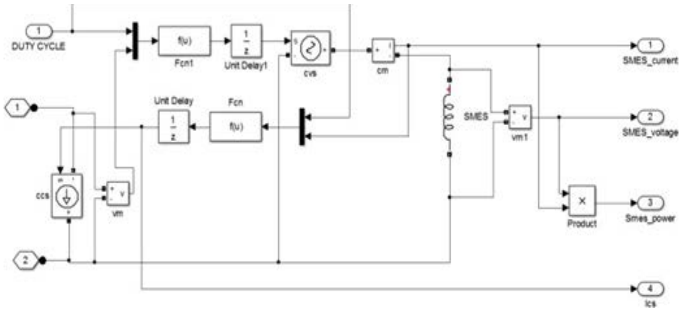

Figure 10: Simulation model of average dc-dc chopper connected to SMES

Figure 10, shows the Simulation model of average dc-dc chopper connected to SMES coil, in which functional blocks are used in order to generate signals for the controlled voltage source and controlled current source blocks (as shown in average model Figure.8) by incorporating formulas for the output voltage across the SMES coil and the current flowing through it.

ADAPTIVE CONTROLLER[4]

In this report, adaptive controller is designed for the SMES unit in order to damp out the power oscillations in the grid, based on the recursive least square's algorithm and model identification techniques. Wind power error is given as an input to the adaptive controller which in turn performs an optimization procedure in each sampling interval to yield an optimal control action to regulate the chopper's duty cycle in order to regulate power oscillations using SMES charging/discharging. In contrast to the PI controller, the suggested adaptive controller's efficacy is unaffected by changes in operating circumstances, parameter uncertainty, or the scale of the power system.[17]

Adaptive controller performs the following steps in each sampling interval:

1) Identify the model parameters

2) update the parameters using past input-output data

3) obtain stabilizing signal to minimize the defined performance index.

A linear discrete-time model is assumed as:[3]

$$y(k) = \sum_{i=1}^{N} a_i y(k-i) + \sum_{i=1}^{N} b_i u(k-i)$$

where; u(k) is the stabilizing signal at Kth sampling instant and y(k) is the wind power deviation. T is the sampling period, (a_i, b_i) are the model parameters to be determined.

The performance index is given by:

$$I(k) = (y(k+1))^2 + (q(k+1) - y(k))^2 + r(u(k) - B * u(k-1))^2$$

$$dI(k) \big/ du(k) = 0$$

$$u(k) = [b1qy(k) - s(k) + tB * u(k-1)] \big/ [r + b1^2(1+q)]$$

Where;

$$s(k) = b1(1+q) \sum_{i=1}^{N} a_i y(k-i+1) + \sum_{i=1}^{N} b_i u(k-i+1)$$

$$\theta(k) = [a1, a2, \dots\dots, a_N, b1, b2, \dots\dots b_N]^T$$

$$h(k) = [y(k-1), .., y(k-N), u(k-1), .., u(k-N)]^T$$

The least square algorithm to determine parameters are as follows:[4]

$$y(k) = \sum_{i=1}^{N} a_i y(k-i) + \sum_{i=1}^{N} b_i u(k-i)$$

$$y(k)^{\wedge} = h(k)^T * \theta(k)$$

$$Error = (y(k) - y(k)^{\wedge})A = \pi r^2$$

$$Term = 1 + h(k)^T P(k-1) * h(k)$$

$$\theta(k) = \theta(k-1) + \frac{P(k-1)h(k)}{Term}(y(k) - y(k)^{\wedge})$$

$$P(k) = P(k-1) + \frac{P(k-1)h(k)h(k)^T p(k-1)}{1 + h(k)^T P(k-1)h(k)}$$

Where;

P(k) is the co-variance matrix; Θ (0) is pre-specified and P (0) is taken as AI with A>>0

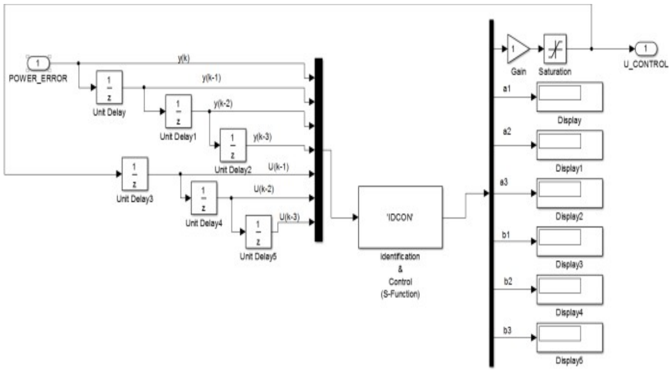

Figure 11: Simulation model of Adaptive Controller[4]

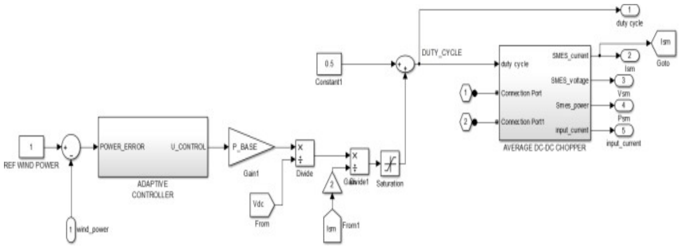

Figure 12: Simulation model of the control scheme of duty cycle of chopper using Adaptive Controller.

SIMULATION RESULTS

The modelling of the horizontal axis wind turbine, controller design and various control techniques used are described in this report. The base wind velocity for the system is taken as 9m/sec and the active wind power generated corresponding to this base wind velocity is considered as the reference wind power (i.e.1 p.u.). Now, when the wind velocity increases beyond 9m/sec, wind power generated will be more than 1p.u. and in this situation our SMES coil should be charged. While for the wind velocity below base wind velocity, power generated is less than 1p.u. and now our SMES coil should deliver energy to the A.C side system. This flow of power from A.C side to D.C side is monitored by the controller of the VSC. The charging/discharging of the SMES coil is controlled by the duty cycle of the dc-dc chopper, which in turn is controlled by the adaptive/P-I controller, whose input is the deviation in wind power from the reference wind power. Simulation results shows that, a sudden change in the wind velocity from 10m/sec to 8m/sec between 4 sec to 4.5 sec of sample time will lead to power oscillations in grid and accordingly charging/discharging of SMES takes place, keeping dc-link voltage constant. The images below illustrate the waveforms of the duty cycle of the DC-DC chopper, SMES power, DC-Link voltage (Vdc), wind generator active power, and comparative graphs of oscillations in grid active power without SMES, with PI logic controlled SMES, and with Adaptive logic controlled SMES.[18-20]

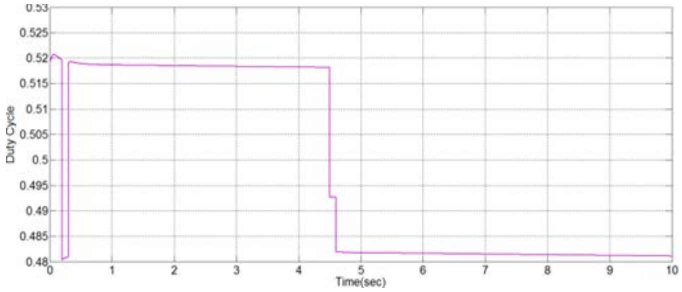

Figure 13: DC-DC Chopper's duty cycle

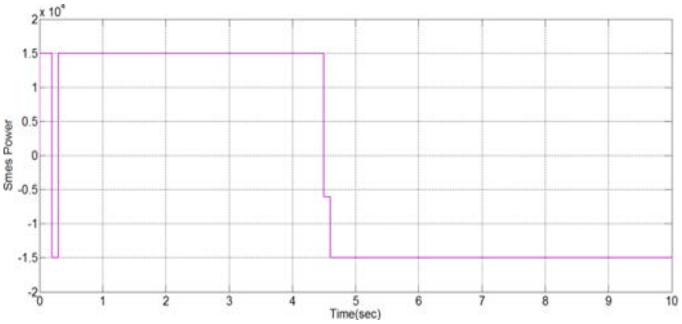

Figure 14: SMES Power

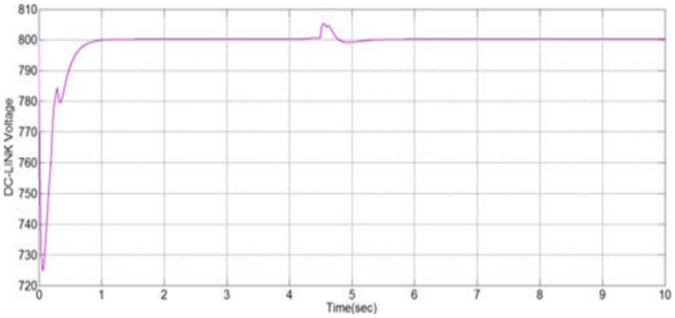

Figure 15: DC-Link voltage (Vdc)

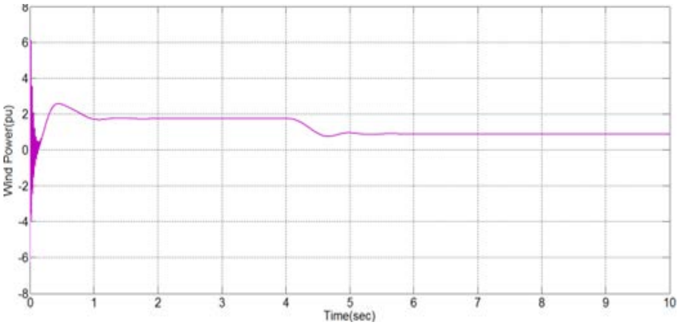

Figure 16: Active electricity from a wind turbine

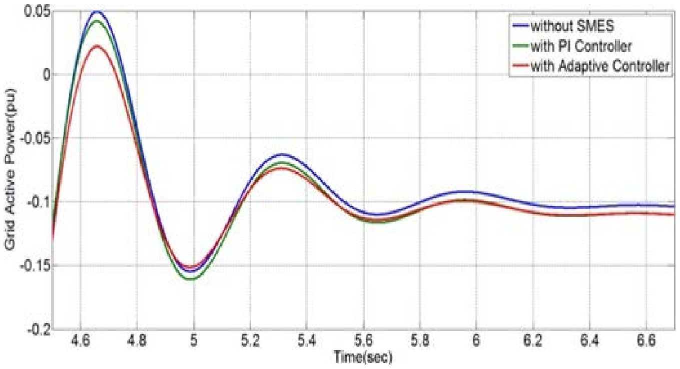

Figure 17: Comparison graph of grid active power oscillations

From Figure 13, Figure 14, Figure 15, Figure 16, it is observed that, when the wind velocity is 10m/sec, active power generated is more than the reference power and the duty cycle of the dc-dc chopper is more than 0.5, and hence SMES coil absorbs energy, keeping the dc link voltage constant. Now, at 4 sec., the wind velocity is reduced from 10m/sec to 8m/sec, thereby reducing the wind power and so the duty cycle of the chopper is now less than 0.5, which causes the SMES coil to deliver energy to the A.C side system, maintaining constant dc link voltage. Figure 17, shows the comparison graph of the grid active power oscillations caused due to the change in the wind velocity. The comparison graph clearly depicts that for the system with adaptive controller, the amplitude of the power oscillations is lowest and the oscillations settles down faster. Thus the performance of the adaptive controller is found superior to that of the P-I controller.[21,22]

CONCLUSION

This report has presented an adaptive logic controlled SMES unit to stabilize the power oscillations in the electrical grid connected to the wind power generator. The modelling of wind energy components, designing of adaptive controller and different control strategies are presented. The results clearly implies that the power oscillations in the grid connected to the wind power generator are damped, when adaptive/PI controlled SMES is introduced in the system. Additionally, while comparing the performance of the system with and without SMES, SMES controlled by PI logic and SMES controlled by adaptive logic, It is found that the performance of the SMES controlled by adaptive logic is better than the SMES controlled by PI logic.

CONFLICT OF INTEREST

Authors declare that there is no conflict of interest, financial or academic, for publication of this report.

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