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Design of a Pole Placement Active Power Control System for Supporting Grid Frequency Regulation and Fault Tolerance in Wind Farms

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Abstract: Among renewable energy sources, wind power is expected to contribute a larger and rapidly growing portion of the world's energy portfolio. However, the increased penetration of wind power into the power grid has challenged the reliable and stable operation of the grid. This motivates new opportunities in design and development of novel control schemes capable of actively maintaining the necessary balance between power generation and load, which in turn regulates the grid frequency when plenty of wind is available. This paper presents a novel Active Power Control (APC) strategy based on an adaptive pole placement control approach. The proposed APC strategy is evaluated by a series of simulations on an advanced wind farm benchmark model in the presence of wind turbulences and grid load variations. It is also demonstrated that the APC strategy is able to tolerate against probable occurrence of sudden changes in the generated power which can be caused by torque offset faults in generator/converter actuators of wind turbines in a wind farm.

Keywords: Active Power Control, Adaptive Control, Fault Tolerance, Frequency Control, Wind Farm

1. INTRODUCTION

Renewable energy technologies are clean and sustainable sources of energy that can serve as alternatives to meet the world's increasing demand for efficient, reliable and affordable energy needs in the years ahead. Among renewable energy sources, wind power is expected to contribute a larger and rapidly growing portion of the world's energy portfolio. Over the past few decades, much research and development have been done on wind power in order to minimize the cost of wind energy. Many large wind farms have already been installed and more in all forms of onshore and offshore are planned to be integrated into the power grids throughout the world.

Since wind energy is naturally a fluctuating source of power which relies on the prevailing wind, the efficient and reliable connection/integration of wind turbines and wind farms to the grid has always been an important issue for grid operation. As long as only small-scale power units of wind turbines are installed and powering the network, wind power only has a small influence on power fluctuations in the network and in turn can easily be integrated. However, the increased penetration of wind power into the power grid has challenged the reliable and stable operation of the grid. This situation has required some transmissions systems operators (TSOs) to formulate grid code requirements exclusively for countries and regions with relatively isolated grids and high levels of wind power penetration. Basically, these grid codes require wind farms to behave as active controllable components which embrace more responsibility in grid operation. This means that wind farms have to participate in grid frequency and voltage regulation through control of active and reactive power, respectively. So, the codes provide specific information such as operational ranges for voltage and frequency as well as control requirements for active and reactive power. For example, in Canada, Hydro-Québec grid code for wind farm interconnection requires that wind farms with installed capacity of more than 10 MW shall have active power control capability for at least 10 seconds to provide power/frequency regulation in response to grid frequency deviations higher than 0.5 Hz (Hydro-Québec, 2005).

In order to meet the ever evolving grid code requirements on frequency variations and to support efficient and reliable integration of wind power, active power control (APC) strategies are essential for actively maintaining the necessary balance between power generation and load, which in turn regulates the grid frequency when plenty of wind is available. Basically, APC in wind turbines can be conducted at both individual turbine and entire wind farm levels (for example, see (Yi et al., 2013, Buckspan et al., 2012, Aho et al., 2013)). However, performing APC collectively across a wind farm can be advantageous in terms of faster response and recovery to grid frequency deviations (Aho et al., 2012).

This paper presents a novel APC strategy/scheme based on an adaptive pole placement control approach. The proposed APC strategy not only provides power tracking and frequency regulation services, but also exhibits favourable passive fault tolerance capabilities against probable occurrence of sudden changes in the generated power which can be caused by torque offset faults in generator/converter actuators of wind turbines in a wind farm.

The effectiveness of the proposed APC strategy is evaluated by a series of simulations on an advanced wind farm

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benchmark model (Soltani et al., 2009), in the presence of wind turbulences and load variations as well as an actuator fault scenario.

The remainder of the paper is organized as follows: In Section 2, the used wind farm benchmark model is briefly overviewed. The proposed APC strategy and the used adaptive pole placement control approach are presented in Section 3 and Section 4, respectively. Section 5 presents the simulation results with some comments and discussions. Finally, conclusions are drawn in Section 6.

2. OVERVIEW OF WIND FARM BENCHMARK MODEL

This paper considers an advanced wind farm simulation benchmark model developed in the EU-FP7 project, AEOLUS (Soltani et al., 2009). The model allows control designers to develop and investigate farm level control solutions under various operating conditions for an optional quantity and layout of wind turbines installed in a wind farm.

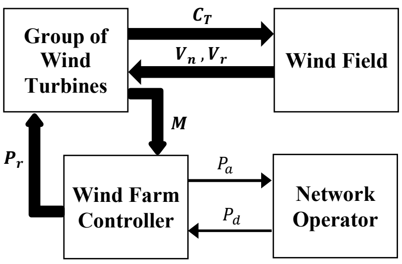

Fig. 1. Illustration of overall model structure (This figure is based on (Soltani et al., 2009)).

As it is shown in Fig. 1, this benchmark model is composed of four major components:

A) Wind Turbines The wind turbines component simulates the dynamics of the wind turbines installed in the farm based on the measured nacelle wind speed V_n, effective wind speed V_r, and power reference P_r at each individual turbine. Each turbine is represented using a simple model of an offshore 5 MW baseline turbine proposed by the U.S. National Renewable Energy Laboratory (NREL) (see (Jonkman et al., 2009)). The wind turbines component generates a set of outputs including a standard set of measurements $\boldsymbol{M}$ required for use by the wind farm controller along with a set of coefficients of thrust $\boldsymbol{C_T}$ for turbines, necessary to calculate the wake effects (i.e., low speed turbulent air flows behind turbine) by wind field component.

B) Wind Field The interactions between the wind turbines installed in a wind farm can be represented through the wind field model. This model simulates the wind speed throughout the farm based on an ambient field model together with a wake model which describes wakes meandering behind turbines and their effect on the ambient wind field.

C) Wind Farm Controller As can be seen in Fig. 1, the wind farm controller plays an interface role which ensures appropriate distribution of operator demanded power P_d among wind turbines in the farm while providing an estimate of total available power P_a in the wind farm to the operator. The baseline wind farm controller in (1) operates using a proportional distribution algorithm which sends the set of power references $P_{r,k,i}$ at the time step k (i.e., $\boldsymbol{P_r}$ in Fig. 1) to each of n individual turbines based on a simple estimate of their current available power $P_{a,k,i}$ and the total available $P_{a,k}$ and demanded $P_{d,k}$ powers in the wind farm at the time step k.

$$P_{r,k,i} = P_{d,k} \frac{P_{a,k,i}}{P_{a,k}} \quad , \qquad i = 1, \dots, n \tag{1}$$

D) Network Operator The network operator determines the active power demand required for safe and reliable connection of wind farm to the electrical grid. The baseline model for network operator can function in different modes such as: absolute, delta, and frequency regulation modes. Basically, in frequency regulation mode, the measured grid frequency f_m is used as a feedback signal in order to set up APC in real-time and maintain the necessary balance between power generation and load, which in turn regulates the grid frequency to its reference value f_r, despite a changing grid load. As presented in the following equations (2-3), the baseline model includes a dead-band proportional gain control which employs frequency error f_e (see (2)) to regulate the grid frequency to its reference value (e.g., 50 Hz in large areas of the world or any other frequencies).

$$f_e = f_m - f_r \tag{2}$$

$$P_{d,k} = \begin{cases} 0.5(P_1) & -d \le f_e \le d \\ 0.5(P_1 - P_2) & f_e \ge c \\ 0.5(P_1 + P_2) & f_e \le -c \\ 0.5(P_1) - 0.5(P_2)\left(\dfrac{f_e - d}{c - d}\right) & d < f_e < c \\ 0.5(P_1) - 0.5(P_2)\left(\dfrac{f_e + d}{c - d}\right) & -c < f_e < -d \end{cases} \tag{3}$$

where c and d are two constants ($c > d$) defined by user to represent control and dead bands, respectively. Moreover, P_1 and P_2 are power parameters defined in (4) and (5), respectively.

$$P_1 = P_{max} + P_{min} \tag{4}$$

$$P_2 = P_{max} - P_{min} \tag{5}$$

in which $[P_{min}, P_{max}]$ denote the prescribed minimum and maximum limits for the total power generated by the wind farm.

3. ACTIVE POWER/FREQUENCY CONTROL

This section presents the APC strategy designed to provide frequency regulation and fault tolerance in a wind farm. Basically, in order to maintain a desired level of frequency, it is required to balance the total power generated with power consumed by loads and losses on the network grid. This balance must be actively maintained against load fluctuations and emergency conditions such as uncontrolled generation. To this end, the proposed strategy is implemented within the general structure shown in Fig. 2 to provide active power/frequency control in a typical large wind farm including n wind turbines.

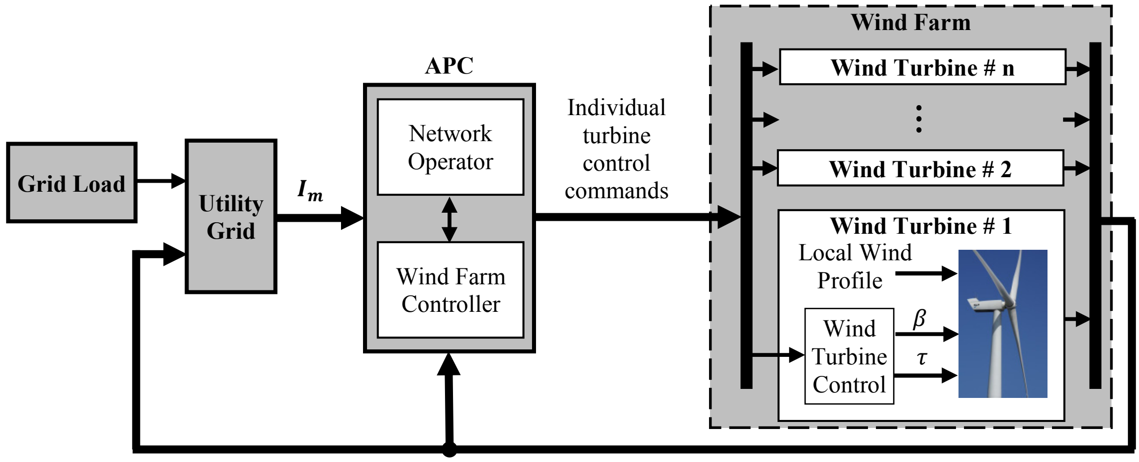

Fig. 2. Wind farm control system setup

All individual wind turbines are equipped with an exclusive torque/pitch control system which can follow the instructions (power references) provided by an APC system.

Basically, APC in wind turbines can be conducted at both individual turbine and entire wind farm levels. However, as it is shown in Fig. 2, performing APC collectively across a wind farm can be advantageous in terms of faster response and recovery to grid frequency deviations (Aho et al., 2012). Therefore, the APC system shown in Fig. 2 controls collectively the power production from the whole wind farm based on the set of measurements $\boldsymbol{I_m}$ at the point of common coupling (PCC) of the wind farm with the utility grid (e.g., measured grid frequency) and on the received information from the wind turbines about the maximum amount of available power at each turbine location. In more detail, the network operator determines the active power demand required to maintain the necessary balance between wind farm generation and grid load, which in turn can regulate the grid frequency. Then, the wind farm controller distributes the demanded active power from network operator to the local wind turbines for achieving the desired generation and frequency level.

In reference to Fig. 2, the proposed APC strategy in this paper addresses the development of an adaptive control scheme for implementation in the network operator module, while the wind farm controller module still employs the baseline proportional distribution algorithm described in Section 2.

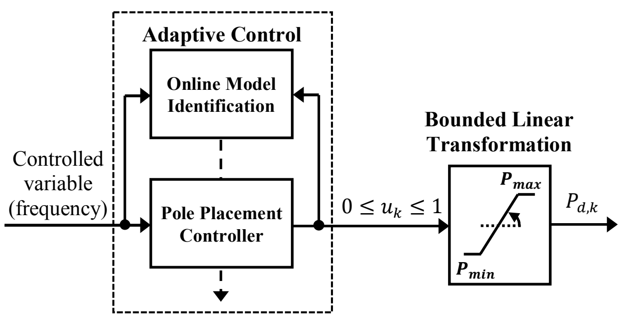

Fig. 3. The APC strategy implemented in network operator module.

The detailed structure of the APC strategy implemented in network operator is shown in Fig. 3. With respect to this figure, in order for the network operator to ensure safe and reliable connection of wind farm to the electrical grid, this paper suggests to determine the active power demand $P_{d,k}$ at the time step k using a simple linear transformation form as follows:

$$P_{d,k} = (P_{max} - P_{min})u_k + P_{min} \quad (6)$$

where $[P_{min}, P_{max}]$ are the prescribed minimum and maximum limits for the total power generated by the wind farm, and u_k is normalized *tunable* value of demanded power between zero and one at the time step k. The tunable parameter u_k is determined online using a *single input-single output (SISO)* adaptive control scheme based on an integrated online modeling and pole placement approach described in Section 4.

4. ADAPTIVE POLE PLACEMENT CONTROL APPROACH

This section is devoted to the adaptive control scheme exploited in the developed APC strategy. The adaptive control scheme aims at efficient integration of an online model identification mechanism and model-based adaptive pole placement control (see Fig. 3). Such an adaptive control system can address the problem of control particularly where the parameters of the process under control are not sufficiently known, or that they change over time.

In the following two subsections, the online model identification and model-based adaptive pole placement control methods are described, respectively.

4.1 Online Model Identification for Control

The design of control strategy incorporates an online model identification approach for obtaining mathematical description of the plant model under control. There exist a wide variety of techniques for modelling and process identification in the literature. However, the online recursive identification technique based on the *Least Squares Method (LSM) with adaptive directional forgetting* discussed here (Kulhavý, 1987) enables the most accurate identification of the given process. In comparison with classical LSM (Ljung, 1999), and LMS with exponential forgetting (Kulhavý, 1987) techniques, LSM with adaptive directional forgetting is the most sophisticated technique that is particularly useful for systems with time-varying parameters. In fact, the employed *signal weighting* process in LSM with adaptive directional forgetting technique makes it possible to finely modify/update a forgetting coefficient with respect to changes in input and output signals.

In the most general case, the purpose of LSM with adaptive directional forgetting technique is to identify online the unknown parameters a_i and b_j of a process described by the following transfer function:

$$G(z)=\frac{B(z^{-1})}{A(z^{-1})}=\frac{b_1z^{-1}+b_2z^{-2}+\cdots+b_mz^{-m}}{1+a_1z^{-1}+a_2z^{-2}+\cdots+a_nz^{-n}}\,z^{-d} \quad (7)$$

in which m, n, and d are integers related to the structure of the model through defining the polynomials $A(z^{-1})$ and $B(z^{-1})$, whereas z is the so-called discrete-time complex variable.

As it is shown by (8), the estimated output of the process $\hat{y}_k$ at each time step k can be represented in the following vector form (Ljung, 1999):

$$\begin{aligned}\hat{y}_k &= \mathbf{\Theta}_{k-1}^T\cdot\mathbf{\Phi}_k\\ \mathbf{\Theta}_{k-1} &= \left[\hat{a}_1,\cdots,\hat{a}_n,\hat{b}_1,\cdots,\hat{b}_m\right]^T\\ \mathbf{\Phi}_k &= \left[-y_{k-1},\cdots,-y_{k-n},u_{k-d-1},\cdots,u_{k-d-m}\right]^T\end{aligned} \quad (8)$$

where the vector $\mathbf{\Theta}_{k-1}$ contains the model parameter estimates $\hat{a}_i$ and $\hat{b}_j$ computed at the time step $k-1$, and the vector $\mathbf{\Phi}_k$ contains the past process inputs u and outputs y data.

The recursive expression in (9) is used to update the process parameters at each time step:

$$\mathbf{\Theta}_k=\mathbf{\Theta}_{k-1}+\frac{\mathbf{C}_{k-1}\cdot\mathbf{\Phi}_k}{1+\xi_k}\cdot\left(y_k-\mathbf{\Theta}_{k-1}^T\mathbf{\Phi}_k\right) \quad (9)$$

where,

$$\xi_k=\mathbf{\Phi}_k^T\cdot\mathbf{C}_{k-1}\cdot\mathbf{\Phi}_k \quad (10)$$

The matrix C is defined by:

$$\mathbf{C}_k=\begin{cases}\mathbf{C}_{k-1}-\dfrac{\mathbf{C}_{k-1}\cdot\mathbf{\Phi}_k\cdot\mathbf{\Phi}_k^T\cdot\mathbf{C}_{k-1}}{\varepsilon_k^{-1}+\xi_k} & ,\ \varepsilon_k>0\\ \mathbf{C}_{k-1} & ,\ \varepsilon_k=0\end{cases} \quad (11)$$

with,

$$\varepsilon_k=\varphi_k-\frac{1-\varphi_k}{\xi_{k-1}} \quad (12)$$

The forgetting coefficient φ_k and its auxiliary variables are updated as follows:

$$\varphi_k=\frac{1}{1+(1+\rho)\left\{ln(1+\xi_{k-1})+\left[\frac{(\nu_{k-1}+1)\eta_{k-1}}{1+\xi_{k-1}+\eta_{k-1}}-1\right]\frac{\xi_{k-1}}{1+\xi_{k-1}}\right\}} \quad (13)$$

where,

$$\nu_k=\varphi_k(\nu_{k-1}+1) \quad (14)$$

$$\eta_k=\frac{\left(y_k-\mathbf{\Theta}_{k-1}^T\mathbf{\Phi}_k\right)^T\left(y_k-\mathbf{\Theta}_{k-1}^T\mathbf{\Phi}_k\right)}{\lambda_k} \quad (15)$$

$$\lambda_k=\varphi_k\left[\lambda_{k-1}+\frac{(y_k-\hat{y}_k)^T(y_k-\hat{y}_k)}{1+\xi_{k-1}}\right] \quad (16)$$

The start-up conditions are represented by a set of well-defined initial values for the parameters $\mathbf{\Theta_0}$, C_0, φ_0, λ_0, ρ, and ν_0. In this way, the recursive identification technique recalled here computes the time-varying parameters of the discrete-time linear model as an approximation of the nonlinear plant process. Accordingly, these parameters will be used by the adaptive controller described in the next subsection.

4.2 *Pole Placement 2DOF Controller with Compensator for Third Order Processes*

This section describes the adaptive controller used in connection with the online identification method presented in subsection 4.1. In more detail, with respect to online determination of tunable parameter u_k in (6), a control scheme based on pole placement 2 DOF control with compensation for processes of third order ($n=3$) is developed (Bobál et al., 2005).

By substituting $n=m=3$ and $d=0$ in (7), the transfer function of the time-varying controlled system has the following form:

$$G(z)=\frac{B(z^{-1})}{A(z^{-1})}=\frac{b_1z^{-1}+b_2z^{-2}+b_3z^{-3}}{1+a_1z^{-1}+a_2z^{-2}+a_3z^{-3}} \quad (17)$$

whose estimated parameter vector using the online identification approach shown in subsection 4.1 is:

$$\mathbf{\Theta}_k=\left[\hat{a}_1,\hat{a}_2,\hat{a}_3,\hat{b}_1,\hat{b}_2,\hat{b}_3\right]^T \quad (18)$$

The 2 DOF control loop is depicted in Fig. 4. In this figure, w_k, u_k and y_k are step reference signal, control signal and process output at the time step k, respectively.

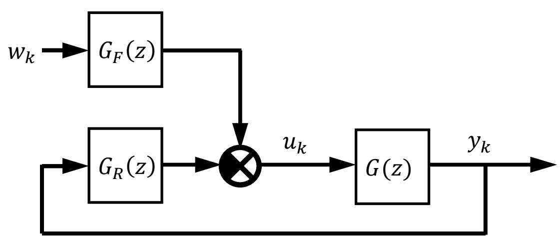

Fig. 4. Closed loop 2DOF control system (This figure is based on (Bobál et al., 2005).

The feedback controller in Fig. 4 can be written as:

$$G_R(z)=\frac{Q}{P\,K}=\frac{q_0+q_1z^{-1}+q_2z^{-2}+q_3z^{-3}}{(1+p_1z^{-1}+p_2z^{-2})(1-z^{-1})} \quad (19)$$

In addition to the above feedback controller, the feedforward control part in Fig. 4 facilitates simpler and more efficient processing of reference signal. This feedforward controller for a step reference signal has the following form:

$$G_F(z) = \frac{R}{P\,K} = \frac{r_0}{(1+p_1 z^{-1}+p_2 z^{-2})(1-z^{-1})} \qquad (20)$$

Characteristic polynomial of closed-loop system is defined as in (21):

$$A(z^{-1})\,P(z^{-1})\,K(z^{-1}) + B(z^{-1})\,Q(z^{-1}) = D(z^{-1}) \qquad (21)$$

where polynomials are as follows:

$$A(z^{-1}) = 1 + \hat{a}_1 z^{-1} + \hat{a}_2 z^{-2} + \hat{a}_3 z^{-3} \qquad (22)$$

$$B(z^{-1}) = \hat{b}_1 z^{-1} + \hat{b}_2 z^{-2} + \hat{b}_3 z^{-3} \qquad (23)$$

$$P(z^{-1}) = 1 + p_1 z^{-1} + p_2 z^{-2} \qquad (24)$$

$$Q(z^{-1}) = q_0 + q_1 z^{-1} + q_2 z^{-2} + q_3 z^{-3} \qquad (25)$$

$$K(z^{-1}) = 1 - z^{-1} \qquad (26)$$

$$D(z^{-1}) = 1 + d_1 z^{-1} + \cdots + d_6 z^{-6} \qquad (27)$$

with:

$$d_1 = \begin{cases} -2e^{(-\xi\omega T_0)}\cos\left(\omega T_0\sqrt{1-\xi^2}\right), & \xi \le 1 \\ -2e^{(-\xi\omega T_0)}\cosh\left(\omega T_0\sqrt{\xi^2-1}\right), & \xi > 1 \end{cases}$$

$$d_2 = e^{(-2\xi\omega T_0)}$$

$$d_3 = d_4 = d_5 = d_6 = 0$$

As it is shown in (27), the dynamic behaviour of closed-loop system is represented by two fundamental parameters ω and ξ which are the natural frequency and damping factor, respectively.

With respect to Fig. 4, it is obvious that the control law corresponding to pole placement 2 DOF control with compensation for a third order process has the form:

$$P(z^{-1})K(z^{-1})u_k = R(z^{-1})w_k - Q(z^{-1})y_k \qquad (28)$$

where u_k is the control signal computed as follows:

$$u_k = r_0 w_k - q_0 y_k - q_1 y_{k-1} - q_2 y_{k-2} - q_3 y_{k-3} + \\ +(1-p_1)u_{k-1} + (p_1 - p_2)u_{k-2} + p_2 u_{k-3} \qquad (29)$$

in which:

$$r_0 = \frac{1 + d_1 + d_2 + d_3 + d_4 + d_5}{b_1 + b_2 + b_3} \qquad (30)$$

As already mentioned, the control signal u_k computed by (29) will be used in (6) for smooth control of active power within its prescribed range.

5. SIMULATION RESULTS

The developed APC strategy with start-up conditions listed in Table 1 is evaluated via simulation tests performed in MATLAB/Simulink using the nonlinear benchmark model presented in Section 2. An offshore wind farm including 10 NREL 5MW turbines is created with the layout as shown in Fig. 5. Simulations are conducted for a realistic wind field with mean speed of 12 m/s, a turbulence intensity of 10%, and over 1000 seconds of run time.

Table 1. Start-up (initialisation) conditions

	Parameter	Value
Identification	$\boldsymbol{\Theta_0}$	$[0.1, 0.2, 0.3, 0.4, 0.5, 0.6]^T$
	C_0	$10^9\, I_6$
	φ_0	1
	λ_0	10^{-3}
	ρ	99×10^{-2}
	ν_0	10^{-6}
Control	ω	1.1
	ξ	3

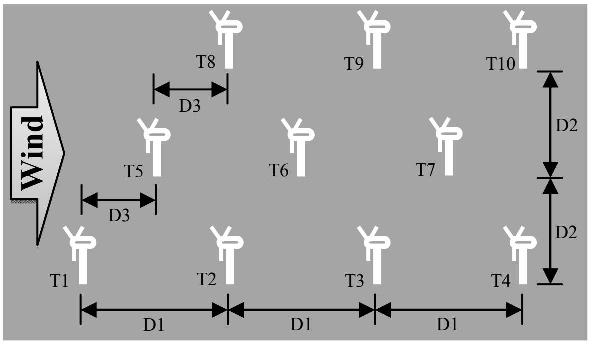

Fig. 5. Wind farm layout (D1=600m, D2=500m, D3=300m).

5.1 Active Power/Frequency Control

In order to demonstrate the active power/frequency control capabilities, a changing grid load ranging from 5MW to 45MW is applied as shown in Fig. 6. In response to the variations in grid load, Fig. 7 provides performance illustration of the wind farm APC using the baseline and adaptive control strategies. As can be seen in this figure, the proposed APC strategy based on adaptive pole placement control approach is more effective than the baseline approach in maintaining the required balance between the wind farm generation and grid load. Accordingly, as shown in Fig. 8, the grid frequency is regulated more successfully at the reference frequency of 50 Hz compared to the frequency response from the baseline control system.

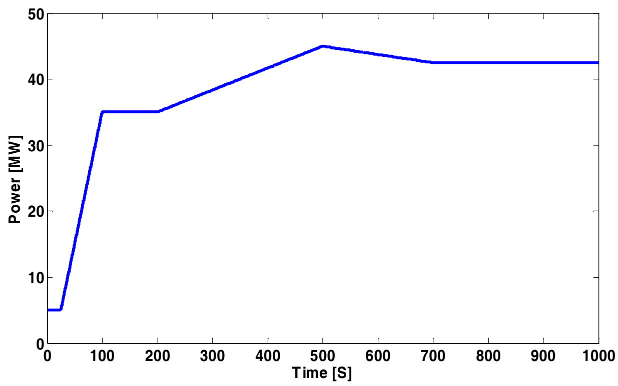

Fig. 6. Grid load.

5.2 Fault Tolerance

It is also demonstrated that the APC strategies are able to tolerate probable occurrence of sudden changes in the generated power which can be caused by torque offset faults in generator/converter actuators of wind turbines in a wind farm. In this case, the benchmark model is modified with a fault scenario representing occurrence of +2000 Nm torque offset in generator/converter actuators of wind turbines 1, 2, 5, and 7 in the wind farm (see Fig. 5) within time period of [250-350] sec. Fig. 9 demonstrates the wind farm active power response during the mentioned fault scenario and under baseline and adaptive APC strategies.

As shown in Fig. 9, although both APC strategies indicate passive fault tolerance capabilities against torque actuator faults in the wind farm, the proposed adaptive APC strategy indicates faster response and recovery times to sudden changes in the generated power compared to the baseline control system.

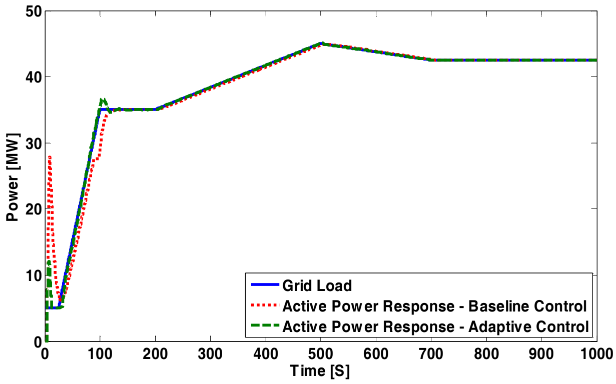

Fig. 7. Grid load and total active power response.

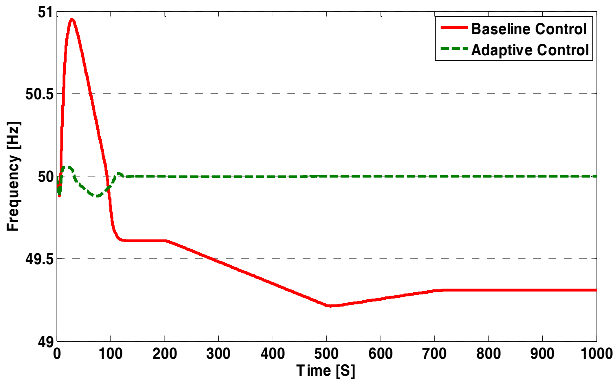

Fig. 8. Grid frequency response.

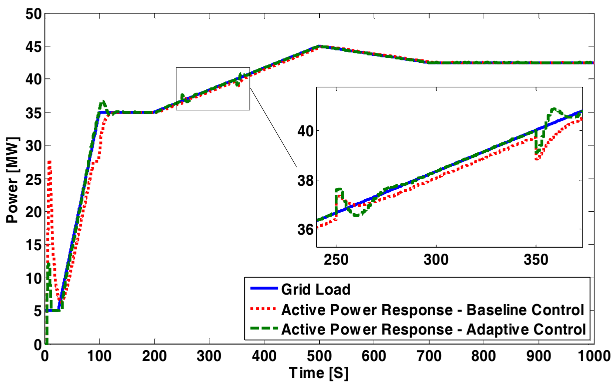

Fig. 9. Grid load and total active power response – faulty conditions.

6. CONCLUSIONS

This paper exploits an adaptive pole placement control approach to address the design of a novel Active Power Control (APC) strategy at entire wind farm level. The proposed strategy not only ensures safe and reliable connection of a wind farm to the electrical grid but also tolerates probable occurrence of sudden changes in the generated power which can be caused by torque offset faults in generator/converter actuators of wind turbines in a wind farm. All simulations have been conducted in 1000 seconds using AEOLUS wind farm model. Simulation results clearly indicate the effectiveness of performing the APC strategy collectively across a wind farm over the entire range of tested wind field and in both fault-free and faulty conditions. Basically, in comparison with APC at individual turbine level, performing APC collectively across a wind farm can be advantageous in terms of faster response and recovery to grid frequency deviations. However, further research on such methodologies is necessary to determine the full capabilities of APC in wind turbines.

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