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Smoothing Output Fluctuations of Wind Turbines and Enhancing Power System Frequency Using Coefficient Diagram Method

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Abstract

Due to recent expansion of renewable energy applications, Wind Energy System (WES) is receiving much interest all over the world. However, output fluctuations of wind generators can cause network frequency variations in power systems, which can consequently decrease the power quality. This problem of output fluctuations needs to be solved for further expanding wind energy conversion into power system. On the other hand, area load change and abnormal conditions can lead to mismatches in frequency and these mismatches have to be corrected by the load frequency system. This paper therefore proposes a new load frequency control (LFC) design using Coefficient Diagram Method (CDM) in the presence of wind turbines (WT), for improving network frequency quality. The CDM technique reduces the effect of uncertainty due to governor and turbine parameters variations and load disturbance. Digital simulation performed on a single-area power system with wind turbines validates the effectiveness of the proposed scheme. Results show that, with the proposed CDM technique, the overall closed loop system performance demonstrated robustness. Performance comparisons between the proposed controller, a classical integral control and Model predictive control is carried out confirming the superiority of the proposed technique in presence of doubly fed induction generator (DFIG) WT.

Keywords: Load frequency control, DFIG wind turbine, integral control, coefficient diagram method, Model predictive control. Wind Energy System (WES).

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Introduction

A good quality of the electric power system requires both the frequency and voltage to remain at standard values during operation. Thus a control system is important to cancel or reduce the effects of the random load changes and to keep the frequency and voltage at the standard values. Frequency is highly dependent on the active power while the voltage is highly dependent on the reactive power. The problem of active power and frequency control is referred to as load frequency control (LFC) [1] which is the major concerned of this paper.

In LFC problem, area load change and abnormal conditions lead to mismatches in frequency and scheduled power interchanges between areas. These mismatches have to be corrected by the LFC system. LFC objectives, which are concerned with, frequency regulation and tracking the load demands, maintaining the tie-line power interchanges to specified values in the presence of modeling uncertainties, system nonlinearities and area load disturbances, determines the LFC synthesis as a multi-objective optimization problem [2,3]. Hence, the LFC becomes an important function of power system operation where the main objective is to regulate the output power of each generator at prescribed levels while keeping the frequency fluctuations within pre-specified limits [4].

On the other hand, with recent expansion of renewable energy applications, Wind Energy System(WES) is receiving much interest all over the world. In fact, WES is the fastest growing and mostly utilized of all the renewable energies in power systems and its global production is predicted to grow to 300GW in 2015 [5]. Hence, wind farms connected to the power systems have created serious interest and concern among researchers. In several research works, for example, in [2] it was pointed out that the renewable integration impacts are non-zero and can become more significant at higher size of penetrations.

The inertial response of WTs is discussed in details as in [6] [7]. In [6], a detailed background of frequency response, including primary and secondary responses, are given. A detailed comparison between fixed-speed wind turbines (FSWTs) and doubly fed induction generator (DFIG) type WTs is shown through detailed simulations where the contribution of DFIG-based WTs was illustrated. In [7], it is reported that full converter (FC) type WTs are completely decoupled from the power grid and no contribution is given to the frequency regulation. Also, it is pointed out that the DFIG-type WTs have some small contribution to the power network.

TODAY, control system designers are trying to apply different control algorithms in order to find the best controller parameters to obtain the optimum solutions. Some of these methods are very successful for special cases while unsuccessful for other general applications. Many control strategies have been proposed and investigated by several researchers for LFC design of power systems [8-11]. Robust adaptive control schemes have been developed in [3,12-16)] to deal with changes in system parameters. Fuzzy logic controllers have been used in many reports for LFC design in a two area power system [17], with and without nonlinearities. The applications of artificial neural network, genetic algorithms, and optimal control to LFC have been reported in [18] [19]. In their findings it is observed that the transient response is oscillatory and it seems some other elegant techniques are needed to achieve a desirable performance. Meanwhile, the MPC appears to be an efficient strategy to control many applications in industries. It has many advantages such as very fast response, robustness against load disturbance and parameters uncertainty. Its straightforward design procedure is considered as a major advantage of the MPC. Given a model of the system, only an objective function incorporating the control objectives needs to be set up. Additional physical constraints can be easily dealt with by adding them as inequality constraints, whereas soft constraints can be accounted for in the objective function using large penalties. Moreover, MPC adapts well to different physical setups and allows for a unified approach [20-22].

Fixed parameters controllers, such as an integral controller or a PI controller, is also widely employed in the LFC application. Fixed parameters controllers are designed at nominal operating points and may no longer be suitable in all operating conditions. For this reason, adaptive gain scheduling approaches have been proposed for LFC synthesis [12-13]. This method overcomes the disadvantages of the conventional PID controllers, which needs adaptation of controller parameters, but actually, it faces some difficulties, like the instability of transient response as a result of abrupt changes in the system parameters in addition to the impossibility of obtaining accurate linear time invariant models at variable operating points [12]. In [23], fast response and robustness against parameter uncertainties and load changes can be obtained using MPC controller for single area load frequency control application, but without WT participation. However, in [24] a new load frequency control (LFC) using the model predictive control (MPC) technique in the presence of wind turbines (WT) was presented and the results demonstrated that the closed-loop system with MPC controller is robust against the parameter perturbation of the system and has more desirable performance in comparison with classical integral control design in all of the tested scenarios. Also, it was denoted that wind turbine has a positive effect on the total response of the system.

In fact, several optimal and robust control strategies have been developed for LFC synthesis according to change of environment in power system operation [14,16,23]. These methods show good dynamic response, but, due to increasing the complexity and change of the power system structure, the robustness in the presence of modeling uncertainties and system nonlinearities were not considered, so, other elegant techniques are needed to achieve a desirable performance

The new robust control strategy involving coefficient diagram method (CDM), is an algebraic approach applied to a polynomial loop in the parameter space, where a special diagram called coefficient diagram, is used as the vehicle to carry the necessary design information, and as the criteria of good design [25,26].

The CDM is fairly new and not well-known, but its basic principle has been known in industry and in control community for more than 40 years with successful application in servo control, steel mill drive control, gas turbine control , and spacecraft attitude control [27]. The most important properties of the CDM technique and its most considerable advantages are discussed in [25, 28-32]

In this paper, the load frequency control for a single area power system in the presence of Wind Energy System has been developed based on the CDM technique. The parameters of the polynomials of CDM technique have been designed based on the dynamic model of the single area power system. The effects of the physical constraints such as generation rate constraint (GRC) and speed governor dead band [2] are considered. The power system with the proposed CDM technique has been tested through the effect of uncertainties due to governor and turbine parameters variation and load disturbance using computer simulation. A comparison has been made between the CDM and the traditional integral controller confirming the superiority of the proposed CDM technique. The simulation results proved that the proposed controller can be applied successfully to the application of power system load frequency control.

The rest of the paper is organized as follows: In section II a general consideration of CDM is presented. Section III describes the configuration of the interconnected power system considering the dynamics of the system and simplified wind turbine model for frequency studies. The implementation scheme of the overall structure of a single area power system together with the CDM technique is described in section IV. In section V simulation results and general remarks are presented and finally, the paper is concluded in section VI.

COEFFICIENT DIAGRAM METHOD

In general, classical control and modern control are mainly used in control design. However, there is a third approach generally called as algebraic design approach [25]. The Coefficient Diagram Method (CDM) is one of the algebraic design approaches where the coefficient diagram is used instead of Bode diagram, and the sufficient condition for stability by Lipatov constitutes its theoretical basis [27].

The CDM is a technique to arrange the poles of a closed loop transfer function, in order to get wanted response in the time domain. [33, 34]

Coefficient Diagram provides to know the stability, time response and robustness characteristics of systems in a single diagram, which is important for systems with large characteristic polynomial degree. In coefficient diagram, logarithmic vertical axis shows the coefficients of characteristic polynomial (a_i) ,stability indices (γ_i) and equivalent time constant (τ) whereas the horizontal axis shows the order i values corresponding to each coefficients. The degree of convexity obtained from coefficients of the characteristic polynomial gives a measure of stability, whereas the general inclination of the curve gives the measure of the speed of response. The shape of the a_i curve due to plant's parameter variation gives a measure of robustness.

The block diagram of a single input single output (SISO) linear time invariant system with CDM control is shown in figure 1, where $N(s)$ is numerator polynomial, $D(s)$ is denominator polynomial of the plant transfer function, $A(s)$ is considered as the forward denominator polynomial while $F(s)$ and $B(s)$ are considered as reference numerator and feedback numerator polynomials. Hence, the transfer function of the controller has two numerators, which implies a 2DOF system structure. In this method, r is taken as the reference input to the system, u as the controller signal, d as the external disturbance signal and y is denoted as the output of the control system.

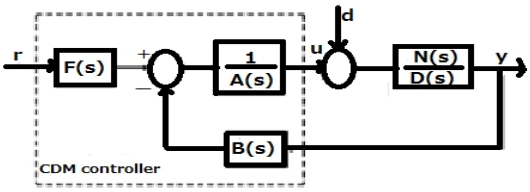

Figure 1. A block diagram of CDM control system

Hence,

$$y = \frac{N(s)f(s)}{P(s)} \quad (1)$$

where $P(s)$ is the characteristic polynomial of the closed-loop system and is defined by

$$P(s) = A(s)D(s) + B(s)N(s) \quad (2)$$

$A(s)$ and $B(s)$ are referred to as the control polynomials and defined as

$$A(s) = \sum_{i=0}^{p} l_i s^i \text{ and } B(s) = \sum_{i=0}^{q} k_i s^i \quad (3)$$

For practical realization, the condition P ≥ q must be satisfied. To get the characteristic polynomial P(s), the controller polynomials A(s) and B(s) from (6) are substituted in (5) and this yields

$$P(s) = \sum_{i=0}^{p} l_i s^i D(s) + \sum_{i=0}^{q} k_i s^i N(s) = \sum_{i=0}^{n} a_i s^i, \; a_i > 0 \quad (4)$$

CDM needs some design parameters with respect to the characteristic polynomial coefficients which are the equivalent time constant (τ) (which gives the speed of closed loop response), the stability indices (γ_i) (which give the stability and the shape of the time response), and the stability limits (γ^*). The relations between these parameters and the coefficients of the characteristic polynomial (a_i) can be described as follows:

$$\gamma_i = \frac{{a_i}^2}{a_i + i a_{i-1}}, \; i \in [1, n-1], \gamma_0 = \gamma_i = \infty \quad (5)$$

$$\tau = \frac{a_1}{a_0} \quad (6)$$

$$\gamma_i^* = \frac{1}{\gamma_{i-1}} + \frac{1}{\gamma_{i+1}}, \quad i \in [1, n-1] \quad (7)$$

According to Manabe's standard form, γ_i values are selected as $\{2.5, 2, 2 \ldots 2\}$. The above γ_i values can be changed by the designer as per the controller's requirement. Using the key parameters (τ) and (γ_i), target characteristic polynomial, $P_{target}(s)$ can be written as:

$$P_{target}(s) = a_0 \left[\left\{ \sum_{i=2}^{n} \left(\Pi_{j=1}^{i-1} \frac{1}{{\gamma^j}_{i-j}} \right) (\tau s)^i \right\} + (\tau s) + 1 \right] \quad (8)$$

where $P(s) = P_{target}(s)$.

Also, the reference numerator polynomials $F(s)$ can be callculated from:

$$F(s) = \left. \left(\frac{P(s)}{N(s)} \right) \right|_{s=0} \quad (9)$$

SYSTEM CONFIGURATION

A. System Dynamics

In this section, a simplified frequency response model for a single area power system with an aggregated generator unit is described [2].

The overall generator–load dynamic relationship between the incremental mismatch power and the frequency deviation can be expressed as:

while the dynamics of the governor can be expressed as:

and the dynamics of the turbine can be expressed as:

The block diagrams of the past equations are included in figure 2 where is change in the governor output, is change in mechanical power, is frequency deviation, is the load change, is the supplementary control action, is the equivalent inertial constant, equivalent damping coefficient, is speed drop characteristics, while are governor and turbine time constant respectively.

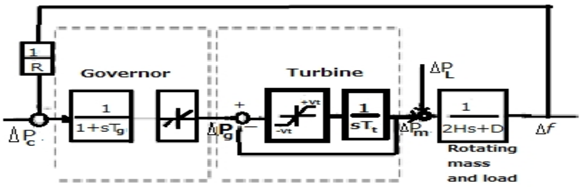

Figure 2. Block diagram of the single area power system

B. Simplified Wind Turbine Model for Frequency Studies

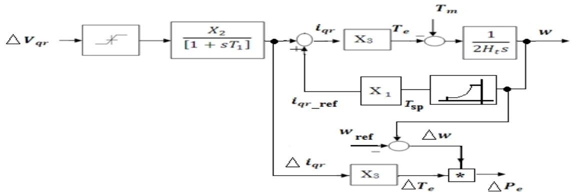

Figure 3. Simplified model of DFIG based wind turbine [19]

A simplified model of DFIG based wind turbine (WT) for frequency response [35] is shown in figure 3. This simplified model can be described by

For linearization, equation (4) can be rewritten as:

where is the operating point of the rotational speed, s is the differential operator, is the electromagnetic torque, is the mechanical power change, is the rotational speed, is the active power of wind turbine, is q-axis component of the rotor current, is -axis component of the rotor voltage and is the equivalent inertia constant of wind turbine. Table I shows the detailed expressions of the main parameters utilized for the simplified model of figure 3.

Table 1. Parameters of Figure 3 [24]

Where:

, and

.

is synchronous speed, is the magnetizing inductance, and are the respective rotor and stator resistances, and are the rotor and stator leakage inductances respectively, while and are the rotor and stator self-inductances respectively.

OVERALL STEM STRUCTURE

The block diagram of a simplified frequency response model of a single area power system with aggregated unit including the proposed CDM controller is shown in figure 4.

The system consists of the rotating mass and load, nonlinear turbine with GRC, and governor with dead-band constraint [1].

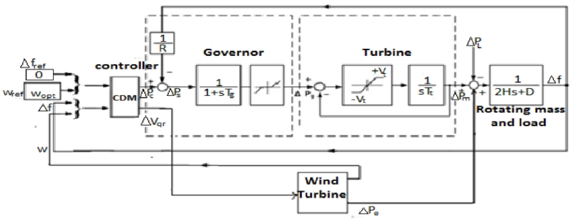

Figure 3. The block diagram of a single area power system including the proposed CDM controller

The frequency deviation is used as feedback for the closed loop control system. The measured and reference frequency deviation and the reference frequency are fed to the CDM in order to obtain the supplementary control action, , which add to the negative frequency feedback signal. The resulting signal is fed the governor giving the governor valve position which supplies the turbine to give the mechanical power change, , which is affected by the load change, , giving the input to the rotating mass and load block in order to provide actual frequency deviation .

RESULTS AND DISCUSSION

Computer simulations have been carried out in order to validate the effectiveness of the proposed scheme. The Matlab/Simulink software package has been used for this purpose. A practical single area power system has the following nominal parameters [2] listed below in table II.

Table 2. Parameters and data of pratical single area power system

D(p.u/Hz)	*H(pu.sec)*	*R(Hz/p.u)*	*(sec)*	*(sec)*
0.015	0.08335	3.00	0.08	0.4

Simulation studies are carried out for the proposed controller with generation rate constraint (GRC) of 10% p.u. per minute. The maximum value of dead band for governor is specified as 0.05%. The parameters of the CDM controller are set as follows:

The time constant can be taken as $\tau = 2sec$. Hence, from (11)

$$P_{tareget} = 1 + 2S + 1.6S^2 + 0.64S^3 + 0.128S^4 + 0.0128S^5$$

the stability indices (γ_i) are determined as:

$$\gamma_i = [2.5,2,1.25,5.12] \quad , i \in [1,4] \quad , \gamma_0 = \gamma_5 = \infty$$

And the stability limits (γ_i^*) are $\gamma_i^* = [0.5,1.2,0.6953,0.8]$

with $, i \in [1,4]$ $k_0 = 1$, then

$$B_i = 1 + 1.036S + S^2 , i \in [1,4]$$

$$A_i = .008 + 2.77S + 2.4S^2 , i \in [1,4]$$

For the simulations studies, three cases are investigated. The first case is a nominal case where the power system operates under normal operating conditions. The second case the changed case where changes are made in the parameters of the power system so as to carry out robustness investigations and comparison is made between the controllers. In the third case, the effect of WT on the power system is investigated considering variable wind speed. Table III shows the parameters and operating points of the wind turbine.

The parameters of the MPC controller are set as follows:

Prediction horizon = 10 , Control horizon = 2, Weights on manipulated variables = 0 ,Weights on manipulated variable rates = 0.1 ,Weights on the output signals = 1 and Sampling interval = 0.0003 sec. Constraints imposed over the control action, and frequency deviation are as follows: Maximum(Max) control action = 0.25 pu, Minimum(Min) control action = 0.25 pu, Max. frequency deviation = 0.25 pu, and Min. frequency deviation = -0.25 pu.

Table 3. Wind Turbine Parameters and operating point

Operating Point(mw)	***Wind speed(m/s)***	***Rotational speed(m/s)***
247	11	1.17
R_r ***(pu)***	R_s ***(pu)***	X_{lr} ***(pu)***
0.00552	0.00491	0.1
X_{ls} ***(pu)***	X_m ***(pu)***	H ***(pu)***
0.09273	3.9654	4.5

X_m is the magnetizing reactance while X_{lr} and X_{ls} are the leakage reactance of the rotor and stator respectively.

A. First Case: Nominal Case

The system performance with the proposed CDM controller in case of nominal parameters is tested and comparison is made between the system performances with conventional integrator $K(s) = -0.3/s$ [2] in the presence of a step load change $\Delta P_L = 0.02\,p.u.$ at $t = 3sec$. Figure 5 shows the simulation results of the proposed CDM and only conventional integrator systems. The results from the top to the bottom are: the governor mechanical power change, ΔP_m , in per unit, the frequency deviations, Δf , in Hertz and the governor's controlled input signals, ΔP_s, in per unit. It can be seen that after a step load changed is experienced by the system at t=30sec, the conventional integral controller gradually brings the system back to its reference point but took a much longer time. With the proposed CDM controller, the system is more stable and faster as compared to the conventional integral controller.

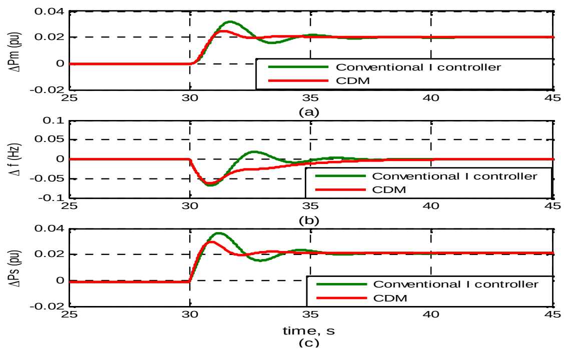

Figure 4. Power system response to a small load change a) Mechanical power change, b) frequency deviation and c) governor's control signal

B. *Second Case: Robustness Evaluation*

To evaluate the robustness of the proposed CDM technique, changes has to be made in the parameters of the power system. Hence, the governor and turbine time constants are increased to $T_g = 0.12\text{sec}$ and $T_t = 0.95\text{sec}$, respectively. Considering repeated comparison between CDM and the model predictive control used in [23], it has been taken into account here that the same parameters and same system conditions should be used. The comparison results are displayed in figure 6, which shows comparison between the CDM and MPC controllers and figure 7 which displays test for robustness between the proposed CDM,MPC and conventional integral control. The figures depicts that with the traditional integral controller, the system becomes the amplitude of the oscillations are high and it takes a considerably longer time before the oscillations can be damped out. This is true only in the presence of wind turbines (WT). As it is shown later in figure 8, during the changed case which is the case of parameters uncertainties where test for robust evaluation is performed, the system with the traditional integral controller in the absence of WT is instable and goes out of step. However, the frequency deviation reaches about 0.05Hz in the case of the traditional integral controller, but it is regulated within about 50% (0.025Hz) in the case of proposed CDM strategy.

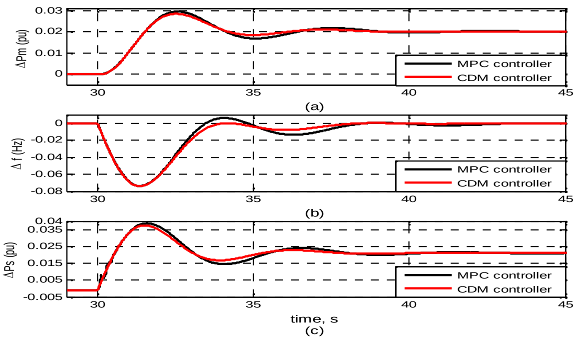

Figure 5. Power system response to different changes a) Mechanical power change , b) frequency deviation and c) governor's control signal.

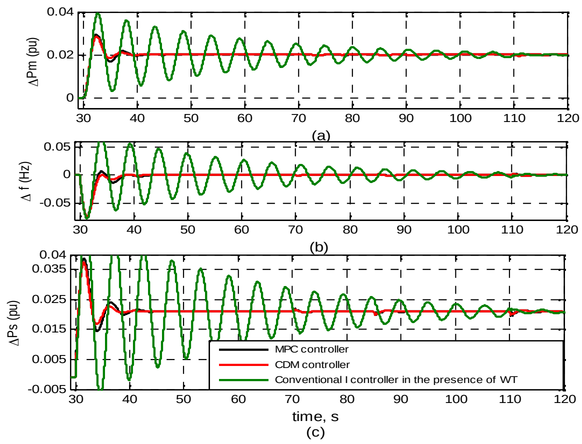

Figure 6. Power system response to different changes a) Mechanical power change , b) frequency deviation and c) governor's control signal.

Hence, with both the proposed CDM and MPC controllers, the system response is more stable with the MPC performance acting better in controlling the governor valve position, while the frequency response of the system with the proposed CDM is much better than the one with MPC. Also, the figure indicates that both CDM and MPC controllers can give the robust response verses load change and parameters uncertainties, but the proposed CDM is more practical in term of the calculation burdens and more economical as compared to the MPC.

C. Third Case: Effect of Wind Turbines

i) Constant Wind Speed

First, the proposed CDM technique was tested on the power system with the wind speed held constant. Then at t=30sec there is a sudden change in load and parameter uncertainties. As explained earlier, figure 8 illustrates the waveforms associated with this simulation. During this changed case, with the conventional integral controller, the system goes out of step in the absence of the wind farm.

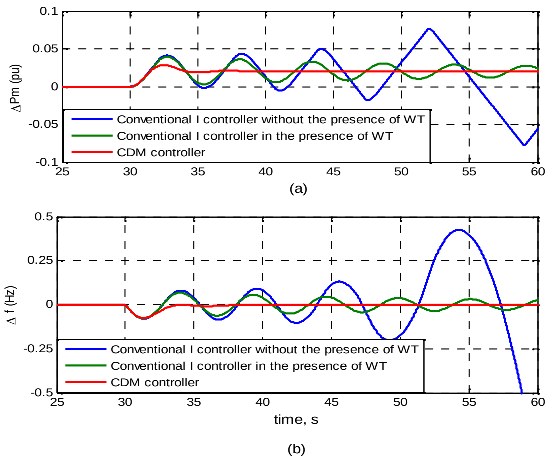

Figure 7. Power system response to a different changes in the presence and absence of Wind Farm a) Mechanical power change, and b) frequency deviation

However, in the presence of the wind farm, the result from the conventional integral controller is enhanced, thus, indicating a positive effective of the wind farm on the stability of the power system. In Figure 9 below, it can clearly be seen that the rotational speed of the WT tracks the power output of the as expected.

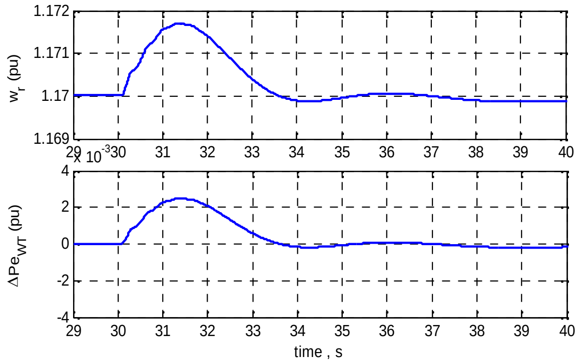

Figure 8. Power system response different changes a) rotational speed and b) WT electrical power output.

ii) Variablet Wind Speed

In order to further test the effectiveness of the proposed CDM control technique, simulation was performed and the system is observed in the presence of variable wind speed fluctuating between 7.5m/s to 15.5m/s as shown in figure 10. From figure 11, it is observed that with the proposed strategy, the system is stable which verifies the effectiveness of the proposed control scheme. Also, the figure indicates that even though the wind speed changes, the presence of wind turbine leaded to enhancement the system performance with the propose CDM controller, significantly.

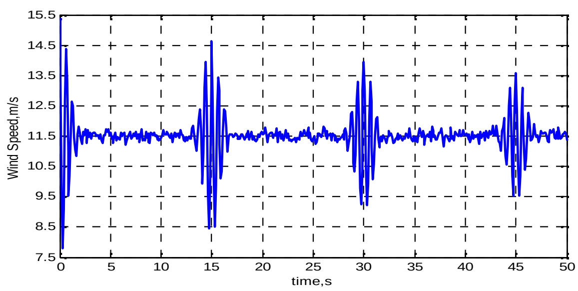

Figure 9. Simulated wind speed in m/s

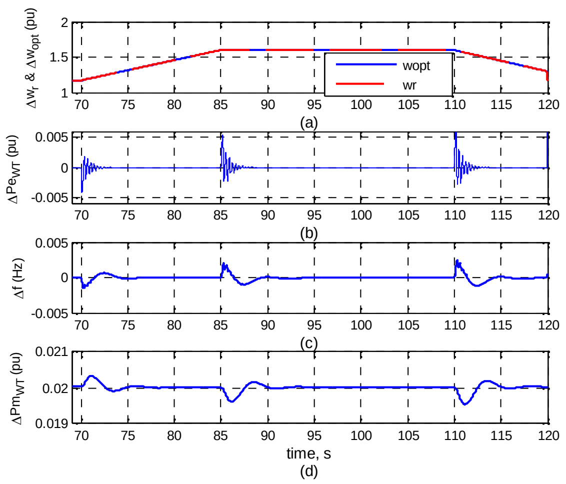

Figure 10. Power system response to variable wind speed a) rotational speed and WT operating point b) WT electrical power output c) frequency deviation Δf , and d) WT mechanical power change

CONCLUSION

This paper investigates robust load frequency control of a single area power system in the presence of wind farm based on the Coefficient Diagram method. Digital simulations have been carried out in order to validate the effectiveness of the proposed scheme. The proposed controller has been tested for several mismatched parameters and load disturbance. Simulation results show that fast response, robustness against parameter uncertainties and load changes can be considered as some advantages of the proposed CDM controller. In addition, a performance Comparison between the proposed controller and both the MPC and a conventional integrator control scheme are carried out. It is shown that the CDM controller response is much more effective than that of the traditional integrator response and is able to deal with both uncertainties in parameters and load changes more efficiently. Also, it is observed that both CDM and MPC are robust, but CDM has the advantage over MPC with respect to reduced calculation burden and is easier to design. Finally, simulations were carried out in the presence and absence of wind turbines. It is observed therefrom that wind turbines have a positive effect on the total response of the power system.

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