Participation of DFIG Based Wind Turbine Generator in Load Frequency Control with Linear Quadratic Regulator and SMES

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ABSTRACT:
For large scale power systems, it is important to keep the frequency and inter area tie line power near to the scheduled values. In current scenario the use of renewable energy sources are given higher priority for the energy generation due to environmental concerns. As the penetration of wind energy using doubly fed induction generator (DFIG) in power system is increasing, it results more disturbance in load frequency due to unbalance between load and demand. This paper presents a novel approach using Linear Quadratic Regulator (LQR) and Superconducting Magnetic Energy Storage (SMES) along with the DFIG to control the frequency and tie-line power deviation. The LQR is designed and the kinetic energy of DFIG is extracted to control the interconnected two area power system. SMES unit is introduced to realize the quick response on load frequency control. The improvement in response after participation of LQR, DFIG & SMES will be observed by the time domain simulation response in MATLAB.

KEYWORDS: Automatic Generation control (AGC), Linear Quadratic Regulator (LQR), Doubly Fed Induction Generator (DFIG), Superconducting Magnetic Energy Storage (SMES).

1. INTRODUCTION
The primary requirement of normally operated power system is constant frequency at the generation output. It is desired that there should be synchronization between the power generation and demand. If there is any mismatch between these two, frequencies will deviate. To eliminate this mismatching, the speed of turbine will be varied to get required amount of energy with the help of stored kinetic energy. It is desired to have constant turbine speed. So it will be achieved when area control error will be zero. The Automatic generation control (AGC) compensates the frequency variation with Load Frequency Control (LFC) [1]. Many useful works has been reported in the area of AGC and it is designed with help of different controllers like PI, PID etc. An adaptive type-2 fuzzy controller has been used in load frequency control [2]. In modern time, the energy generation using non-conventional sources is desired due to environmental concerns. The wind energy is a best generation source. Doubly Fed Induction generator (DFIG) based wind turbine is a good choice for the energy generation. The response time of conventional power system is very large as compared to the DFIG. The kinetic energy stored in DFIG can compensate the demand of energy if load is increased. This extraction of kinetic energy from DFIG takes lower time as compared to the conventional turbine-generator [3-4]. The concept of optimal feedback controller is explained in [8]. The scope for optimal controller in power system is described in [9]. The method related to the designing of controller using optimal control theory with the help of LQR-method is reported in [10-11]. Some time it is not possible to absorb frequency fluctuation by the conventional power system due to its slower response even during small load variation. To compensate the sudden load changes, it is required to provide instant relief for the frequency fluctuation. SMES is an active power source which shows fast response and thus can be considered as most effective source of stored energy. In literature the detailed study of SMES is reported. Literature also shows that there are so many works has been performed with concern to SMES. It is described that the SMES can be used in both the areas of two area power system [12-14]. The application of SMES in power system is described as Enhanced Power System.
Stability and Power Quality Improvement in [15]. The role of SMES in transient stability of power system has been observed in [16]. The effect and advantages of SMES in single area only is also reported and thus work shows that we can use SMES, only in single area of two area power system effectively [14].

Taking above into consideration, in this paper, an approach is proposed for the frequency deviation control using LQR method along with DFIG. An interconnected two area power system is considered in this paper. State space form of the two area power system is obtained and then optimal control theory is applied by which an optimal controller is designed. The designed controller is applied in state feedback. Thus the effect on frequency of each area and tie line power is observed. DFIG is inserted in both the areas. The effect of DFIG on conventional power system is analyzed using time domain response.

2. MATHEMATICAL DESCRIPTION

The mathematical approach behind designing of two area power system, DFIG and LQR-method is described under this section.

Structure of interconnected Two Area Power System in State Variable Form

Power system with single turbine and generator is popularly stated as single area and when the number goes to two, and then it is known as two area power system. In this paper, the both areas are considered for the experimental point of view. A thermal plant is considered for the generation. For the experimental concern, it is required to convert it into state space form. As the number of generation area increases, the numbers of disturbance forces will increase. The generalized state space form for the power system is stated below.

\[ \dot{x} = Ax + Bu + GP \]  

(1)

Integral controllers are used to reduce ACE to zero so that the frequency fluctuation will be settled down within a short period of time. The gain of integral controller used with these two power systems is obtained using trial and error method along with the SMES only. The signal fed into the integrator is referred to as “Area Control Error (ACE)” i.e.

\[ ACE \approx \Delta f \]  

(2)

If we are considering two areas then there will be some role of tie line in adjustment of ACE and thus it can be represented by-

\[ ACE_1 = B_1 \Delta f_1 + \Delta P_{ne12} \]  

(3)

\[ ACE_2 = B_2 \Delta f_2 + \Delta P_{ne21} \]  

(4)

Concept of SMES in Power System

The dc voltage is given by [14]

\[ E_d = 2V_d \cos \alpha - 2I_d R_C \]  

(5)

where \( E_d \) is the dc voltage applied to the inductor in kV, \( \alpha \) is the firing angle in degrees, \( I_d \) is the current flowing through the inductor in kA, \( R_C \) is the equivalent commutating resistance in k\( \Omega \) and \( V_{do} \) is the maximum circuit bridge voltage in kV. When there is increase in load demand, the frequency will decrease and thus to control this deviation SMES will introduce some energy into the power system. The control voltage \( E_d \) is to be negative since the current through the inductor and the thyristors cannot change its direction. The incremental change in the voltage applied to the inductor is expressed as

\[ \Delta E_d = \left[ \frac{K_{SMES}}{1 + sT_{DC}} \right] \Delta Error \]  

(6)

Inductor current deviation is defined as

\[ \Delta I_d = \frac{\Delta E_d}{sL} \]  

(7)

Where \( \Delta E_d \) delta is the incremental change in converter voltage, \( T_{DC} \) is the converter time delay, \( K_{SMES} \) is the control loop gain and \( \Delta Error \) is the input to the SMES unit.

In this paper, area control error (ACE) of area-1 is taken, which will be given to the gain of SMES as input. Thus the \( \Delta E_d \) will become

\[ \Delta E_d = \left[ \frac{K_{SMES}}{1 + sT_{DC}} \right] (B_1 \Delta f_1 + \Delta P_{ne12}) \]  

(8)

It is reported in [14] that, in SMES, the inductor current will return very slowly to its normal value, which is not desired. Inductor current should be settled to its normal value as quick as possible. So to enhance current restoration, a negative feedback in SMES control loop is provided by sensing inductor current deviation. The block diagram and dynamic equation related to feedback in SMES is shown in Figure.1 and equation (9) respectively.
The demand of \( \eta_1 \) support \( \eta_2 \)-line power deviation. It is described below in equation form

\[
\Delta E_d = \left[ \frac{1}{1 + sT_{pc}} \right] [K_{SMES} (B_1 \Delta f_1 + \Delta P_{\text{net}12}) - K_{d} \Delta J_d] \quad (9)
\]

**Optimization of Integral Controller Gain ( \( K_{i1} \) and \( K_{i2} \) )**

The optimization of Integral controller in two area power is performed using Integral Square Error technique (ISE). The performance index contains the frequency deviation of both the areas and tie line power deviation. It is described below in equation form

\[
J = \int_0^\infty (\Delta f_1^2 + \Delta f_2^2 + \Delta P_{\text{net}12}^2) dt \quad (10)
\]

**Doubly Fed Induction Generator (DFIG)**

As the penetration of wind energy is increasing into conventional power system, it is desired that DFIG should participate in load frequency control. The DFIG stores the kinetic energy in its turbine blade. So the extraction of this kinetic energy depends on the inertia of the turbine. By controlling this inertia, the stored energy can be extracted from the blade. Under normal operation, the converter controllers of the DFIG keep the turbine at its optimal speed in order to extract maximum power. Figure 2 shows the model used for active power control. The model shows the essence of emulation inertial control in which an additional control signal tries to adapt the power set-point \( \Delta P_f^* \) as a function of change of frequency and rate of change of frequency. The controller provides a power set-point \( \Delta P_{\text{ref}} \) which is based on measured speed and electrical power. As the grid frequency deviates from its schedule value, the set-point torque is increased. Thus the rotor speed gets down and kinetic energy is released. This released kinetic energy will compensate the demand of power. The total injected non-conventional power is given by \( \Delta P_{\text{NC}} \) as [12].

\[
\Delta P_{\text{NC}} = \Delta P_f^* + \Delta P_{\text{ref}}^* \quad (11)
\]

The contribution of DFIG in modified inertial control is given by:

\[
\frac{2H}{f} \int \frac{df}{dt} = \frac{\Delta f}{f} - D \Delta f = \Delta f + \Delta P_{\text{nc}} - \Delta P_{\text{f1}} - \Delta P_{\text{f2}} - D \Delta f \quad (12)
\]

It has an additional reference power setting that is developed on the change in frequency using washout filter having a time constant \( T_{\text{io}} \). The reference point \( \Delta P_f^* \) can be obtained from equation (13).

\[
\Delta P_f^* = \frac{1}{R} (\Delta X_2) \quad (13)
\]

Where \( R \) is the speed regulation parameter as used conventionally and \( \Delta X_2 \) represents the frequency change measured where the wind is connected to the network.

The DFIG responds to change in frequency during load disturbances by using their stored kinetic energy. The proposed controller makes use of frequency deviations instead of derivative of frequency, to provide fast active power injection control. The achieved power injected by wind turbine during any disturbances is \( \Delta P_{\text{NC}} \). The power injected by the wind turbine is compared with \( \Delta P_{\text{NCref}} \) so as to obtain maximum output power, which is obtained by maintaining reference rotor speed, where maximum power is obtained. The mechanical power captured by the wind turbine is given by equation (14).

\[
P_{\text{mech}} = \frac{1}{2} C_p \rho T \pi R^2 V_{\text{wind}}^3 \quad (14)
\]

DFIG provides dynamic active power \( \Delta P_{\text{NC}} \) support for step load perturbation. To achieve this, \( \Delta P_{\text{NC}} \) is multiplied with the wind penetration level. In this work it is assumed that the 20% wind energy is penetrating into the grid.

**Linear Quadratic Regulator (LQR)**

The linear quadratic regulator method gives algorithm to design optimal controller and generally known as LQR-method. The designed controller is used in feedback of system and thus it is also known as optimal feedback controller. The objective of this method is to generate a control law \( u(x, t) \) which helps to transfer the system from initial to final state with minimizing the performance index. The Performance Index that is
widely used in optimal control design is known as the quadratic performance index. This is based on minimum error and minimum energy criteria. The basic representation of a system in state space form is

\[
\dot{x} = Ax + Bu
\]  

(15)

So to represent the power system in state space form, it is required to assign state variables to the output of each block and thus ‘A’ and ‘B’ matrix is generated. In LQR method, the main task is to minimize the performance index which is described by

\[
J = \frac{1}{2} \int_0^\infty (x^T Q x + u^T R u) dt
\]  

(16)

The ‘Q’ and ‘R’ are matrices and in this paper, Q and R matrices are taken as Identity matrix. The dimension of ‘Q’ matrix depends upon the number of state variables. In this paper, the total number of state variables is 9. So the ‘Q’ matrix taken here is a identity matrix of dimension 9*9. Similarly the ‘R’ matrix depends upon the number of control law has to be designed. In this work, two control law has been designed and thus the dimension of ‘R’ matrix will be of 2*2. To obtain the minimum value of performance index, it is required to generate control law ‘u’, which can be determined by:

\[
u = -Kx
\]  

(17)

Here ‘K’ matrix defines the feedback controller gain and it depends upon the number of state variables. So dimension of ‘K’ matrix is 1*9. It is required to generate ‘K’ matrix to obtain control law ‘u’ and can be calculated by the following relation:

\[
K = R^{-1}B^T P
\]  

(18)

Here the dimension of ‘P’ matrix is 9*9 and is a real symmetric matrix. To generate ‘P’ matrix, optimal control literature gives a relation called as ‘RICCATI EQUATION’ and can be shown by [7]:

\[
A^T P + PA - PBR^{-1}B^T P + Q = 0
\]  

(19)

Using above relations, a control law ‘u’ is obtained with the help of ‘K’ matrix. This ‘K’ matrix can be directly obtained by solving RICCATI EQUATION in MATLAB-2010.

\[
u_1 = [K_{11}x_1 + K_{12}x_2 \ldots \ldots \ldots . K_{1n}x_n]
\]  

(20)

\[
u_2 = [K_{21}x_1 + K_{22}x_2 \ldots \ldots \ldots . K_{2n}x_n]
\]  

(21)

After finding ‘K’ the control law ‘u’ can be calculated and the optimal feedback controller is designed with the help of feedback gain. The gain will be defined by the value of ‘K’, obtained from the ‘K’ matrix for each state variable respectively. Thus the designed controller will be implemented on the system with the help of feedback gain. Each state variable will be selected and passed through the respective gain. The output of controller will be given to AGC to make ACE zero as soon as possible.

The main task here is the selection of ‘Q’ and ‘R’ matrices. It depends on designer that which parameter has to be minimized. In this paper, we are considering to minimize each blocks output and thus an Identity matrix of 9*9 is selected. Similarly the ‘R’ matrix is also chosen as identity matrix of 2*2 dimension so that each control law ‘u’ is participating to minimize the performance index ‘J’, which is explained in equation (14).

**Fig. 2. Model of DFIG based inertial control [3]**

3. RESULTS AND DISCUSSIONS

In this section, time response of frequency deviation in Area-I & Area-2 and Tie Line Power Deviation is being discussed. In this work, it is assumed that there is 10% load perturbation in Area-1. Energy generated from the wind is merged with the total generation. Insertion of DFIG will lead to the improvement in transient response of the system. it is examined that the performance index increases as we increase the penetration of wind energy into the grid. Thus a 20% of wind penetration is considered in this work and the responses have been taken for this value. Fig. 3 & Fig.4 explain the response of both the areas and Figure.5 shows tie-line power deviation when LQR has been implemented along with the DFIG in the power system Vs power system with DFIG. A feedback regulator in the form of LQR tries to minimize the error of each state of power system with the help of state variables. The LQR forces the error of each state to get zero. Thus transient time response has been improved with the inclusion of LQR. LQR guarantee about stability.
because it forces the poles to stay in left side of the s-plain. Thus after inserting LQR along with DFIG gives improvement in transient response of the frequency deviations and stability simultaneously. The table-1 describes the improvement in undershoot, overshoot and thus the performance index is also enhanced when LQR and DFIG are simultaneously inserted. Figure 6 & Figure 7 shows the time response of Area-1 & Area-2 when the LQR and DFIG along with an SMES unit is inserted. Figure 8 explains the response of tie-line power deviation when these three units are inserted. From these figures it can be observed that insertion of SMES unit makes system faster. There are some issues related with stability due to increase in damping factor but when we analyse the overall response, it is better to use SMES unit with LQR & DFIG. Table 1 describes undershoot, overshoot and performance index.

**Fig. 3.** Frequency Deviation in Area-1 (With DFIG Vs with LQR & DFIG)

**Fig. 4.** Frequency Deviation in Area-2 (With DFIG Vs with LQR & DFIG)

**Fig. 5.** Tie line Power Deviation (With DFIG Vs with LQR & DFIG)

**Fig. 6.** Frequency Deviation in Area-1 (With LQR & DFIG Vs with LQR, DFIG & SMES)

**Fig. 7.** Frequency Deviation in Area-2 (With LQR & DFIG Vs with LQR, DFIG & SMES)

**Fig. 8.** Tie line Power Deviation (With LQR & DFIG Vs with LQR, DFIG & SMES)


**APPENDIX**

**Table 1. Feedback Controller gain**

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<tr>
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<th>$k_{p1}$</th>
<th>$k_{p2}$</th>
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<tbody>
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<td>$k_{i2}$</td>
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<tr>
<td>$k_{i9}$</td>
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**Table 2. Dynamic Characteristics of Two Area Power System**

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<th>US</th>
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<th>Settling Time (sec.)</th>
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<td>0.02105</td>
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<td></td>
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<tr>
<td></td>
<td>Tie-1 Line</td>
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<td>-</td>
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<td>With LQR, DFIG &amp; SMES</td>
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<td>-</td>
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<tr>
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<tr>
<td></td>
<td>Tie-1 Line</td>
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<td>0.00507</td>
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**Table 3. Tuning Parameters**

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<tr>
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<th>With LQR and DFIG</th>
<th>With LQR, DFIG &amp; SMES</th>
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**Table 4. Constant Parameters [1, 14]**

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<td>$T_{i2}$</td>
</tr>
<tr>
<td>$K_{p1}$</td>
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**REFERENCES**


