Design and Analysis of Minimax Linear Quadratic Gaussian based Power Oscillation Damper in Large scale PV Plants

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Abstract- The use of renewable energy sources like solar, wind etc.,is increasing nowadays. Transmission voltage level PV plants is becoming a reality in many countries. Majority of large-scale PVs are located far away from load centers and connected to relatively weak transmission networks. Increased PV penetrations on weak transmission links affect power system stability.They cause low frequency oscillations . Depending upon the location and sizes, large scale PV plants could have either positive or negative influence on low frequency oscillations. Even though depending upon the location, the low frequency oscillation (LFO) changes, these plants cannot be shifted to an ideal location where the impact of low frequency oscillation is less. In order to mitigate the LFO it is important to consider the design of a damping controller. Here, in order to avoid low frequency oscillation in large scale PV plant, a power oscillation damper (POD) is used. The POD is based on minimax linear quadratic gaussian method. The test system and the PV model are simulated individually and then connected together to analyse the oscillations produced. Simulation results demonstrate that large scale PV plants when connected to the test system produce oscillations. This necessitates the design of a damping controller.

Keywords— Large-scale PV plants, Low frequency oscillation (LFO), Power Oscillation Damper (POD), minimax linear quadratic gaussian method

I.INTRODUCTION

Due to the problems of climate change and energy security renewable energy is increasingly used. By using renewable sources there occurs reduction in energy related environmental problems. Renewable energy can be simply defined as a new, large, and inexhaustible source of energy that has capability to generate power requirements of the world.Among renewable energy options wind and photovoltaic generations are the important ones. Photovoltaic generation has some advantages over wind generation, like easy installation, low operating and maintanence cost, lowemission, also the decreasing price of the module it is increasingly used in many developed and some of the developing countries nowadays . Due to the advancement in technology, the cost of PV module has decreased almost 90% since early 1980s. One of the disadvantage with PV is that the initial investment is high.However, two of the problems associated with PV generation for grid integration are intermittency and power quality.The problems with grid connected PV generation are , it can cause unwanted conditions to power systems, such as high transmission and distribution losses, flicker and harmonics, overloading, and voltage fluctuation in distribution feeder. The unpredictable natures of PV generation may have impact on power system stability, which in turn needs to be maintained to provide reliable quality power to customers all the time.

Following the increased use of renewable energy sources, many large scale PV plants are already integrated or expected to be integrated into the existing netwok.But these large scale PV's are not located very near to the load centres. Majority of them are connected located geographically far away from the load centres.

Moreover these plants are connected to relatively weak transmission networks. Increased PV penetrations on weak transmission link raise possible negative negative impacts on stability[2] Depending upon the penetration level, location and control techniques large scale PV plants adversely affect low frequency oscillations. However, due to intermittentand voltaile solar insolation to PV plant, auxillary devices such as battery energy storage or ultra capacitor are used for grid interconnection so that these devices helps in damping of the oscillations occurred during interconnection. But due to the increased cost of technology, the large scale application of these devices is limited.

In this paper, a power oscillation damper is proposed for low frequency oscillation damping. The H∞ optimization with linear matrix in equalities has been predominantly used for a robust controller design in non linear system including power system . However the method is too conservative when dealing with less severe disturbance. The minimax optimal controllers are similar in structure to that of H∞ controllers. These controllers guarantee robustness properties and have better performance.

II. PHOTOVOLTAIC ARRAY

The basic building blocks of the photovoltaic array is the solar cell , which is a semiconductor device capable of generating electric power from solar radiations. Ideal solar cell at no illumination shows the same characteristic as ideal diode. Characteristic of the solar cell can be expressed by the following equation,

$$I_D=I_0(e^{V_C Q/KT}-1) \quad (1)$$

where,

- I_D = dark current (A)
- I_o =saturation current of the diode (A)
- V_C=cell voltage (V)
- T= cell temperature
- Q represent the charge of electron
- K is the Boltzmann constant.

The performance of solar cell strongly depends on radiation and environmental condition. Commercially available solar cell never exhibits ideal characteristic as described in equation above.Photovoltaic generator is based on semiconductor device and solid-state synchronous voltage source converter that is analogous to a synchronous machine except the rotating part. It generates a balanced set of sinusoidal voltage at fundamental frequency with rapidly controllable amplitude and phase angle. Voltage source converter in photovoltaic generator converts a DC input voltage into AC output voltage and supply active and reactive power to the system

Photovoltaic modules are produced by connecting these cells in parallel and series, which is capable of generating power in Watt range. Large application requires parallel and series connection of these modules which is known as photovoltaic array.

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III. OSCILLATORY STABILITY ANALYSIS

A. Low Frequency Oscillations

Oscillatory stability falls under the category called rotor angle stability. The main reason why oscillatory instability in low frequency range happens in power system is the lack of damping torque which is primarily given by damper winding of machines. Other controllers in the system also influence damping torque in a positive or negative way. Oscillatory stability analysis of power systems deals with the small disturbance and the ability of power system to maintain synchronism under such disturbances. Typical analysis that provides valuable information about the inherent dynamic nature of the system is based on the linearized system. Linearization holds true as disturbance considered is small.

Oscillatory instability problems can be either local or global in nature. Local oscillation is one of the common instability problems in power systems and this type of problem can be easily dealt with. Local problems involve a small area of the power system, and are usually associated with rotor angle oscillations of a single generator or single power plant against the rest of the power system. Such oscillations are called local plant mode oscillations a group of generators in one area swing against another group of generators in other area. This type of problem is known as inter-area oscillation. The dimension and complexity of this type of oscillation is completely different from local area oscillation. In a large interconnected system, there are two types of inter-area oscillations; one is with very low frequency where all the generators in the system are involved, in which case, the whole system is essentially split into two parts and one part of the system swinging against another part with typical frequency range of 0.1-0.3 Hz. Another is with higher frequency, where a subgroup of generators swinging against one another with typically frequency range of 0.4 -1 Hz

High tension transmission lines connects widely dispersed conventional and non-conventional generators in modern power systems. The dynamics of power transfer in such grid can be categorized by low frequency oscillatory behavior of synchronous generator, static generator and their controllers. Low frequency oscillation of power system is mainly of two types, local mode and inter area mode. Local mode (frequency range 0.7 Hz to 2.0 Hz) and inter-area mode oscillation (frequency range 0.1 Hz to 0.7 Hz).

B.Mitigation of LFO

While considering small scale the impact of a PV plant on power system stability is minimum. However, the dynamic performance of the power system can be significantly affected when penetration level increases. Since PV plants are based on power electronics converters, there are primarily four mechanisms by which the EM modes can be affected. These are as follows.

1) Redispatch of conventional generators with power system stabilizers (PSS) due to PV power.
2) By impacting on the major line flows in the system.
3) Controller interaction between PV plant controls and nearby synchronous generators.
4) The physical difference between the synchronous generators and PV generators, i.e., inertial contribution of rotating mass.

For power system with large-scale PV penetration, due to the aforementioned mechanisms, the damping of EM and other lightly damped modes can be negatively affected . Tuning of a PSS could help to improve the damping of EM modes. But, it requires coordinated tuning of PSSs; otherwise, a tuned PSS could have a detrimental effect on system transient stability . Moreover, retuning of a PSS can be time consuming with high computational burden, which limits optimal real-time operation . On the contrary, the centralized POD at a PV plant can ensure the required system performance without retuning of other system controllers. This type of a controller at the PV plant would allow a flawless integration.

In this paper, a minimax linear quadratic Gaussian-based power oscillation damper (POD) for a large-scale PV plant is proposed for interarea oscillation damping.The minimax LQG method is based on state space representation . So the entire power system model has to be represented in state space form.

IV. MATHEMATICAL BACKGROUND -STATE SPACE REPRESENTATION

A.Modelling of Power System

The power system can be modelled in different ways. Each of the different components has to be modelled individually. The components of the power system includes Synchronous generator,Exciter, Steam turbine governor, PSS, Network modelling equations includes transmission lines , transformers and loads. Synchronous Generator can be modelled in different ways depending on the application of the model. Here modelling is done by considering both field as well as the damper winding. In general, the integrated generator model consists of excitation system.Here, the simplified version of the IEEE type DC1 excitation system is used for all synchronous generators.

B.State space representation

The power system model consists of nonlinear model of generators, loads, PV generators, and the associated controls, which can be described using a set of algebraic differential equations .Linearizing the nonlinear differential algebraic equations of all the power system components, using Taylor series expansion around an equilibrium point we get linearised model of our power system.Linearised equations can be used to represent it in state space form.The general form of state space form can be represented as

$$\Delta \dot{x} = A\Delta x + B\Delta u \qquad (2)$$

$$\Delta y = C\Delta x + D\Delta u \qquad (3)$$

where, Δx is the system state vector of dimension n
Δy is the output vector of dimension p
Δu is the input vector of dimension m

A is the state matrix of size n×n
B is the input matrix of size n×m
C is the output matrix of size p× n
D is the feed-forward matrix of size p×m

Many control design algorithms cannot handle time delays directly. For example, techniques such as root locus, LQG, and pole placement do not work properly if time delays are present.Time delays bring about a phase lag which can affect the controller performance and interactions among system dynamics. Thereby, the time delays associated need to be considered in the design.

The state-space representation of the time delay can be represented as

$$\Delta \dot{x}_d = A_d \Delta x_d + B_d \Delta u_d \qquad (4)$$

$$\Delta y_d = C_d \Delta x_d + D_d \Delta u_d \qquad (5)$$

where

Δx_d is the delay state vector
Δu_d delay input vector
Δy_d is the delay output vector.

The delay free system described by (2) and (3) can be connected in cascade with (4) and (5) to get the system with output time delay and can be expressed as follows:

$$A_1 = \begin{bmatrix} A & 0 \\ B_d C & A_d \end{bmatrix}, \qquad B_1 = \begin{bmatrix} B \\ B_d D \end{bmatrix}, \qquad C_2 = \begin{bmatrix} D_d C & D_d \end{bmatrix}$$

V. MINIMAX LQG CONTROL

For damping controller design , minimax LQG method is used.Minimax LQG methodology can be considered as a robust version of standard LQG controller design. Within the minimax optimal control design framework, robustness is achieved via optimization of the worst-case quadratic performance of the underlying uncertain system. This helps to achieve an acceptable trade-off between control performance and robustness of the system. The minimax LQG method is described as:

$$\Delta x' = A_1 \Delta x(t) + B_1 \Delta u(t) + B_2 \xi(t) + B_2 \omega(t) \qquad (6)$$
$$\Delta y(t) = C_2 \Delta x(t) + D_2 \xi(t) + D_2 \omega(t) \qquad (7)$$
$$\zeta(t) = C_1 \Delta x(t) \qquad (8)$$

where ζ(t) is known as uncertainty output, y(t) is the measured output, w(t) is Gaussian white noise process corresponding to the nominal disturbance, and ξ(t) is an uncertainty input. The underlying physical system does not include noise-like inputs. The white noise term is a technical addition to enable the design of a robust output feedback controller which computes control inputs to drive the system to its equilibrium point in the presence of uncertain disturbances in the system such as those due to the effect of nonlinearities. It is suggested that the optimal minimax LQG controller for the above system is also a quadratically stabilizing robust controller for the deterministic system with norm bounded uncertainty subject. This motivates using the stochastic minimax LQG control design methodology to design a robust controller for the problem in this paper. As compared to the standard LQG control this minimax LQG controller provides robustness due to uncertainties. In the minimax LQG problem for the stochastic system, the following quadratic cost functional is considered

$$J = \lim_{T \to \infty} \frac{1}{2T} E \times \int_0^T (\Delta x(t)^T \; R \, \Delta x(t) + \Delta u(t)^T \Delta u(t)) dt \qquad (9)$$

where $R \geq 0$ and $G > 0$,$R \in R^{n\times n}$,$G \in R^{m\times m}$ and E are the expectation operator. The minimax optimal control finds the controller which minimizes J over all admissible uncertainties.

The general control configuration for minimax LQG control is illustrated in Fig.1 and Fig .2

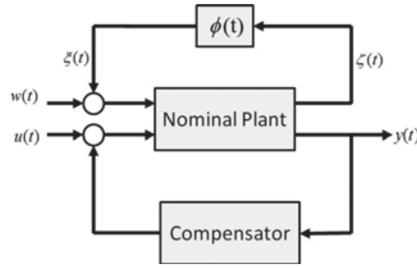

Fig. 1. Minimax LQG control scheme.

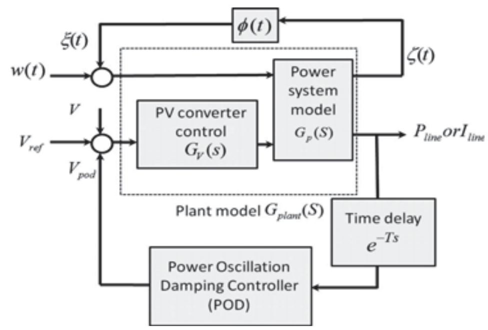

Fig. 2. Damping control design scheme for PV.

V. TEST SYSTEM AND PROCEDURE OF CONTROLLER MATRIX FORMATION

A. Test System

The single line diagram of four-machine two-area test system is depicted in Fig.3.The test system consists of two fully symmetrical areas linked together by two 230 kV lines of 220 km length. It was specifically designed to study low frequency electromechanical oscillations in large interconnected power systems.Despite its small size, it mimics very closely the behavior of typical systems in actual operation. Each area is equipped with two identical round rotor generators rated 20 kV/900 MVA. This system consists of four synchronous generators associated with four 20/230-kV step-up transformers. The synchronous machines have identical parameters except for inertias which are H = 6.5s in area 1 and H = 6.175s in area 2. Thermal plants having identical speed regulators are further assumed at all locations, in addition to fast static exciters with a 200 gain. The load is represented as constant power and split between the areas in such a way that area 1 is exporting power to area 2. The reference load-flow with M3 considered the slack machine is such that all generators are producing about 700 MW each. An aggregated PV plant is connected to the grid at bus 6 in Area 1. There are two load buses in the system: Load 1 consists of 1767 MW and 100 MVAr, whereas Load 2 consists of 967 MW and 100 MVAr. A PV plant is connected to the grid in Area 1.

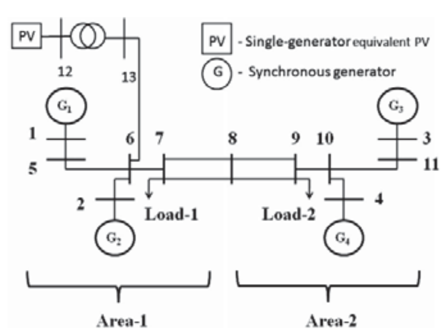

Fig. 3. Two area test system – single line diagram

B.Formation of state space matrices of the system

The following is the step by step design procedure for the formation of state space matrices

Step 1:Loading of the system data includes system details- number of lines, buses, transformers, generator data, load data
Step 2:Load flow data analysis includes
Data initialisation
Load the system data &and form admittance matrix
Step 3:Form Jacobian and solve for bus voltages and angles which includes bus power calculations(S,P,Q) , finding non slack and non PV buses
Step 4:Checking for bus power mismatches, updation of bus voltages and bus angles in each bus.
Step 5:Check wheather Q limit is exceeded. The solution is converged only if the values of ΔP and ΔQ is less than the tolerance value .
Step 6:Enter values for generator and calculating values of field current, Td' and Td''etc
Step 7:Entering values of IEEE type 1 exciter
Step 8:Entering values of steam turbine.
Step 9:Formation of Pg and Pl matrices
Step 10:Formation of matrix incorporating all the power system components- generator, exciter, turbine ,load.

C.Step by step procedure of controller design

Design of a POD can be done by using the following steps

Step 1: Linearize the two-area system so that we get the state space form.
Step 2: Finding the eigen values of the linear system and find frequencies, and damping ratios corresponding to it.
Step 3: Form a state-space model of the system with time
delays .
Step 4: Calculation of state matrices A_1 for minimax LQG controller

Step 5: Calculation of state matrices B_1 for minimax LQG controller.

Step 6: Calculation of state matrices C2 for minimax LQG controller

Step 7: Solving continous time algebraic riccati equation for obtaining the gain matrix G

Step 8: Formation of the controller matrix

VI. SIMULATION RESULTS

The simulation for PV is done and the output is obtained.Four synchronous generators are used in the test system.Test system is simulated and system voltage is analysed. Then PV is connected to the system and the output waveform is analysed.

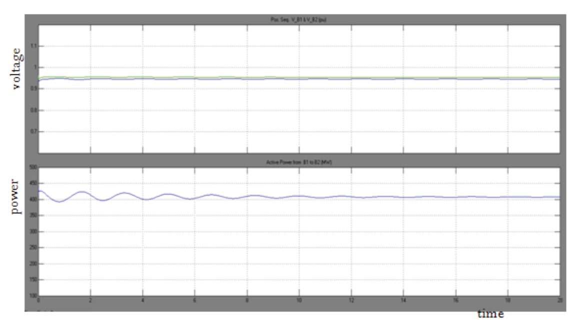

Fig. 4.Output waveform of bus voltages and tieline power

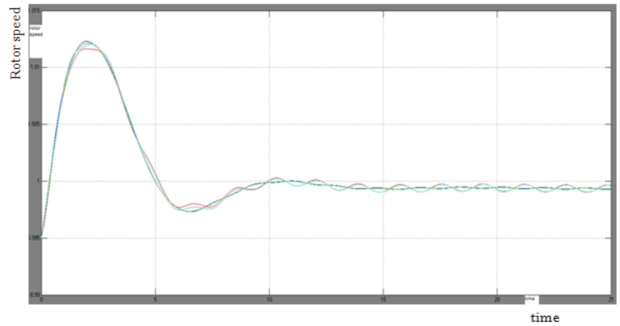

Fig. 5.Output waveform of rotor speed after connecting PV

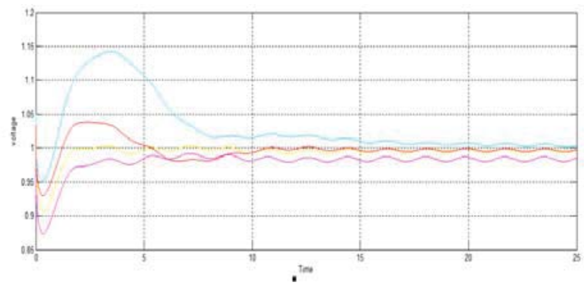

Fig. 6.Output waveform of terminal voltage after connecting PV

After modeling the power system components, we get the state space form of order 64. The state vectors for a single generator include 16 state variables and they are

$$\underline{x}_g = \Big[\delta \quad S_m \quad \psi_f \quad \psi_h \quad \psi_g \quad \psi_k \quad E_{fd} \quad v_R \quad x_B \quad x_F \quad x_1 \quad x_2 \quad x_3 \quad y_1 \quad P_{GV} \quad z\Big]^T$$

V.CONCLUSION

This paper has demonstrated the possibility of using a damping controller at a PV plant to effectively damp out the interarea oscillation resulting in a interconnected power grid. A systematic approach of designing POD based on the minimax LQG technique is described here.A reduced-order model of the designed controller has been formulated.

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