Small Signal Stability Enhancement of Distribution System with Distributed Generation using Exact Model Matching

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***Abstract*— the market deregulation of power sector have encouraged the distributed generation, mainly in distribution systems. Due to the dynamics of distributed generator and dynamics of large loads the distribution systems are facing different types of stability issues. This paper examines the small signal stability of a distributed generation based distribution system. The different oscillatory modes in the system are investigated. A control methodology using exact model matching technique to support small signal stability of a distribution system is proposed. The effectiveness of controllers is illustrated by obtaining closed loop response of the system for input disturbance and comparing the closed loop response with response of desired model.**

Keywords— distributed generation , exact model matching, participation factors, small signal stability,

I. INTRODUCTION

Recent trends of legislative changes around the globe are likely to increase the penetration of distributed generation (DG) units into power systems. The integration and high penetration of DG units into a distribution system could introduce a number of key issues including oscillatory stability which is also referred to as small signal stability [1].oscillatory instability may be caused by dynamic characters of the distributed generators[2].It is one of the limiting criteria for synchronous operation of distributed generators[3].

Apart from the dynamics of the distributed generator, large dynamic loads in the distribution system also play a key role in the small signal stability of the distribution system, it is observed that dynamics of induction machine has a significant contribution to the power system oscillations [4][5][6].As of now, most of the works on small signal stability are on transmission systems. But with distributed generation and large dynamic loads the small signal stability investigation of the distribution systems is gaining importance. In [7] the small signal stability of a renewable energy based distribution system is investigated using Eigen value sensitivity. In [8] the critical parameters of distributed generators and dynamic loads that affect the power system stability are given. The existing literatures mainly deal with either voltage stability or rotor angle stability taking one at a time [2][7][9].Most of the literatures focused on Eigen value sensitivity for the small signal stability assessment[2][3][7][8][9]. In some other literatures it is investigated through time domain analysis [4][9].

On the other hand after assessment of stability proper controllers are to be designed for the enhancement of the stability. In [11] controllability and observability indices are used for designing a damping controller. In [10] the comparison of PSS, SVC, STATCOM controllers for damping power system oscillations is given. However model matching techniques are well suited in these situations. They reduce the complexity in the design of the controller. In [11] the exact model matching of linear time varying multivariable systems is given. The exact model matching of the linear discrete time systems by periodic state or feedback law is given in [12][13].

The aim of the paper is investigation of the small signal stability of a distribution system considering both voltage stability and rotor angle stability of the distributed generator at a time. The various oscillatory modes in the system are observed using Eigen values. The critical modes are identified based on modes having least damping .The transfer function of the controllers that enhance the small signal stability are found using exact model matching. The test system is taken as a single machine infinite bus system with induction motor as load.

The rest of the paper is organized as follows: In section II, the mathematical modeling of the distribution system is given. In section III, the linearization of the whole system is given. In section IV the key investigations in small signal stability assessment are presented. Section V provides approach for controller design using exact model matching technique. Finally, the conclusion drawn from the results are summarized in section VI.

II MATHEMATICAL MODELS

The test system taken is a single machine infinite bus system with induction motor load. In this model, the power is supplied to the load (P_L=1500MW,Q_L=150MVAR) from the infinite bus which is a distribution substation and local DG unit (approximately P_G=300MW,Q_G=225MVAR). The load at bus 2 is made of three parts: (i) one part represented by constant impedance load, (ii) another part represented by an equivalent large induction motor and (iii) a shunt capacitor for compensation purposes. The major portion of these loads is induction motor i.e. P=1485MW and Q=15 MVAR. The parameters of the induction motor, DG unit, transformers and transmission lines are given in Appendix.

With some typical assumptions the synchronous generator can be modeled by the following set of nonlinear differential equations [14]:
Mechanical equations:

$$\dot{\delta} = \omega_s(\omega - 1) \quad \ldots\ldots (1)$$

$$\dot{\omega} = \frac{1}{2H}[P_m - E'_q - (X'_d - X'_q)I_d I_q - D\omega] \quad \ldots\ldots (2)$$

Generator electrical dynamics:

$$\dot{E}'_q = \frac{1}{T'_{do}}[K_A(V_{ref} - V_o) - E'_q + (X_d - X'_d)I_d] \quad \ldots\ldots (3)$$

$$\dot{V}_0 = \frac{1}{T_r}[V_t - V_0] \quad \ldots\ldots (4)$$

Where δ is the power angle of the generator, ω is the per unit rotor speed with respect to the synchronous reference, ω_s is the synchronous speed, H is the inertia constant of the generator, P_m is the mechanical input power to the generator which is assumed to be constant, D is the damping constant of the generator, E'_q is the quadrature axis transient voltage, K_A is the gain of the exciter amplifier, V_{ref} is the reference voltage, V_0 is the output of terminal voltage transducer, T'_{do} is the direct axis open circuit transient time constant of the generator, T_r is the time constant of the terminal voltage regulator, X_d is the direct axis synchronous reactance , X_d is the direct axis transient reactance, I_d and I_q are the direct axis, quadrature axis currents of generator respectively and V_t is the terminal voltage of the generator which is given by :

$$V_t = \sqrt{[(E'_q - X'_d I_d)^2 + (X'_d I_q)^2}$$

A simplified transient model of a single cage induction machine with the stator transients neglected and rotor currents eliminated, is described by the following algebraic-differential equations written in a synchronously-rotating reference frame [15]:

$$\dot{s} = \frac{1}{2H}[T_e - T_L]$$

$$T'_{dom}\dot{e}'_{qm} = -e'_{qm} + (X - X')i_{dm} - T'_{dom} s\omega_s e'_{dm}$$

$$T'_{dom}\dot{e}'_{dm} = -e'_{dm} - (X - X')i_{qm} + T'_{dom} s\omega_s e'_{qm}$$

$$v_{ds} + jv_{qs} = (R_s + jX')(i_{dm} + ji_{qm}) + j(e'_{qm} - je'_{dm})$$

Where X' = X_s +X_m X_r /(X_m + X_r), is the transient reactance, X = X_s+ X_m, is the rotor open-circuit reactance, T'_{dom} = (L_r + L_m) / R_r, is the transient open-circuit time constant, Te is the electrical torque, s is the slip, e'_{dm} is the direct-axis transient voltage, e'_{qm} is the quadrature - axis transient voltage, T_L is the load torque, X_s is the stator reactance, X_m is the magnetizing reactance, R_s is the stator resistance, H_m is the inertia constant of the motor, V_{ds} is the d-axis stator voltage, V_{qs} is the q-axis stator voltage, i_{dm} and i_{qm} are d- and q-axis components of stator current respectively.

Here, this model represents the induction machine in its own direct and quadrature axes, which is different from the d- and q-axes of the synchronous generator. Therefore, axes transformation is used to represent the dynamic elements of both the induction motor and synchronous generator with respect to the same reference frame and to do so we use the following relations:

$$E'_m = \sqrt{(e'_{dm})^2 + (e'_{qm})^2}$$

$$\delta_m = \tan^{-1}\left(\frac{-e'_{dm}}{e'_{qm}}\right)$$

$$(I_{dm} + jI_{qm}) = -(i_{dm} + ji_{qm})e^{-j\delta_n}$$

$$V_d + jV_q = (v_d + jv_q)e^{-j\delta_m}$$

$$T_m = -T_L$$

Here the negative sign with i_{dm} and i_{qm} indicates that they are opposite to I_{dm} and I_{qm} when expressed in the same reference frame with synchronous generator. With this relation, a modified third-order induction machine model can be rewritten as:

$$(V_d + jV_q) = -(R_s + jX')(I_{dm} + jI_{qm}) + jE'_{qm}$$

$$\dot{s} = \frac{1}{2H}[T_m - E'_m I_{qm}] \quad \ldots\ldots (5)$$

$$\dot{E}'_m = \frac{-1}{T'_{dom}}[E'_m + (X - X')I_{dm}] \quad \ldots\ldots (6)$$

$$\dot{\delta}_m = s\omega_s - \omega_s - \frac{(X - X')}{T'_{dom}E'_m}I_{qm} \quad \ldots\ldots (7)$$

To complete the model, the d- and q-axis components of currents for both the generator and motor are given by the following network interface equations:

$$I_{d_i} = \sum_{j=1}^{n}[(B_{ij}\cos\delta_{ij} - G_{ij}\sin\delta_{ij})E'_{qj} + (B_{ij}\sin\delta_{ij} + G_{ij}\cos\delta_{ij})E'_{dj}] \quad \ldots\ldots\ldots (8)$$

$$I_{qi}=\sum_{j=1}^{n}[(B_{ij}\sin\delta_{ij}+G_{ij}\cos\delta_{ij})E'_{qj}-(B_{ij}\cos\delta_{ij}-G_{ij}\sin\delta_{ij})E'_{dj}]$$
……….. (9)

where $\delta_{ji} = (\delta_j - \delta_i)$, $E'_{dj} = 0$, parameters G_{ij} and B_{ij} are the real and imaginary parts of the equivalent transfer impedances of the reduced network between i^{th} and j^{th} bus of the test system shown in Fig. 1.

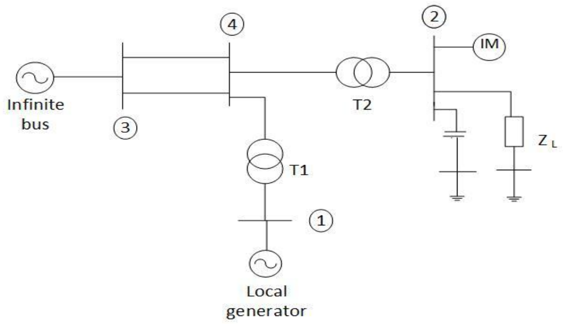

Fig. *1Test System*

III LINEARIZATION OF DISTRIBUTION SYSTEM MODEL

The power system model with dynamic load is expressed by equation (1)-(7). Using Taylor series expansion method and truncating the higher order terms, the linearized form of the equations (1)-(7) can be written as follows:

$$\Delta\dot{\delta} = \omega_{s0}\Delta\omega$$
………. (10)

$$\Delta\dot{\omega} = \frac{1}{2H}[\Delta P_m - E'_{q0}\Delta I_q - I_{q0}\Delta E'_q - (X'_d - X'_q)\Delta I_d I_{q0} - (X'_d - X'_q)I_{d0}\Delta I_q - D\Delta\omega]$$
………… (11)

$$\Delta\dot{E}'_q = \frac{1}{T'_{do}}[K_A(\Delta V_{ref} - \Delta V_o) - \Delta E'_q + (X_d - X'_d)\Delta I_d]$$
……… (12)

$$\Delta\dot{V}_0 = \frac{1}{T_r}[\Delta V_t - \Delta V_0]$$
……… (13)

$$\Delta\dot{s} = \frac{1}{2H}[\Delta T_m - \Delta E'_m I_{qm_0} - E'_{m0}\Delta I_{qm}]$$
……… (14)

$$\Delta\dot{E}'_m = \frac{-1}{T'_{dom}}[\Delta E'_m + (X - X')\Delta I_{dm}]$$
……… (15)

$$\Delta\dot{\delta}_m = \Delta s\omega_{s0} - \frac{(X - X')}{T'_{dom}E'_{m0}}\Delta I_{qm} + \frac{(X - X')}{T'_{dom}E'^{2}_{m0}} I_{qm0}\Delta E'_m$$
………… (16)

here the suffix '0' denotes the value at initial operating point which can be obtained from the load flow analysis .ΔI_d, ΔI_q, ΔI_{dm}, ΔI_{qm} are the linearized form of currents obtained in equations (8) and (9).

IV. KEY INVESTIGATIONS IN SMALL SIGNAL STABILITY ASSESSMENT

From the linearized equations (10)-(16) the linearized model of the whole system considering interconnection dynamics can be represented in the form of linear state space equations:

$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x + D\Delta u$$

Where A is the state matrix, B is the input matrix, C is the control matrix and D is the output matrix. Δx are the states of the system. The states are $\Delta\delta$, $\Delta\omega$, $\Delta E'_q$, ΔV_0, Δs, $\Delta E'_m$, $\Delta\delta_m$. Δu is the input disturbance. ΔV_{ref} is taken as the input disturbance. Δy is the change in the output for the input disturbance. As the complete small signal stability assessment requires investigation of both voltage and rotor angle stabilities the system is taken as single Input two output system. The outputs are $\Delta\omega$ and ΔV_t.

A. Eigen values and participation factors of the system

Using the distribution system parameters given in the appendix and the values at the operating point obtained from the load flow analysis the state matrix A of the system can be calculated. The Eigen values are the roots of the characteristic equation of the state matrix A .The Eigen values and their damping's and frequency of oscillations are given in table I. From the table we can observe that mode 6 and mode 7 has the least damping of 0.235.Hence they cause sustained oscillations in the system in the case of a disturbance and leads to instability. Hence these two modes are taken as the critical modes.

Table I. Eigen modes and their dampings

Eigen mode	value	damping	Freq(rad/s)
1	-14.5	1	14.5
2	-5.23+j9.54	0.48	10.9
3	-5.23-j9.54	0.48	10.9
4	-0.004+j0.19	0.23	0.20
5	-0.004-j0.19	0.23	0.20
6	-0.277+j0.29	0.68	0.48
7	-0.277-j0.29	0.68	0.48

The contribution of states on oscillations was observed by evaluating the participation factors of each state on a particular mode. Participation factors gives the relationship among the states and Eigen mode [1].The normalized form of participation of the k^{th} state in the i^{th} Eigen mode can be given by:

$$P_{ki} = \frac{|\Phi_{ki}||\psi_{ki}|}{\sum_{1}^{n} |\Phi_{ki}\Psi_{ki}|}$$

Where Φ_{ki} is the K^{th} entry of right Eigen vector Φ. Ψ_{ki} is the k^{th} entry of left Eigen vector Ψ_i and 'n' is number of state variables. The participation factors for the critical modes 6,7 are shown in tableII.From the table we can observe that deviation in rotor angle of DG unit and deviation in slip of induction motor are the dominant states that are contributing the oscillations in the critical modes.

Table II. Participation factors for critical modes

state	mode4	mode5
$\Delta\delta$	0.1974	0.1974
$\Delta\omega$	0.0951	0.0951
$\Delta E'_q$	0.0212	0.0212
ΔV_0	0.0008	0.0008
Δs	0.2728	0.2728
$\Delta E'_m$	0.4086	0.4086
$\Delta\delta_m$	0.0041	0.0041

B. open loop response of the system

Fig.2 shows the open loop of the distribution system model shown in fig.1.It is a single input; two output system.$G_{11}(s)$ represents the open loop transfer function for the output ΔV_t and input ΔV_{ref}. $G_{21}(s)$ is the open loop transfer function for the output Δω and input ΔV_{ref}. The transfer functions are obtained through:

$$\frac{\Delta y(s)}{\Delta u(s)} = C(sI - A)^{-1}B + D$$

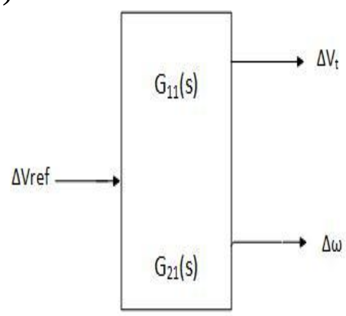

Fig 2 *Open loop of the system*

The open loop response of ΔV_t and Δω for a step disturbance of ΔV_{ref} are shown in Fig4 and Fig5.From Fig4 and Fig5 we can observe that the open loop response of ΔV_t and Δω are oscillatory. Also the steady state values of ΔV_t and Δω are not zero, but settling above zero. This indicates that terminal voltage and speed of the DG unit have changed from the nominal values and settled at new values given by:

$$V_{t,new} = V_{t0} + \Delta V_t$$
$$\omega_{new} = \omega_0 + \Delta\omega$$

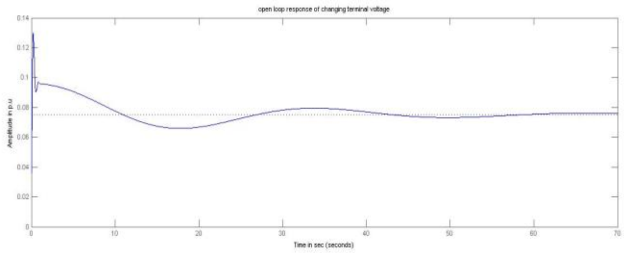

Fig 4 *open loop response of $G_{11}(s)$*

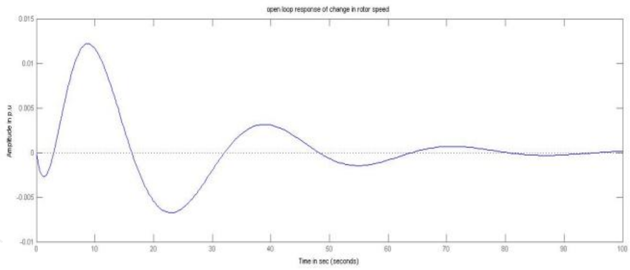

Fig 5 *open loop response of $G_{21}(s)$*

System is stable when terminal voltage and rotor speed of the DG unit are kept constant. For this to happen ΔVt and Δω should be zero. Otherwise change in terminal voltage may lead to circulating currents in the distribution system and change in speed of the rotor of DG unit will lead to frequency deviations. Hence a control system is to be designed for the enhancement of the small signal stability which is given in the next section

V.DESIGN OF CONTROLLER USING EXACT MODEL MATCHING

Controller for the enhancement of small signal stability is designed using exact model matching.

A. meaning of exact model matching:

The exact model matching design problem consists of determining a control law such that the input-output description of the closed loop system with controller is equal to that of a desired model and the orders of closed loop system and the desired model are strictly equal. The solution of this problem is of obvious practical importance, since it makes it possible to adapt the performance of a given system to that of a desired model.

B. Control law

The control part for the enhancement of the small signal stability is shown in Fig3.$c_1(s)$ and $c_2(s)$ are the transfer functions of the controllers which are to be determined using exact model matching. The closed loop transfer functions are given as:

$$G_{11C}(s) = \frac{c_1(s)G_{11}(s)}{1 + c_1(s)G_{11}(s) + c_1(s)c_2(s)G_{21}(s)} = \frac{\Delta V_t}{\Delta V_{ref}} \quad \text{......... (17)}$$

$$G_{21C}(s) = \frac{c_1(s)G_{21}(s)}{1 + c_1(s)G_{11}(s) + c_1(s)c_2(s)G_{21}(s)} = \frac{\Delta \omega}{\Delta V_{ref}} \quad \text{.............. (18)}$$

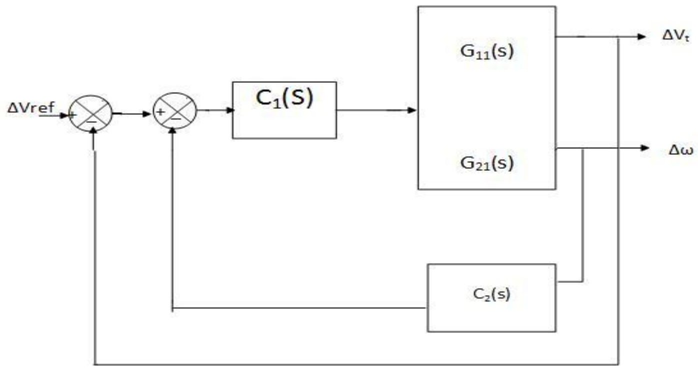

Fig.3 *closed loop of the system with controllers*

Now two model functions $M_{11}(s)$ and $M_{21}(s)$ which indicates the desired performance of closed loop transfer functions are taken. The control law is defined as:

$$G_{11C}(s) = M_{11}(s) \quad \text{.......... (19)}$$

$$G_{21C}(s) = M_{21}(s) \quad \text{......... (20)}$$

From equations (17) and (19) we can write

$$\frac{\dfrac{c_{1N}(s)G_{11N}(s)}{c_{1D}(s)G_{11D}(s)}}{1 + \dfrac{c_{1N}(s)G_{11N}(s)}{c_{1D}(s)G_{11D}(s)} + \dfrac{c_{1N}(s)c_{2N}(s)G_{21N}(s)}{c_{1D}(s)c_{2D}(s)G_{21D}(s)}} = \frac{M_{11N}(s)}{M_{11D}(s)} \quad \text{............. (21)}$$

And from equations (18) and (20) we can write

$$\frac{\dfrac{c_{1N}(s)G_{21N}(s)}{c_{1D}(s)G_{21D}(s)}}{1 + \dfrac{c_{1N}(s)G_{11N}(s)}{c_{1D}(s)G_{11D}(s)} + \dfrac{c_{1N}(s)c_{2N}(s)G_{21N}(s)}{c_{1D}(s)c_{2D}(s)G_{21D}(s)}} = \frac{M_{21N}(s)}{M_{21D}(s)} \quad \text{............. (22)}$$

Where
c_{1N} (s) and c_{1D}(s) are numerator and denominator of c_1(s).
c_{2N} (s) and c_{2D}(s) are numerator and denominator of c_2(s).
G_{11N}(s) and G_{11D}(s) are numerator and denominator of G_{11}(s).
G_{21N}(s) and G_{21D}(s) are numerator and denominator of G_{21}(s).
M_{11N}(s) and M_{11D}(s) are numerator and denominator of M_{11}(s).
M_{21N}(s) and M_{21D}(s) are numerator and denominator of M_{21}(s)

Also $G_{11D}(s) = G_{21D}(s) = G_D(s)$
$M_{11D}(s) = M_{21D}(s) = M_D(s)$

The numerator of model function M_{11N}(s) is taken as c_{1N}(s) c_{2D}(s) G_{11N}(s) and M_{21N}(s) is taken as $c_{1N}(s)c_{2D}(s)G_{21N}(s)$.From these approximations the equations(21) and (22) are reduced to a single equation

$$M_D(s) = c_{1D}(s)c_{2D}(s)G_D(s) + c_{1N}(s)G_{1N}(s) + c_{1N}(s)c_{2N}(s)G_{21N}(s) \quad \text{........... (23)}$$

M_D is taken as 13^{th} order function. For the exact model matching the orders on both sides of equation (23) should be same. Hence the controller transfer functions are of the form:

$$c_1(s) = \frac{c_{1N}(s)}{c_{1D}(s)} = \frac{s}{s^6 + a_1 s^5 + b_1 s^4 + c_1 s^3 + d_1 s^2 + e_1 s + f_1} \quad \text{............... (24)}$$

$$c_2(s) = \frac{c_{2N}(s)}{c_{2D}(s)} = (a_2 s^6 + b_2 s^5 + c_2 s^4 + d_2 s^3 + e_2 s^2 + f_2 s + g_2) \quad \text{............(25)}$$

c_{1N}(s) ,c_{1D}(s) from (24) and c_{2N}(s),c_{2D}(s) from (25)are placed in the equation (23) .The equations then obtained are solved by equating the equal powers of 's' on both sides of the equation (23).Thus the controller transfer functions are obtained. The controller transfer functions c_1(s) and c_2(s) are then placed in equations (21) and (22) to obtain the closed loop response of ΔV_t and $\Delta\omega$ for a step disturbance in ΔV_{ref}. The responses are shown in Fig6 and Fig7.From Fig6 and Fig7 we can observe that the closed loop response G_{11c}(s) and G_{21c}(s) are exactly matching desired responses M_{11}(s) and M_{21}(s).

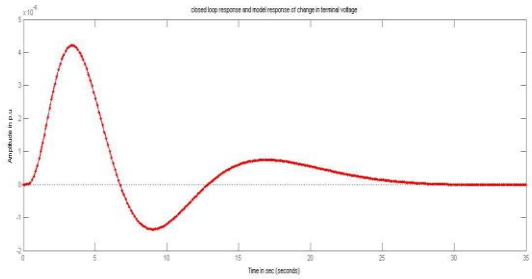

Fig 6 *closed loop response and model response of* ΔV_t

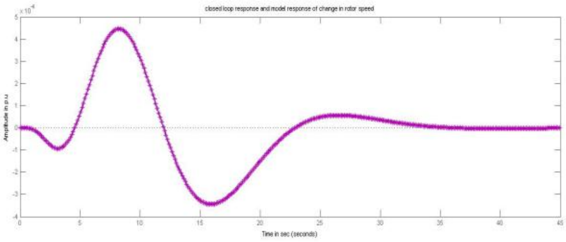

Fig 7 *closed loop response and model response of* $\Delta\omega$

VI. CONCLUSION

This paper has presented a systematic approach for assessment and enhancement of small signal stability of DG based distribution system. The critical oscillatory modes in the system are identified with the help of Eigen values. The open loop response of the change in terminal voltage and deviation in rotor speed of DG unit for a disturbance in the field circuit is assessed. The desired models M11(s) and M_{21}(s) are chosen by providing sufficient damping to the Eigen values of models. Finally the controllers c_1(s) and c_2(s) are designed using exact model matching to ensure that the closed loop response of ΔV_t and $\Delta\omega$ for a disturbance in ΔV_{ref} is having oscillatory stability and also ensured that they match the model functions M_{11}(s) and M_{21}(s).The controller transfer functions obtained are of higher orders i.e. sixth order. Physical implementation of such higher order controllers is a difficult task. The desired response can be obtained with lower order controllers also. But in that case the orders of closed loop transfer function and model fiction may or may not equal. Also the closed loop response will approximately follow desired response. Using optimization techniques we can design the controllers such that the error between actual and desired response will be minimum. That is called approximate model matching which will be the future work.

APPENDIX

POWER SYSTEM PARAMETERS

The parameters used for the SMIB system are given below:

Synchronous generator parameters:

X_d= 2.1, X'_d= 0.4, H = 3.5*s*, T'_{do}= 8, D = 4.

Automatic Voltage Regulator (AVR) Parameters:

K_A = 50, T_r = 0.1.

Transformer Parameter:

X_T = 0.016.

Transmission Line Parameters:

X_e = 0.027.

Infinite bus:

V_{inf} = 1.0

Induction motor parameters:

Rs = 0, X_s= 0.1, X_r= 0.18, R_r= 0.18, X_m = 3.2, H_m = 1.5*s*.

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