Optimised Controllers for Excitation system of Conventional Power System and Wind Turbines to mitigate small signal and transient stability

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Abstract—The objective of this paper is to show the effect of proper design of controllers parameters on transient and small signal stability of the power system, and to model dynamics of various Distributed Generation (DG) technologies or Distributed Energy Resources (DER) for power system stability analysis issues. These models are studied in transient and small signal stability of power system; thus differential and algebraic equations of various DGs and conventional synchronous generators are formulated together with dynamics of other elements, such as exciters and so on. Two types of Wind turbines (WT) used, (1) Doubly Fed Induction Generator (DFIG) (2) constant speed wind turbine (CSWT). These models are used to investigate the effects of optimization of controllers on small signal and transient stability of the power system. The results are applied for stability studies of a power system i.e. Modified IEEE 14 bus test system to demonstrate a typical application. Results shows that there is an appropriate impact on stability control of the power system with optimization of controllers for excitation system of conventional power system, and also wind turbine integrated to system in the typical power system.

Key-Words: Doubly fed induction generator Wind Turbines, Constant speed Wind turbines, Dynamic Algebraic Equations, Exciter, small signal stability, transient stability.

1 Introduction

Nowadays renewable energies are more common to use instead of fossil fuels power generation systems . In this way Distributed generations (DGs) commonly implemented as a green energy and renewable energies and are developing fast. With the increase on level of wind energy the need for appropriate controllers and proper optimisation of controller's are necessary, although control of primary frequency with turbine governer , and other controllers like exciter controllers and power system stabilizer is done in recent power system, there is a need to their optimization. This paper shows that appropriate controller parameters can change system behaviour, and increase or decrease its oscillations in transients studies. The work in this paper is base on small signal and transient stability studies. First, small signal stability is investigated on power system and its eigenvalues derived, and the eigenvalues that are changeable with optimisation of controllers are find, then their participation factor and most associated eigenvalues took under consideration that mostly have affect which poles or eigenvalues of the system. Then with respect to root locus and small signal stability , the transient stability is investigated for the states variables of the system that mostly affected as we can see this in their oscillations by changing the value of controllers and find their optimal one. There are some works in the literature about this issue which are investigated in this paper [1-8], but they didn't consider the effect of each controller in the system on oscillations and enhancement of small signal stability of power system. The authors in [1], addresses the low frequency relative stability problem in paralleled inverter-based distributed generation (DG) units in microgrids. In the sense of the small-signal dynamics of a microgrid, it can be shown that as the demanded power of each inverter changes, the low frequency modes of the power sharing dynamics drift to new locations and the relatively stability is remarkably affected. The authors in [2], proposed a novel method using particle swarm optimisation for optimising parameters of controllers of a wind turbine (WT) with doubly fed induction generator (DFIG). The authors in [3], presented a systematic approach to small signal modelling of a microgrid system that includes conventional and electrically interfaced distributed resources (DR) units. The authors in [4] presented fundamental concepts of a central power management system and a decentralized, robust control strategy for autonomous mode of operation of a microgrid that includes multiple distributed energy resource (DER) units. The authors in [5] presented a new family of comprehensive control and management strategies for microgrids in smart distribution grids. The author in [6], proposed a study of small signal behaviour of power systems including wind generation units and energy capacitor systems. The author in [7], presents a robust hierarchical control system of distributed generation converters for robust microgrid operation and seamless transfer between grid-connected and isolated modes.

2 System Dynamic Modelling

A. Wind Energy system Modeling:

A1) Constant speed Wind Turbine (CSWT): The simplified electrical circuit used for the squirrel cage induction generator is the same as the one for the single-cage induction motor. The equations are formulated in terms of the real (r) and imaginary (m) axis, with respect to the network reference angle. In a synchronously rotating reference, the link between the network and the stator machine voltages is as follows,

$$v_r = V sin(-\theta) \tag{1}$$
$$v_m = V cos(\theta) \tag{2}$$

And the power absorptions are,

$$P = v_r i_r + v_m i_m \tag{3}$$
$$Q = v_m i_r - v_r i_m + b_c(v_r^2 + v_m^2) \tag{4}$$

Where b_c is the fixed capacitor conductance which is determined at the initialization step. The differential equation in terms of the voltage behind the stator resistance r_s are,

$$e_r^{'} - v_r = r_S\, i_r - x^{'} i_m \tag{5}$$
$$e_m^{'} - v_m = r_S\, i_m - x^{'} i_r \tag{6}$$

Whereas the link between voltages, currents and state variables is as follows,

$$\dot{e}_r^{'} = \Omega_b(1-\omega_m)e_m^{'} - (e_r^{'} - (x_0 - x^{'})i_m)/T_0^{'} \tag{7}$$
$$\dot{e}_m^{'} = -\Omega_b(1-\omega_m)e_r^{'} - (e_m^{'} - (x_0 - x^{'})i_r)/T_0^{'} \tag{8}$$

Where x_0, x' and T_0 can be obtained from the generator parameters,

$$x_0 = x_S + x_m \tag{9}$$
$$x^{'} = x_S + \frac{x_R x_m}{x_R + x_m} \tag{10}$$
$$T'_0 = \frac{x_R + x_m}{\Omega_b r_R} \tag{11}$$

The mechanical differential equation which take into account the turbine and rotor inertias H_{wr} and H_m, respectively, and shaft stiffness K_s are as follows,

$$\dot{\omega}_{wr} = (T_{wr} - K_s\gamma)/(2H_{wr}) \tag{12}$$
$$\dot{\omega}_m = (K_s\gamma - T_e)/(2H_m) \tag{13}$$
$$\dot{\gamma} = \Omega_b(\omega_{wr} - \omega_m \tag{14}$$

Where the electrical torque(T_e) *is*,

$$T_e = e'_r i_r + e'_m i_m \tag{15}$$

The mechanical torque is,

$$T_{wr} = \frac{P_w}{\omega_{wr}} \tag{16}$$

Being P_w the mechanical power extracted from the wind. The latter is a function of both the wind and the rotor sppeds and can be approximated as follows,

$$P_w = \frac{\rho}{2} c_p(\lambda) A_r v_w^3 \tag{17}$$

In which ρ is the air density, c_p the performance coefficient or power coefficient, λ the tip speed ratio and A_r the area swept by the rotor. The speed tip ratio λ is the ratio between the blade tip speed v_t and the wind upstream the rotor v_w,

$$\lambda = \frac{v_t}{v_w} = \eta_{GB} \frac{2R\omega_{wr}}{p v_w} \tag{18}$$

Where η_{GB} is the gear box ratio, p the number of poles of the induction generator and R the rotor radius. Finally, the $c_p(\lambda)$ curve is approximated as follows,

$$c_p = 0.44\left(\frac{125}{\lambda_i} - 6.94\right)e^{-\frac{16.5}{\lambda_i}}$$

(19)

$$\lambda_i = \frac{1}{\frac{1}{\lambda} + 0.002} \tag{20}$$

A2) Doubly Fed Induction Generator (DFIG):

This section describes the dynamic modeling of variable speed wind turbine with doubly-fed (DFIG) induction generator as implemented in current study. These kind of generators are widely use nowadays. As the stator and rotor flux dynamics are fast comparing with grid dynamics, also the converter controls basically decouple the generator from the grid, as a result of these assumption, one has,

$$v_{ds} = -r_s i_{ds} + (x_s + x_m)i_{qs} + x_m i_{qr} \tag{21}$$
$$v_{qs} = -r_s i_{qs} - (x_s + x_m)i_{ds} - x_m i_{dr} \tag{22}$$
$$v_{dr} = -r_R i_{dr} + (1-\omega_m)((x_R + x_m)i_{qr} + x_m i_{qs} \tag{23}$$
$$v_{qr} = -r_R i_{qr} - (1-\omega_m)(x_R + x_m)i_{dr} + x_m i_{ds} \tag{24}$$

In which the stator voltages are functions of the grid voltage magnitude and phase,

$$v_{ds} = V sin(-\theta) \tag{25}$$
$$v_{qs} = V cos(\theta) \tag{26}$$

The active and reactive powers injected into the grid depend on the stator current, and the grid side current of the converter, as follows:

$$P = v_{ds} i_{ds} + v_{qs} i_{qs} + v_{dc} i_{dc} + v_{qc} i_{qc} \tag{27}$$
$$Q = v_{qs} i_{ds} - v_{ds} i_{qs} + v_{qc} i_{dc} - v_{dc} i_{qc} \tag{28}$$

Which can be written considering the converter power equation, as discussed below. Firstly the converter powers on the grid side are,

$$P_c = v_{dc} i_{dc} + v_{qc} i_{qc} \tag{29}$$

$$Q_c = v_{qc}i_{dc} - v_{dc}i_{qc} \quad (30)$$

Whereas, on the rotor side:

$$P_r = v_{dr}i_{dr} + v_{qr}i_{qr} \quad (31)$$

$$Q_r = v_{qr}i_{dr} - v_{dr}i_{qr} \quad (32)$$

Secondly, assuming a lossless converter model and a unity power factor on the grid side of converter leads to,

$$P_c = P_r \quad (33)$$

$$Q_c = 0 \quad (34)$$

Therefore the active power injected in the grid result,

$$P = v_{ds}i_{ds} + v_{qs}i_{qs} + v_{dr}i_{dr} + v_{qr}i_{qr} \quad (35)$$

The reactive power injected into grid can be approximated neglecting stator resistant and assuming that d-axis coincide with the maximum stator flux,

$$Q = v_{qs}i_{ds} - v_{ds}i_{qs} \quad (36)$$

The generator motion equation is modeled as a single shaft, as it assumed that the converter controls are able to alter shaft dynamics. For the same reason no tower shadow effect is considered in this model. Thus one has,

$$\dot{\omega}_m = (T_m - T_e)/2H_m \quad (37)$$

$$T_e = \psi_{ds}i_{qs} - \psi_{qs}i_{ds} \quad (38)$$

The link between stator fluxes and generator current is as follows,

$$\psi_{ds} = -((x_s + x_m)i_{ds} + x_m i_{dr}) \quad (39)$$

$$\psi_{qs} = -((x_s + x_m)i_{qs} + x_m i_{qr}) \quad (40)$$

Thus the electrical torque T_e, results,

$$T_e = x_m(i_{qr}i_{ds} - i_{dr}i_{qs}) \quad (41)$$

The mechanical torque is,

$$T_m = \frac{P_w}{\omega_m} \quad (42)$$

Being P_w the mechanical power extracted from the wind. The latter is a function of the wind speed v_w, the rotor speed ω_m and the pitch angle θ_p, the mechanical power P_w can be approximated as follows,

$$P_w = \frac{\rho}{2}C_p(\lambda,\theta_p).A_r.v_w^3 \quad (43)$$

The $C_p(\lambda,\theta_p)$ is coefficient of power approximated as,

$$C_p = 0.22\left(\frac{116}{\lambda_i} - 0.4\theta_p - 5\right)e^{-\frac{12.5}{\lambda_i}}$$

(44)

λ, is tip speed ration, which,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta_p} - \frac{0.035}{\theta_p^3 + 1} \quad (45)$$

Converter dynamics are highly simplified, as they are fast respect to the electromechanical transients. Thus the converter is modeled as an ideal current source, where i_{qr} and i_{dr} are state variables and are used for the rotor speed control, and the voltage control respectively.

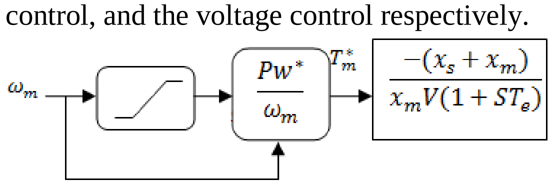


Fig. (1) Rotor speed control loop

Differential equation for the converter current are as follows,

$$p(i_{qr}) = \left(-\frac{x_s + x_m}{x_m.V}\frac{P_w^*(\omega_m)}{\omega_m} - i_{qr}\right)\frac{1}{T_e} \quad (46)$$

$$p(i_{dr}) = K_v(V - V_{ref}) - \frac{V}{x_m} - i_{dr} \quad (47)$$

Where $P_w^*(\omega_m)$ is the power-speed characteristic which roughly optimizes the wind energy capture and is calculated using the current rotor speed value (see figure [3]).

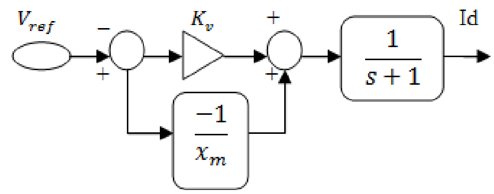


Fig (2): Voltage control loop

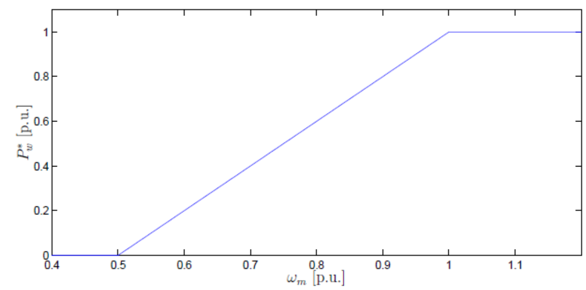


Figure (3): Power-speed characteristics

It is assumed that $P_w^* = 0$, if $\omega_m < 0.5 p.u.$, and that $P_w^* = 1$

If $\omega_m > 1(p.u)$. Thus the rotor speed control only has effect on sub-synchronous speeds. Both the speed and voltage control loops undergo anti-windup limiters to avoid converter over-current. Current limits are approximated as,

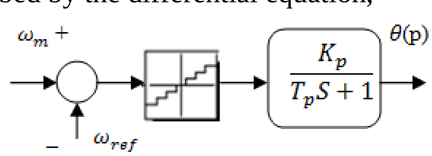
$$i_{qr,max} = -\frac{x_s + x_m}{x_m}P_{min} \quad (48)$$

$$i_{qr,min} = -\frac{x_s + x_m}{x_m}P_{max} \quad (49)$$

$$i_{dr,max} = -\frac{x_s + x_m}{x_m}Q_{min} - \frac{1}{x_m} \quad (50)$$

$$i_{dr,min} = -\frac{x_s + x_m}{x_m}Q_{min} - \frac{1}{x_m} \quad (51)$$

Finally the pitch angle control is illustrated in figure (4) and described by the differential equation,



Figure(4): pitch angle control loop

B. Synchronous generator

For synchronous generator model, the sixth order is obtained assuming the presence of a field circuit and an additional circuit along the d-axis and two additional circuits along the q-axis. The system has six state variables $(\delta, \omega, e'_d, e'_q, e''_q, e''_d)$, and the following equations,

$$p(\delta) = \Omega_b(\omega - 1) \quad (52)$$
$$p(\omega) = (P_m - P_e - D(\omega - 1))/M \quad (53)$$
$$p(e'_q) = -e'_q - \left(x_d - x'_d - \frac{T''_{d0}x''_d}{T'_{d0}x'_d}(x_d - x'_d)\right) i_d + (1 - \frac{T_{AA}}{T'_{d0}})v_f)/T'_{d0} \quad (54)$$
$$p(e'_d) = -e'_d + \left(x_q - x'_q - \frac{T''_{q0}x''_q}{T'_{q0}x'_q}(x_q - x'_q)\right) \frac{i_q}{T'_{q0}} \quad (55)$$
$$P(e''_q) = -e''_q + e'_q - \left(x'_d - x''_d + \frac{T''_{d0}x''_d}{T'_{d0}x'_d}(x_d - x'_d)\right) i_d + \frac{T_{AA}}{T'_{do}}v_f)/T''_{do} \quad (56)$$
$$p(e''_d) = -e''_d + e'_d + \left(x'_q - x''_q + \frac{T''_{qo}x''_q}{T'_{q0}x'_q}(x_q - x'_q)\right) i_q)/T''_{q0} \quad (57)$$

Where the electrical power (P_e) is defined as follows:

$$P_e = (v_q + r_a i_q)i_q + (v_d + r_a i_d)i_d \quad (58)$$

The algebraic constraints are as follows,

$$0 = v_q + r_a i_q - e''_q + (x''_d - x_l)i_d \quad (59)$$
$$0 = v_d + r_a i_d - e''_d - (x''_q - x_l)i_q \quad (60)$$

The wind speed is assumed as an input to wind turbine, and is assumed as following figure,

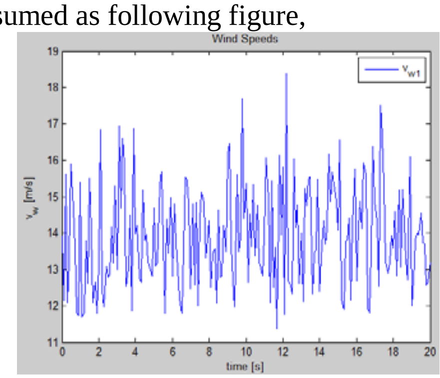


Figure (5): wind speed

C. Excitation system

The basic function of an excitation system is to provide direct current to the synchronous machine field winding. In addition, the excitation system performs control and protective function essential to the satisfactory performance of the power system by controlling the field voltage and thereby the field current. The control functions include the control of voltage and reactive power flow, and the enhancement of system stability. The performance requirements of the excitation system are determined by considerations of the synchronous generator as well as the power system. The basic requirement is that the excitation system supply and automatically adjust the field current of the synchronous generator to maintain the terminal voltage as the output varies within the continuous capability of the generator. This requirement can be visualized from the generator V-curve. In addition, the excitation system must be able to respond to transient disturbances with field forcing consistent with the generator instantaneous and short-term capabilities. The generator capabilities in this regard are limited by several factors: rotor insulation failure due to high field voltage, rotor heating due to high field current, and stator heating due to high armature current loading. From the power system viewpoint, the excitation system should contribute to effective control of voltage and enhancement of system stability. It should be capable of responding rapidly to a disturbance so as to enhance transient stability, and of modulating the generator field so as to enhance small signal stability. Historically, the role of the excitation system in enhancing power system performance has been growing continually. Early excitation systems were controlled manually to maintain the desired generator terminal voltage and reactive power loading.

Mathematical models of excitation system are essential for the assessment of desired performance requirement, for the design and coordination of supplementary control and protective circuits, and for system stability studies related to the planning and operation of power system. The detail of the model required depends on the purpose of the study. The control and protective features that impact on transient and small signal stability studies are the voltage regulator, power system stabilizer, and excitation control stabilization. Some excitation systems are provided with fast-acting terminal voltage limiters in conjunction with power system stabilizers; these have to be modelled in transient stability simulations. In this part modelling of excitation system is described.

The exciter and AVR model is as below,

$$\dot{v}_m = (V - v_m)/T_r \quad (61)$$
$$\dot{v}_{r1} = (K_a\left(v_{ref} - v_m - v_{r2} - \frac{K_f}{T_f}v_f\right) - v_{r1})/T_a \quad (62)$$
$$v_r = \begin{cases} v_{r1} & if\ v_{r,min} \le v_{r1} \le v_{r,max} \\ v_{r,max} & if\ v_{r1} > v_{r,max} \\ v_{r,min} & if\ v_{r1} < v_{r,min} \end{cases} \quad (63)$$
$$\dot{v}_{r2} = -(\frac{K_f}{T_f}v_f + v_{r2})/T_f \quad (64)$$
$$\dot{v}_f = -(v_f\left(1 + S_e(v_f)\right) - v_r)/T_e \quad (65)$$

Where $S_e(v_f)$ is ceiling function as below,

$$S_e(v_f) = A_e(e^{B_e|v_f|} - 1) \quad (66)$$

3 Small Signal Stability

Small signal stability is the ability of power system to maintain synchronism when subjected to small disturbances. In this context, a disturbance is considered to be small if the equation that describe the resulting response of the system may be linearizes for the propose of analysis. Instability that may result can be of two forms: (1) steady increase in generator rotor angle due to lack of synchronizing torque, or (ii) rotor oscillations of increasing amplitude due to lack of sufficient damping torque. In today's practical power systems, the small signal stability problem is usually one of insufficient damping of system oscillations. Small signal analysis using linear techniques provides valuable information about the inherent dynamic characteristics of the power system and assist in its design. The system used for the small signal stability analysis is set of differential algebraic equations, in the form,

$$\dot{x} = f(x, y) \quad (67)$$

$$0 = g(x.y) \quad (68)$$

Where x is the vector of the state variables and y the vector of algebraic variables, f is the vector of the differential equation, and g is the vector of algebraic equations. Small signal stability analysis studies the properties of equilibrium or stationary points (x_0, y_0) that satisfies,

$$0 = f(x_0, y_0) \quad (69)$$

$$0 = g(x_0, y_0) \quad (70)$$

Through an eigenvalue analysis of the state matrix A_s of the system.

The state matrix, A_s is obtained by manipulating the complete jacobian matrix A_c , that is defined by the linearization of the DAE system equations at the equilibrium point,

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} f_x & f_y \\ g_x & g_y \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = A_C \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \quad (71)$$

The state matrix A_s is obtained by eliminating the algebraic variables and, thus, it is implicitly assumed that g_y is not singular (i.e. absence of singularity-induced bifurcation),

$$A_S = f_x - f_y g_y^{-1} g_x \quad (72)$$

It is now recognized that the singularity of g_y at an equilibrium point is a folding of the manifold of algebraic variables. This is not actually a stability issue, but rather a modeling one. If g_y is singular at a given equilibrium, then the dynamic of some of the algebraic variables y_h cannot be considered infinitely fast (e.g., its time constant cannot be considered zero).

The stability of the system is determine by the eigenvalues as follows,

(a) A real eigenvalue corresponds to a non oscillatory mode. A negative real eigenvalue represents a decaying mode. The larger its magnitude, the faster the decay. A positive real eigenvalue represent a periodic instability.

(b) Complex eigenvalues occur in conjugate pairs, and each pair corresponds to an oscillatory mode. The real component of the eigenvalues gives the damping, and the imaginary component gives the frequency of oscillation. A negative real part represents a damped oscillation whereas a positive real part represents oscillation of increasing amplitude. Thus for a complex pair of eigenvalues,

$$\lambda = \sigma \pm j\omega \quad (73)$$

The frequency of oscillation in Hz is given by,

$$f = \frac{\omega}{2\pi} \quad (74)$$

The objective function and optimisation criteria is that the real part of oscillatory modes related to excitation system and wind turbine should be far from imaginary axis (maximized) in negative part of root locus figure as small signal enhancement, and their imaginary part should be minimized, as a result of damping oscillation and transient stability of power system under study. Therefore we should have,

$$Maximize \qquad Real(\lambda) = \sigma \quad (75)$$

$$Minimize \qquad Imag(\lambda) = \omega \quad (76)$$

$$Subjected\ to \qquad a(i) < x(i) < b(i) \ \ (system\ limits)$$

The constraints in above optimisation are system limits such as limits on voltage , reactive power, etc.

4 Transient Stability

Transient stability is the ability of power system to maintain synchronism when subjected to a severe transient disturbance such as a fault on transmission facilities, loss of generation, or loss of a large load. The system response to such disturbance involves large excursion of generator rotor angle, power flow, bus voltages, and other system variables. Stability is influence by the nonlinear characteristics of the power system. If the resulting angular separation between the machines in the system remains within certain bounds, the system maintains synchronism. Loss of synchronism because of transient instability, if it occurs, will usually be evident within 2 to 3 seconds of the initial disturbance. The eigenvalues of system are as Table (1).

5 Simulation Results

The simulation results are in two parts, firstly the effect of controller optimisation on exciter of the power system is investigated. The system in this part assumed that have two types of wind turbines namely, doubly fed induction generator (DFIG), Constant Speed Wind Turbines (CSWT), on bus no. 2. The second part of simulation results are assumed that all two types of wind energy systems are integrated in bus no. 1 of the test system in Figure(6). In this part wind turbines are constant speed wind turbine (CSWT), doubly fed induction generator (DFIG), which are two types of wind power commonly used in practice today. The controllers of these two types of generation systems optimised then to get the best result to small signal stability enhancement and transient stability enhancement.

Table (1): eigenvalues of the test case

Eigevalue	Most Associated States	Real part	Imag. Part	Frequency
Eigenvalue 1	vm_Exc_3	-1000	0	0
Eigenvalue 2	vm_Exc_4	-1000	0	0
Eigenvalue 3	vm_Exc_2	-1000	0	0
Eigenvalue 4	vm_Exc_1	-1000	0	0
Eigenvalue 5	iqr_Dfig_1	-101.3386	0	0
Eigenvalue 6	vr1_Exc_1	-49.9605	0	0
Eigenvalue 7	vr1_Exc_2	-49.9379	0	0
Eigenvalue 8	vr1_Exc_3	-49.8541	0	0
Eigenvalue 9	vr1_Exc_4	-49.8846	0	0
Eigenvalue10	e1r_Cswt_1, omega_m_Cswt_1	-7.7745	28.1713	4.6512
Eigenvalue11	e1r_Cswt_1, omega_m_Cswt_1	-7.7745	-28.1713	4.6512
Eigenvalue12	e2q_Syn_2	-33.7544	0	0
Eigenvalue13	e2q_Syn_1	-31.1083	0	0
Eigenvalue14	e2q_Syn_4	-27.937	0	0
Eigenvalue15	e2q_Syn_3	-24.6696	0	0
Eigenvalue16	e2d_Syn_2, e2d_Syn_1	-16.255	1.7107	2.6013
Eigenvalue17	e2d_Syn_2, e2d_Syn_1	-16.255	-1.7107	2.6013
Eigenvalue18	e2d_Syn_1	-15.5494	0	0
Eigenvalue19	e2d_Syn_3	-13.5868	0	0
Eigenvalue20	omega_Syn_4, delta_Syn_4	-3.9589	10.8428	1.8371
Eigenvalue21	omega_Syn_4, delta_Syn_4	-3.9589	-10.8428	1.8371
Eigenvalue22	omega_Syn_2, delta_Syn_2	-1.2113	10.5027	1.6826
Eigenvalue23	omega_Syn_2, delta_Syn_2	-1.2113	-10.5027	1.6826
Eigenvalue24	omega_Syn_3, delta_Syn_3	-2.8197	9.0389	1.507
Eigenvalue25	omega_Syn_3, delta_Syn_3	-2.8197	-9.0389	1.507
Eigenvalue26	e2d_Syn_3	-10.4495	0	0
Eigenvalue27	omega_Syn_1, delta_Syn_1	-0.59023	6.4074	1.0241
Eigenvalue28	omega_Syn_1, delta_Syn_1	-0.59023	-6.4074	1.0241
Eigenvalue29	e1d_Syn_2	-8.6385	0	0
Eigenvalue30	e1d_Syn_1	-6.9792	0	0
Eigenvalue31	e1r_Cswt_1, e1m_Cswt_1	-1.2323	3.8721	0.64671
Eigenvalue32	e1r_Cswt_1, e1m_Cswt_1	-1.2323	-3.8721	0.64671
Eigenvalue33	e1m_Cswt_1, idr_Dfig_1	-0.31796	2.4263	0.38946
Eigenvalue34	e1m_Cswt_1, idr_Dfig_1	-0.31796	-2.4263	0.38946
Eigenvalue35	e1q_Syn_3, vf_Exc_3	-1.1593	1.5409	0.3069
Eigenvalue36	e1q_Syn_3, vf_Exc_3	-1.1593	-1.5409	0.3069
Eigenvalue37	idr_Dfig_1, e1q_Syn_2	-1.7563	1.027	0.32381
Eigenvalue38	idr_Dfig_1, e1q_Syn_2	-1.7563	-1.027	0.32381
Eigenvalue39	e1q_Syn_2, idr_Dfig_1	-0.93047	1.1056	0.22998
Eigenvalue40	e1q_Syn_2, idr_Dfig_1	-0.93047	-1.1056	0.22998
Eigenvalue41	tg3_Tg_1	-0.01674	0	0
Eigenvalue42	omega_m_Dfig_1	-0.19768	0	0
Eigenvalue43	e1q_Syn_2, vf_Exc_1	-0.71274	0.65338	0.15389
Eigenvalue44	e1q_Syn_2, vf_Exc_1	-0.71274	-0.65338	0.15389
Eigenvalue45	omega_m_Dfig_1	-0.75761	0	0
Eigenvalue46	e1d_Syn_3	-0.89904	0	0
Eigenvalue47	e1d_Syn_4	-0.93743	0	0
Eigenvalue48	vr2_Exc_1	-1.007	0	0
Eigenvalue49	vr2_Exc_4	-1.0003	0	0
Eigenvalue50	vr2_Exc_1	-1.0037	0	0
Eigenvalue51	vr2_Exc_3	-1.0026	0	0
Eigenvalue52	vw_Wind_1	-0.25	0	0
Eigenvalue53	vw_Wind_2	-0.25	0	0
Eigenvalue54	theta_p_Dfig_1	-0.33333	0	0

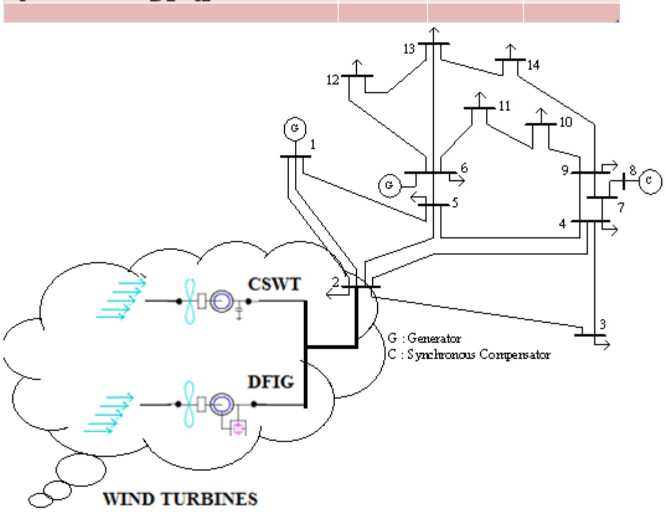
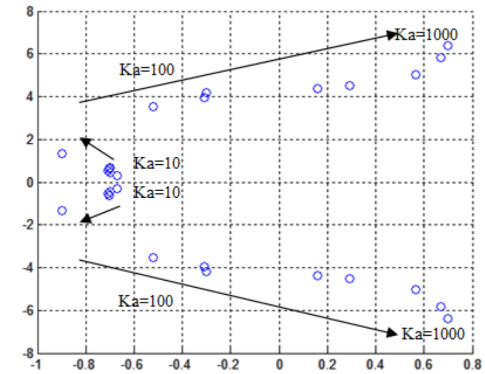


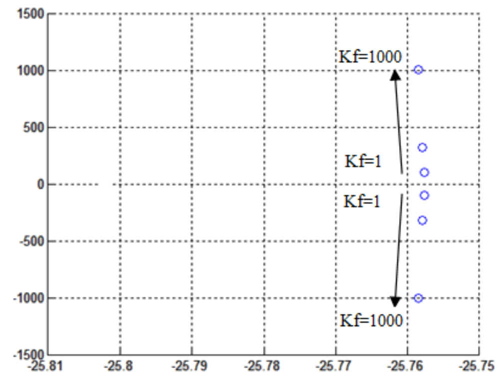
Figure (6): Modified IEEE 14 bus test case, wind turbines are on bus (2)

Part I) The results below is for optimisation of excitation system of synchronous generator on bus no. (2), namely ka and kf which are in equation (42) and (44) are optimised considering small signal stability results in loci of figures (7,8).

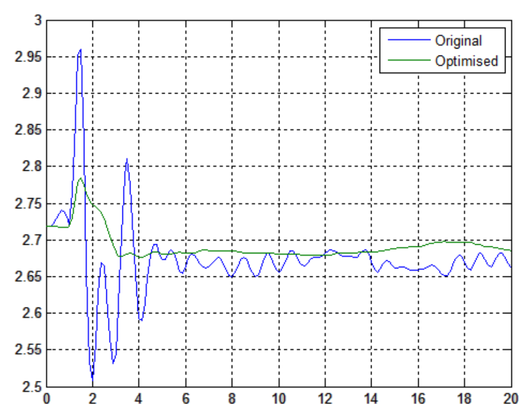
Then transient simulation is done base on these two figures and as one can see the results in figures (9,10) shows that the oscillation in system damped properly as a result of using appropriate controller.



Figure(7): Loci of eigenvalue associated with (Vf-Exciter1, eq1Syn. G.1) when Ka changed from 10 to 1000



Figure(8): Loci of eigenvalue associated with (Vf-Exciter1, Vr1-Exciter1) when Kf changed from 1 to 1000



Figure(9):Vf(Exciter 1) with original controller gain ka=500, and optimised controller gain ka=40

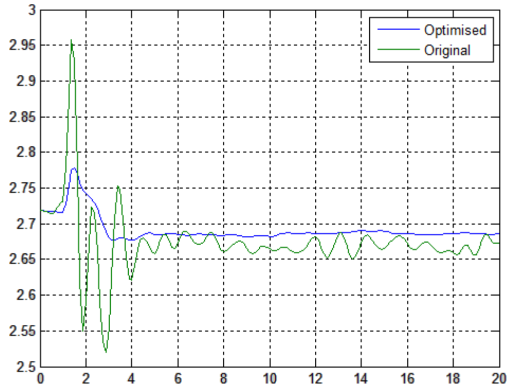
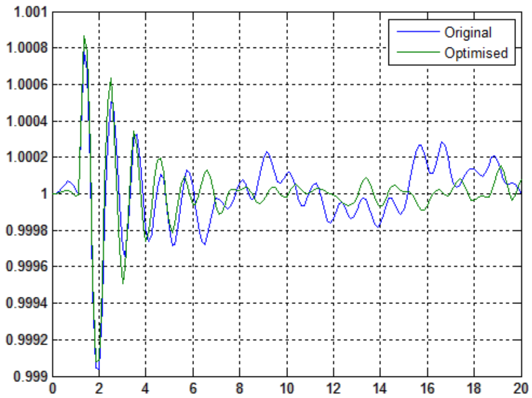
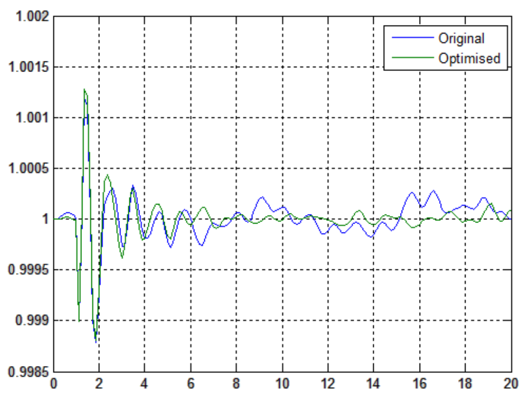


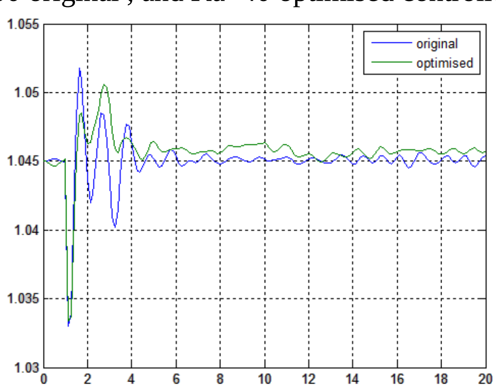
Figure (10): Vf(Exciter1) when Kf=0.01, Ka=500 Original and Ka=40 Optimised controller gain



Figure(11): Speed of Synch. Generator No. 1 when Ka=500 original , and Ka=40 optimised controller gain.



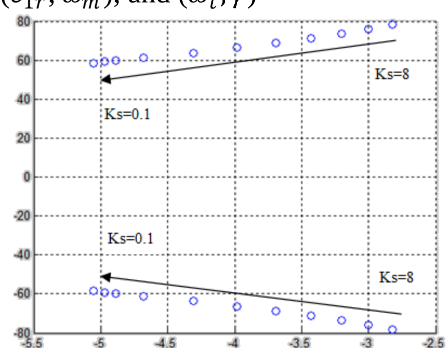
Figure(12): Speed of Synch. Generator No. 3 when Ka=500 original , and Ka=40 optimised controller gain.



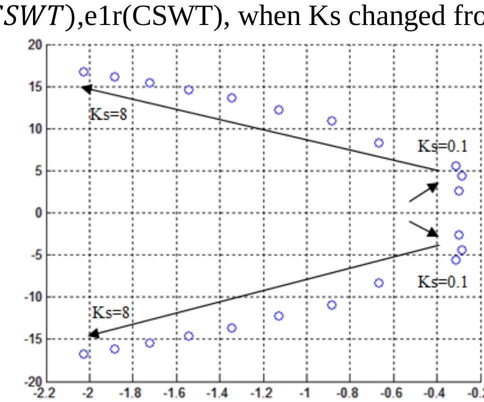
Figure(13): Voltage on bus.2 changes when Ka=500, and Ka=40 original and optimised controller gain.

As shown in figure (7) the location of eigenvalue associate with voltage of exciter is stable and unstable, both by changing in controller gain. Therefore by proper design of controller on exciter is important. Also figure (8) shows that changes in controller gain have effects on imaginary part of eigenvalue of the system. Then we can investigate the changes on waveform to discuss transient stability of the system. According to figure (9-10) the voltage of the exciter is optimised appropriately when using optimisation for its controller. Figures (11-12) shows that there is low effect on speed of generators when changing exciters controllers' gain. But figure (13) also shows that oscillations on voltage of bus 2 which the synchronous generator and exciter is connected , is damped respectively.

Part II) In below simulation results it is assume that breaker on bus 2 opens in t=1 second of simution. The two types of wind turbines are considered connected to bus (2) at the rated values of 200MW for DFIG, 100MW for CSWT, and 69KV and 60 Hz. The optimisation on controllers is of these two types is done to enhance small signal stability of the system. Then figures about transient stability of system shown that the oscillations in system damped appropriately. There are two sections in this part, when k>10 (from k=10 to k=100) the system behavior with two eigenvalues associated with (γ, ω_m) and (ω_t, e_{1r}), but when (k<10 to k=0.1) the system eigenvalues act differently by having two oscillation poles on (e_{1r}, ω_m), and (ω_t, γ)



Figure(14): Loci of eigenvalue associated with $\omega_m(CSWT)$,e1r(CSWT), when Ks changed from 0.1 to



Figure(15): Loci of eigenvalue associated with $\omega_T(CSWT)$,γ (CSWT), when Ks changed from 0.1 to 8.

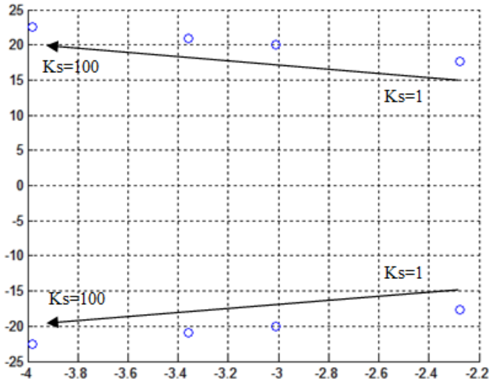


Figure (16): Loci of eigenvalue associated with $\omega_T(CSWT)$, $e_{1r}(CSWT), Ks = 10\ to\ 100$

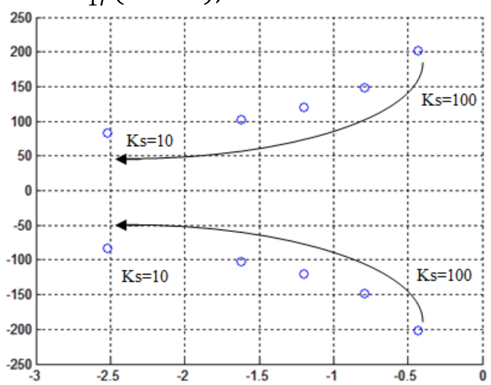
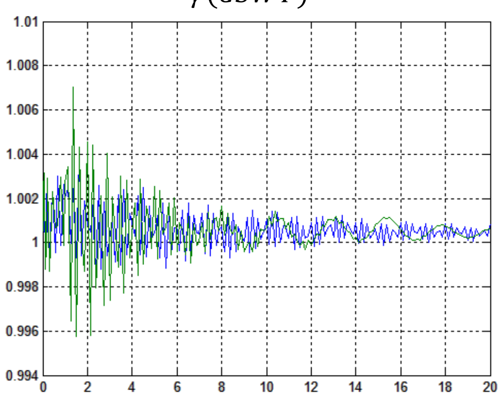
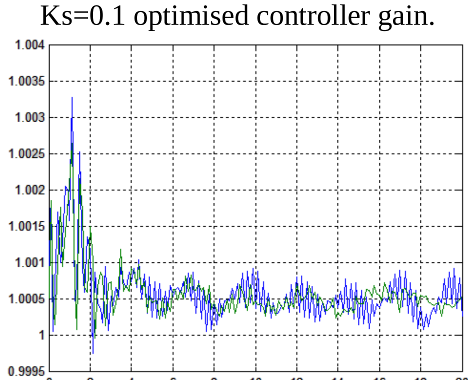


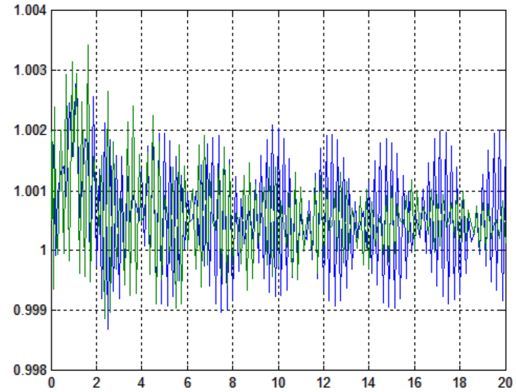
Figure (17): Loci of eigenvalue associated with $\omega_m(CSWT)$, $\gamma(CSWT)$



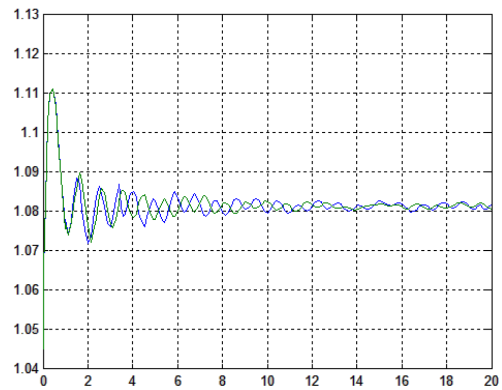
Figure(18): $\omega_m(CSWT)$ when Ks=8 original , and Ks=0.1 optimised controller gain.



Figure(19):$\omega_t(CSWT)$ when Ks=100 original , and Ks=10 optimised controller gain.



Figure(19): $\gamma(CSWT)$ when Ks=100 original , and Ks=10 optimised controller gain.



Figure(19): voltage on bus (2) when Ks=100 original , and Ks=10 optimised controller gain.

6 Conclusion

The dynamic modelling and simulation of the power system is investigated in this paper. In first part of results the gain of controller on one of the exciters of a synchronous generator, took as a variable, and the results of their change investigated in small signal loci of eigenvalues and transient stability of the modified IEEE 14 bus test case, It is shown according to figures that oscillation are damped properly when optimised controller gains for exciter assigned. It is shown that the oscillatory eigenvalue has the main effect on its associated state variable which the result can be damped properly by changing controller gain, but some parameters like speed of generators or bus voltages don't show any change with optimisation of controllers parameters. The second part results, are related to the modified IEEE 14 bus system with two types of wind turbines, i.e. DFIG, and CSWT, connected to bus (2) of the system. This system is relatively highly complicated with more than 50 state variables. Results shown as eigenvalues loci and their change considering variations in gain parameter in CSWT. It can be seen that with proper optimization of controllers, we can enhance small signal and transient stability of system.

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Appendix (A)
Table (2): System dynamic data

Synchronous Generator (p.u.)	
$X_d = 1.8$	$R_a = 0.0025$
$X'_d = 0.3$	$T'_{d0} = 8\sec$
$X''_d = 0.25$	$T'_{q0} = 0.4\sec$
$X_l = 0.2$	$T''_{d0} = 0.03\sec$
$X_q = 1.7$	$T''_{q0} = 0.05\sec$
$X'_q = 0.55$	$A_{sat} = 0.015$
$X''_q = 0.25$	$B_{sat} = .6$
$H_{G1,G2} = 6.5$	$\psi_{Tl} = 0.9$
$H_{G3,G4} = 6.175$	$K_D = 0$
Wind Generator (p.u.)	
$R_s = 0.01$	$X_s = 0.1$
$R_r = 0.01$	$X_r = 0.08$
$K_p = 10$	$X_m = 3$
$T_p = 3$	$H_m = 3$
$K_v = 10$	$poles = 4$
$Te = 0.1$	$gearbox\ ratio = 1/90$
$P_{\max} = 1$	$blade\ number = 2$
$P\min = 0$	$blade\ length = 123$
$Q_{\max} = 0.7$	$V_{wind-no\min al} = 50\ m/s$
$Q_{\min} = -0.7$	