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Transient Stability Investigations of the Wind-Diesel Hybrid Power Systems

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Abstract

This paper presents automatic reactive power control of the isolated wind-diesel hybrid power systems. The synchronous generator (SG) is used for power generation from diesel and the induction generator (IG) is used for electric power generation from wind turbine. To minimize the gap between reactive power generation and demand, the variable sources of reactive power is used such as static synchronous compensator (STATCOM). The mathematical model of the STATCOM based on reactive power flow equations is developed with the wind-diesel hybrid power system. The examples of the wind-diesel hybrid power systems considered in the paper are multi-wind/single diesel, and single wind/multi- diesel. The study is based on small signal analysis by considering IEEE type-1 excitation system for the synchronous generator. The paper also shows the dynamic performance of the hybrid system for 1% step change in reactive power load without any change in input wind power i. e. constant slip, and for 1% step change in reactive power load with 1% step increase in input wind power i. e. variable slip.

Keywords: *Induction generator, synchronous generator, wind-diesel hybrid power system, STATCOM..*

1. Introduction

There has been a continuous enhancement of power generation from renewable energy sources in recent years. The reasons for renewable energy sources getting more and more popular are that they are clean sources of energy, able to replenished quickly, sustainable, and eco-friendly. The only disadvantage is that they are intermittent in nature. To enhance the capacity and reliability of the power supply of local grids, the renewable energy sources like solar, wind, mini/micro hydro, etc. are integrated with diesel system. This combination of conventional and non-conventional energy sources is called as isolated hybrid power system [1]-[3]. Normally, synchronous generators and induction generators are chosen with diesel generators and wind turbines respectively [3]. Reduction in unit cost, ruggedness, brushless (in squirrel cage construction), absence of separate DC source for excitation, easy maintenance, self protection against severe overloads and short circuits etc, are the main advantages of an IG [4]-[7], but they require reactive power for their operation. Due to the mismatch between generation and consumption of reactive power, more voltage fluctuations at generator terminal occur in an isolated system which reduces the stability and quality of the supply. The problem becomes more complicated in hybrid system having both induction and synchronous generators. Many papers have appeared in the literature, which suggest different methods using fixed capacitors bank for providing the reactive power under steady state conditions [5]. As induction generator reactive power demand varies, the fixed capacitors are unable to provide adequate amount of reactive power support to isolated power system under varying input wind power and load conditions [6]. Various Flexible AC transmission system (FACTS) devices are available which can supply fast and continuous reactive power [9]-[11]. For standalone applications, effective capacitive VAR controller has become central to the success of the induction generator system. Switched capacitors, static VAR compensator (SVC) and static synchronous compensator (STATCOM) can provide the reactive power. A switched capacitor scheme is cheaper, but it regulates the terminal voltage in discrete steps. Large values of capacitors and reactors are required in SVC scheme [9]. STATCOM employs a voltage source converter (VSC) that internally generates inductive/capacitive reactive power which has the advantages over the SVC scheme [9].

The different isolated hybrid power systems considered in the paper are multi-wind/single diesel, and single wind/multi- diesel. Multi-wind/single diesel systems attenuate the effect of power fluctuations produced by the turbulence of the wind. In fact, it is estimated that the variability of the power should decrease by the square root of the number of wind turbines [1]. Thus the need for short-term storage would decrease when the wind generation capacity is made up of more than one machine. Single wind/ multi-diesel systems allow a variety of possible operation and control strategies. Typically the most efficient diesel generators are allowed to run at their rated output. Load fluctuations are supplied by one of the less efficient diesel generators, which are allowed to cycle up and down. Diesel grid of Block Island, USA [1] is such type of an example.

First the system state equations are derived from real and reactive power balance equations of the system. A voltage deviation signal is used by STATCOM controller to eliminate the reactive power mismatch in the system. Also the voltage deviation signal is used by excitation system of the synchronous generator to eliminate the voltage deviation. The integral square error (ISE) criterion is used to evaluate the optimum gain settings of the controller parameters. Finally, the transient responses of the hybrid systems are also shown for IG coupled with wind turbine.

2. Mathematical Modeling of Wind-Diesel Hybrid Power System

A wind-diesel hybrid power system with STATCOM considered for study is shown in Fig.1. The real and reactive power balance equations of the system under steady state conditions are
given by

$$P_{IG} + P_{SG} = P_L \tag{1}$$

$$Q_{SG} + Q_{com} = Q_L + Q_{IG} \tag{2}$$

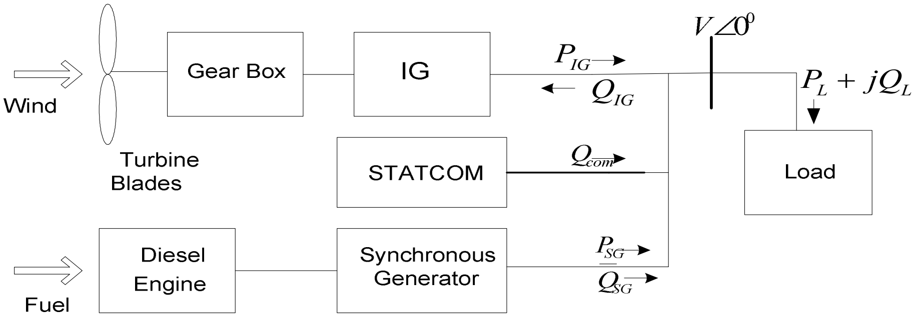


Figure 1. Single Line Diagram of the Wind-Diesel Hybrid Power System

Due to disturbance in load reactive power ΔQ_L, the system voltage may change which results an incremental change in reactive power of other components. The net reactive power surplus is $\Delta Q_{SG} + \Delta Q_{com} - \Delta Q_L - \Delta Q_{IG}$ and it will change the system bus voltage which will govern by the following transfer function equation [8]:

$$\Delta V(s) = \frac{K_V}{1+sT_V}\left[\Delta Q_{SG}(s)+\Delta Q_{com}(s)-\Delta Q_L(s)-\Delta Q_{IG}(s)\right], \tag{3}$$

where, K_V and T_V are the system gain and time constant. All the connected loads experience an increase with the increase in voltage due to load voltage characteristics as shown below

$$D_V = \frac{\partial Q_L}{\partial V} \tag{4}$$

The composite loads can be expressed in exponential voltage form as

$$Q_L = c_1 V^q \tag{5}$$

The load voltage characteristics D_V can be found empirically as

$$D_V = \frac{\Delta Q_L}{\Delta V} = q.\frac{Q_L{}^0}{V^0} \tag{6}$$

In equation (3) $K_V = 1/D_V$ and T_V is the time constant of the system which is proportional to the ratio of electromagnetic energy stored in the winding to the reactive power absorbed by the system. An IEEE type-1 excitation control system as shown in Fig. 2 is considered for the synchronous generator of the hybrid system with saturation neglected, therefore the state transfer equations [8] are

$$\Delta E_{fd}(s) = \frac{1}{K_E + sT_E}\Delta V_a(s) \tag{7}$$

$$\Delta V_a(s) = \frac{K_A}{1+sT_A}\left(-\Delta V(s) - \frac{K_F}{T_F}\Delta E_{fd}(s) + \Delta V_f(s)\right) \tag{8}$$

$$\Delta V_f(s) = \frac{K_F}{T_F}.\frac{1}{1+sT_A}\Delta E_{fd}(s) \tag{9}$$

The small change in voltage behind transient reactance $\Delta E'_q(s)$ by solving the flux linkage equation [3] for small perturbation is given below

$$\Delta E'_q(s) = \frac{1}{(1+sT_G)}\left[K_1 \Delta E_{fd}(s) + K_2 \Delta V(s)\right] \tag{10}$$

where

$$K_1 = X'_d / X_d \tag{11}$$

$$K_2 = \left[\left(X_d - X'_d\right)\cos\delta\right] / X'_d \tag{12}$$

and

$$T_G = T'_{do}\, X'_d / X_d \tag{13}$$

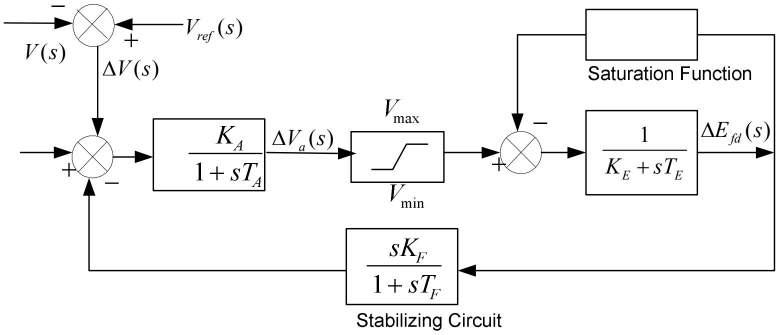


Figure 2. IEEE Type-1 Excitation Control System

The small change in synchronous generator reactive power in terms of state variables is given by [8]

$$\Delta Q_{SG}(s) = K_3 \Delta E'_q(s) + K_4 \Delta V(s) \tag{14}$$

where

$$K_3 = V \cos\delta / X'_d \tag{15}$$

and

$$K_4 = \left[E' \cos\delta - 2V\right] / X'_d \tag{16}$$

Similarly $\Delta Q_{IG}(s)$ can be expressed in terms of system state variables as given below. For small perturbations, the reactive power absorbed by induction generator, ΔQ_{IG}, in terms of generator terminal voltage, and generator parameters can be written as [8]

$$\Delta Q_{IG}(s) = K_5 \Delta V(s) \tag{17}$$

where

$$\mathrm{K}_5 = 2VX_{eq} / \left(R^2_y + X^2_{eq}\right) \tag{18}$$

$$R_Y = R_P + R_{eq} \tag{19}$$

$$R_P = \frac{r'_2}{s}(1-s) \tag{20}$$

Similarly, for variable slip conditions, the reactive power absorbed by induction generator, ΔQ_{IG}, in terms of generator terminal voltage, slip and generator parameters can be written as [8]

$$\Delta Q_{IG}(s) = K_6 \Delta P_{IW}(s) + K_7 \Delta V(s) \tag{21}$$

where

$$K_6 = X_{eq} / \left[R_p - \left\{\left(R^2_Y + X^2_{eq}\right) / 2R_Y\right\}\right] \tag{22}$$

$$K_7 = \left[2V/(R_Y^2 + X_{eq}^2)\right] / [X_{eq} - \left\{(R_p X_{eq}) / R_P - \{(R_Y^2 + X_{eq}^2)/2R_Y\}\right\} \tag{23}$$

The STATCOM is based on a solid state synchronous voltage source that is analogous to an ideal synchronous machine which generates a balanced set of three sinusoidal voltages, at the fundamental frequency, with rapidly controllable amplitude and phase angle. The configuration of a STATCOM is shown in Fig. 3. It consists of a voltage source converter (VSC), a coupling transformer, and a d. c. capacitor as shown in Fig. 3(a). The real current of the STATCOM is negligible and is assumed to be zero. Control of reactive current is possible by variation of δ and α as shown in Fig. 3 (b). Here δ is the phase angle of the system bus voltage, V where STATCOM is connected and α is the angle of the fundamental output voltage, kV_{dc} of the STATCOM [12]. The magnitude of the fundamental component of the converter output voltage is kV_{dc}, where V_{dc} represent the voltage across the capacitor. The reactive power injection to the system bus has the form: [12],

$$Q_{com} = kV_{dc}^2 B - kV_{dc} VB \cos(\alpha - \delta) + kV_{dc} VG \sin(\alpha - \delta) \tag{24}$$

The system bus voltage V is taken as reference voltage, therefore the angle δ is zero. Also G is negligible as $G + jB$ represent the step down transformer admittance. Therefore, considering the value of G and δ to be zero, equation (24) can be written as

$$Q_{com} = kV_{dc}^2 B - kV_{dc} VB \cos\alpha \tag{25}$$

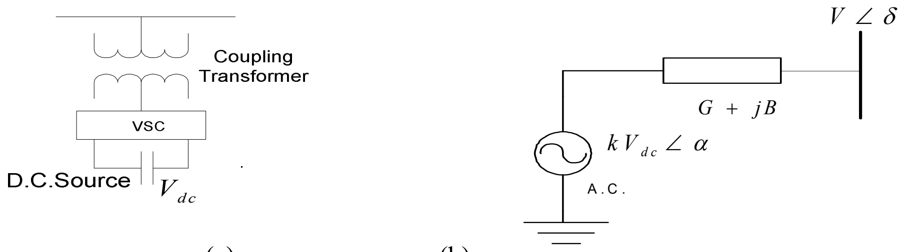
The flow of reactive power depends upon the variables V and α, therefore for small perturbation the linearized STATCOM equation can be

$$\Delta \mathrm{Q}_{\mathrm{com}} = \frac{\partial \mathrm{Q}}{\partial \alpha} \Delta \alpha + \frac{\partial \mathrm{Q}}{\partial \mathrm{V}} \Delta \mathrm{V} \tag{26}$$

Substituting the value of partial derivatives from equation (25) in equation (26), we get

$$\Delta Q_{com}(s) = K_8 \Delta\alpha(s) + K_9 \Delta V(s) \tag{27}$$

$$K_8 = kV_{dc} VB \; Sin\alpha \tag{28}$$



(a) (b)

Figure 3. STATCOM Configuration (a) Schematic Diagram (b) Equivalent Circuit

$$K_9 = -kV_{dc}B\cos\alpha \tag{29}$$

where, $k = \frac{p}{6}.\frac{\sqrt{6}}{\pi}$ and p is the pulse number of the inverter with modulation index unity [12].

A simulation model of the system has been developed as shown in Fig. 4 (Matlab/Simulink). The dotted line blocks are shown when variable slip is considered. The constants, shown in Fig. 4, are given in the Appendix. The constant K_5 in eq. (12) is replaced by K_{51}, and K_{52} in the case of multi-wind/ single diesel system as induction generators are used with two wind sources. The constant K_6 in eq. (16) is replaced by K_{61}, and K_{62} and K_7 in eq. (16) is by K_{71} and K_{72} in the case of multiple wind/single diesel system shown in Fig. 4(a) as IGs are used with multi-wind sources. In case of single wind/multi-diesel system, the constants K_1, K_2, K_3,and K_4 in eq. (10) and 11 for SG_1 is replaced by K_{11},K_{21}, K_{31} and K_{41} respectively, and for SG_2, is replaced by K_{12},K_{22}, K_{32}, and K_{42}, respectively as shown in Fig. 4 (b)

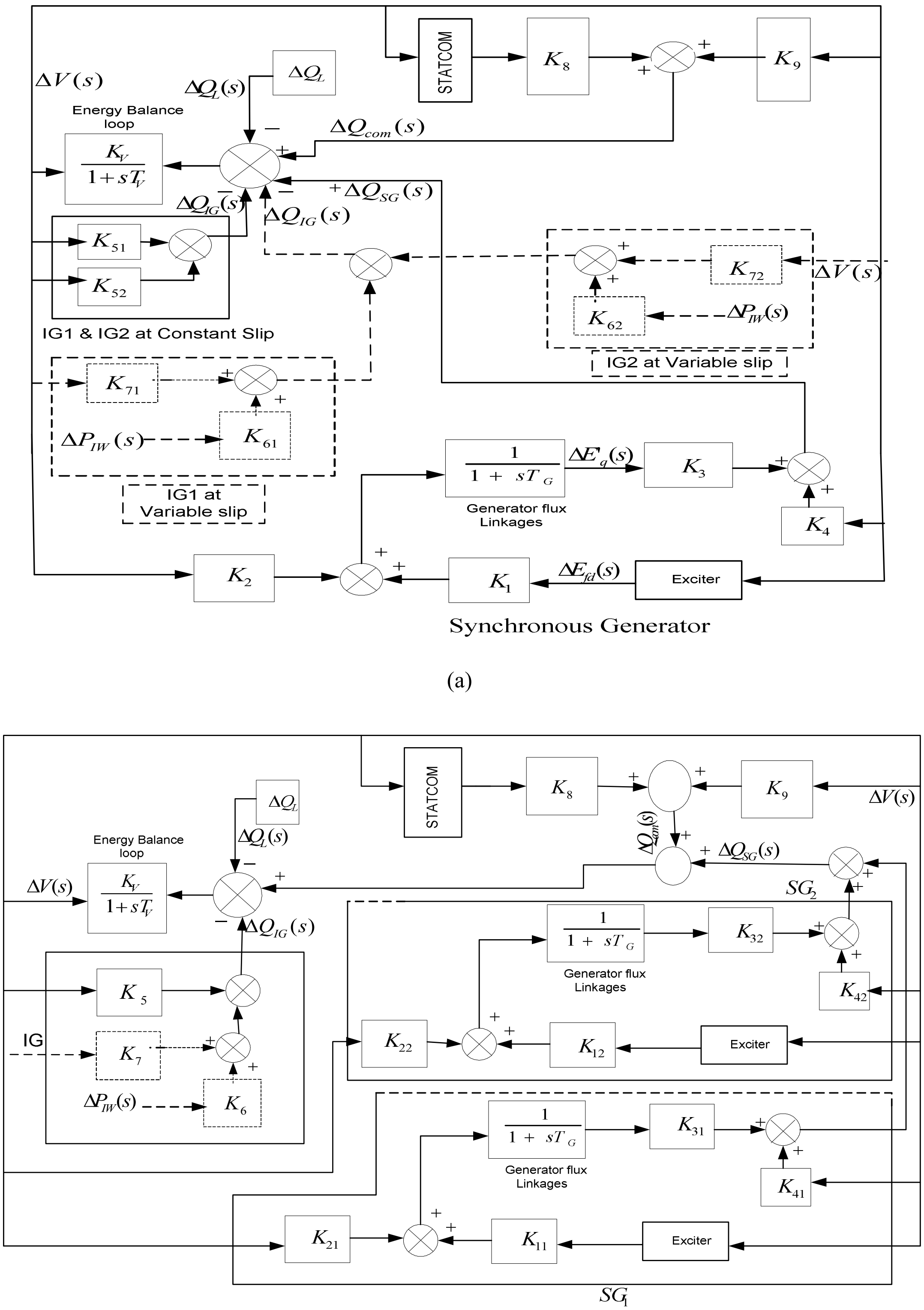
3. Transient Response of the Hybrid Power Systems

The computer simulation of the wind-diesel hybrid systems have been carried out and the transient/dynamic performance is presented in this section. Two examples of the wind-diesel hybrid system as multi-wind/single diesel, single wind/multi-diesel have been investigated. The data of the wind-diesel hybrid power systems are given in the Appendix. The proportional and integral gains, K_P and K_I of the STATCOM were optimized using Integral Square Error (ISE) technique and the values of the gains are given in Table 1.

Table 1 Optimized gain values of the PI controller

Hybrid Power systems data	Constant Slip		Variable Slip	
	K_P	K_I	K_P	K_I
Multi-Wind/Single diesel system	44	6818	41	6491
Single Wind /Multi-diesel system	108	14800	101	14687

The dynamic performances for 1% step increase in load, ΔQ_L without any change in input wind power, ΔP_{IW}, for multi-wind/single diesel system are shown in Fig. 5 and dynamic performances for 1% step increase in load, ΔQ_L with 1% step increase in input wind power, ΔP_{IW} , for multi-wind/single diesel system are shown in Fig. 6. The dynamic performances for 1% step increase in load, ΔQ_L without any change in input wind power, ΔP_{IW}, for single wind/multiple diesel system are shown in Fig. 7 and dynamic performances for 1% step increase in load, ΔQ_L with 1% step increase in input wind power, ΔP_{IW} , for single wind/multiple diesel system are shown in Fig. 8.



(a)

(b)

Figure 4. Transfer Function Block Diagram of the Systems (a) Multi-wind/ Single-diesel System (b) Single-wind/Multi-diesel

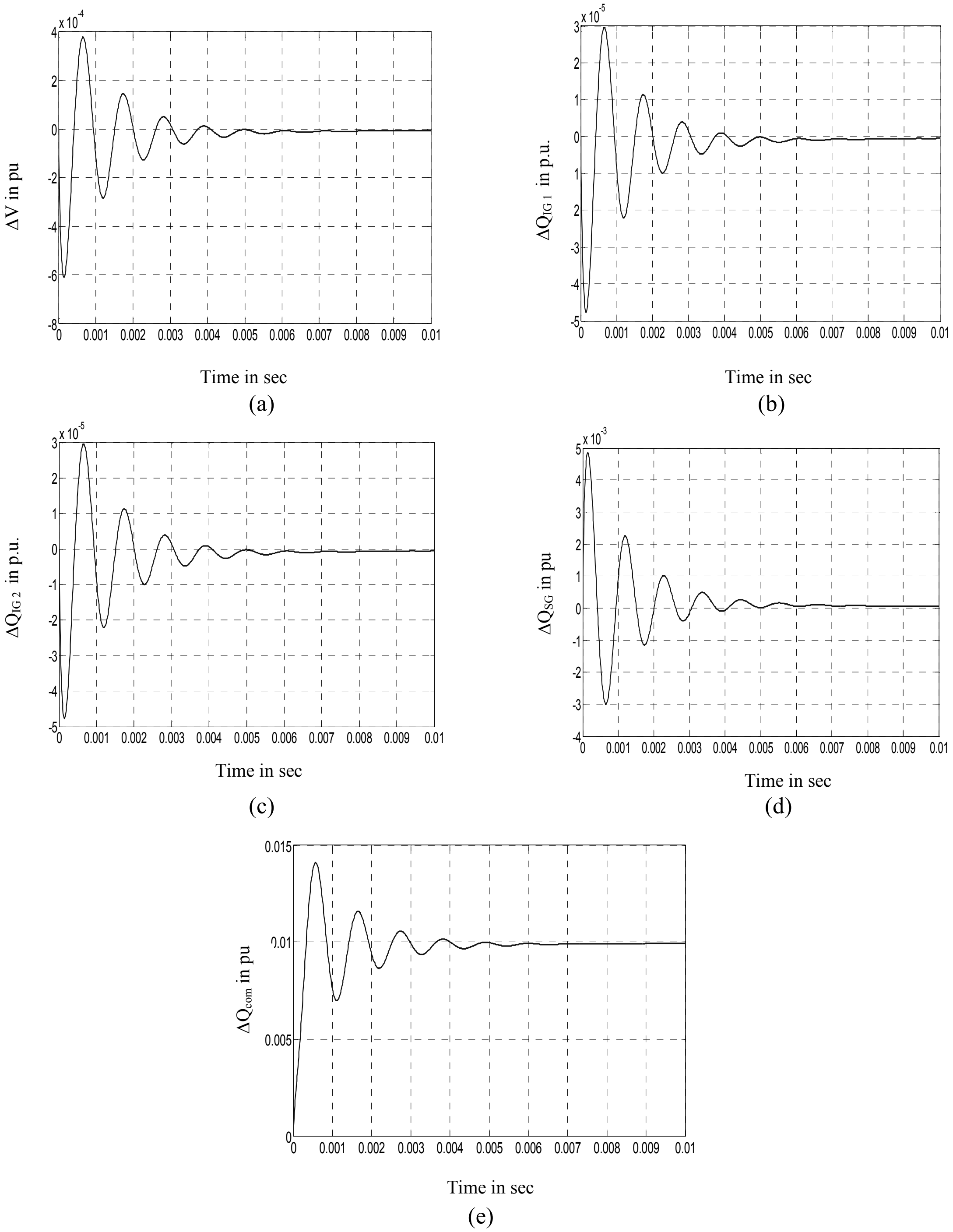
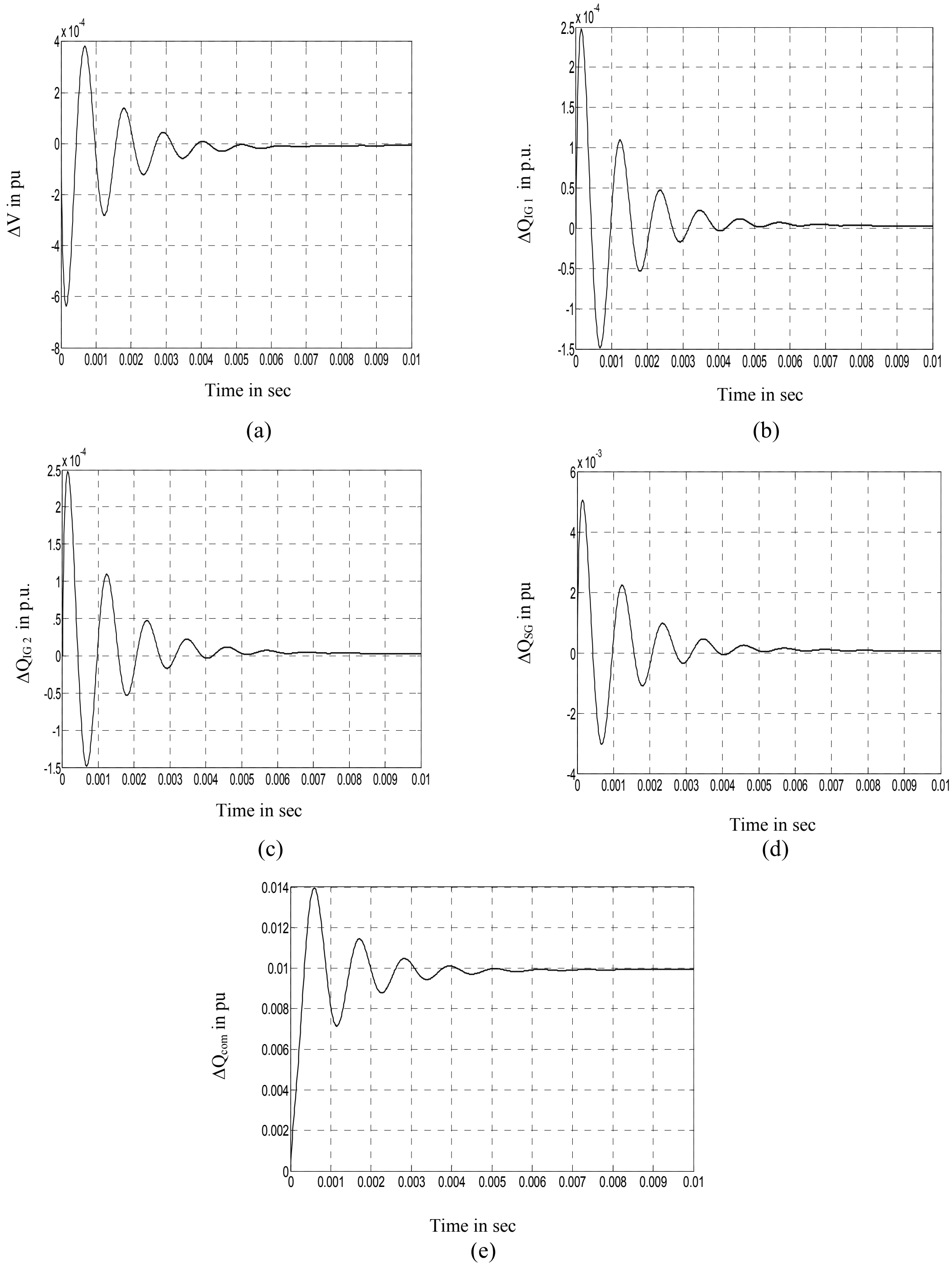
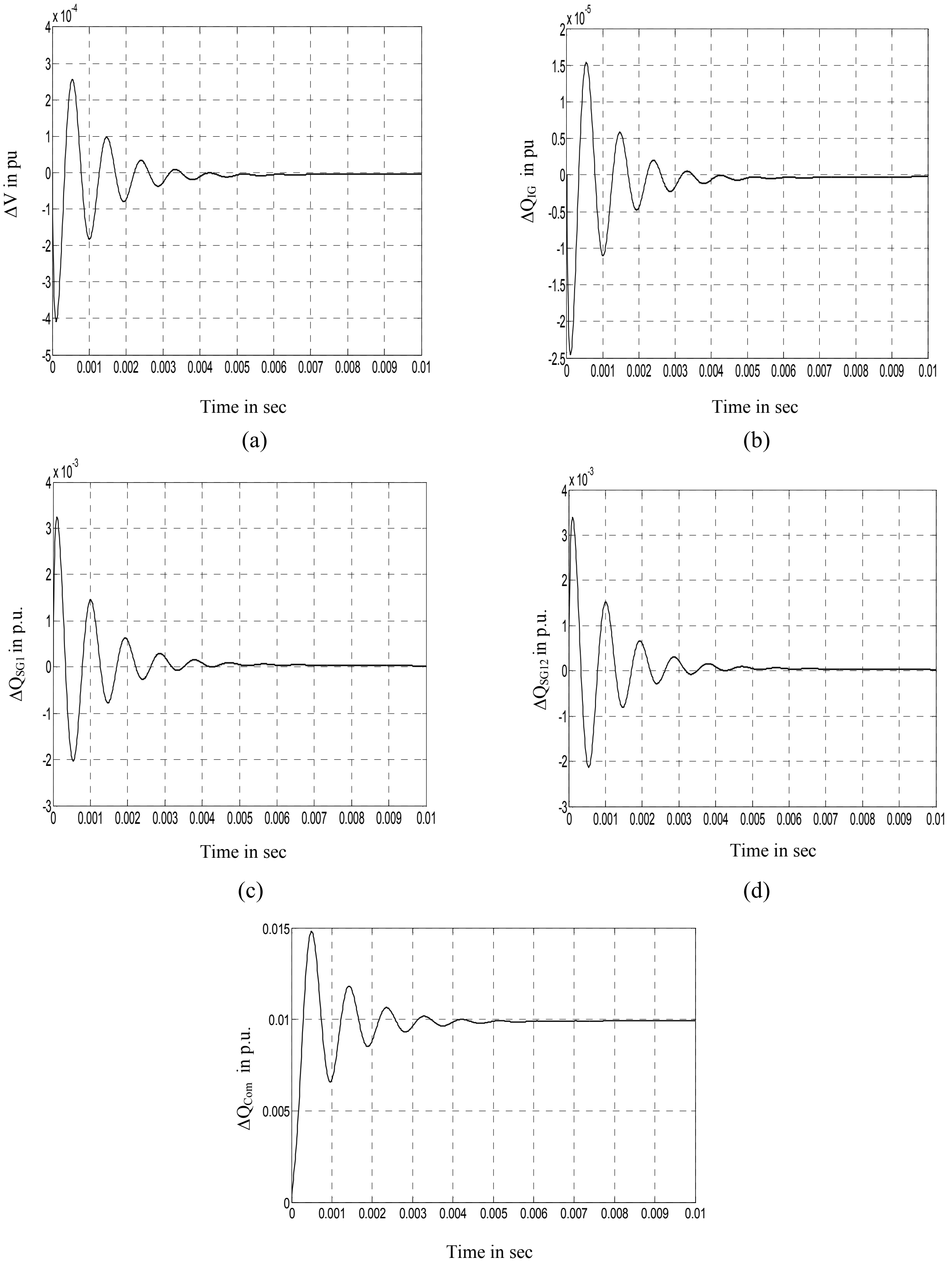


Figure 5.Transient responses of the multi-wind/single diesel hybrid power system for a 1% step increase load, and without any increase in input wind power showing time vs (a) ΔV **, (b)** ΔQ_{IG1} **, (c)** ΔQ_{IG2} **,(d)** ΔQ_{SG} **, and (e)** ΔQ_{com}



(a) (b) (c) (d) (e)

Figure 6. Transient responses of the multi-wind/single diesel hybrid power system for a 1% step increase load, and 1 % increase in input wind power showing time vs (a) ΔV , (b) ΔQ_{IG1} , (c) ΔQ_{IG2} ,(d) ΔQ_{SG} , and (e) ΔQ_{com}

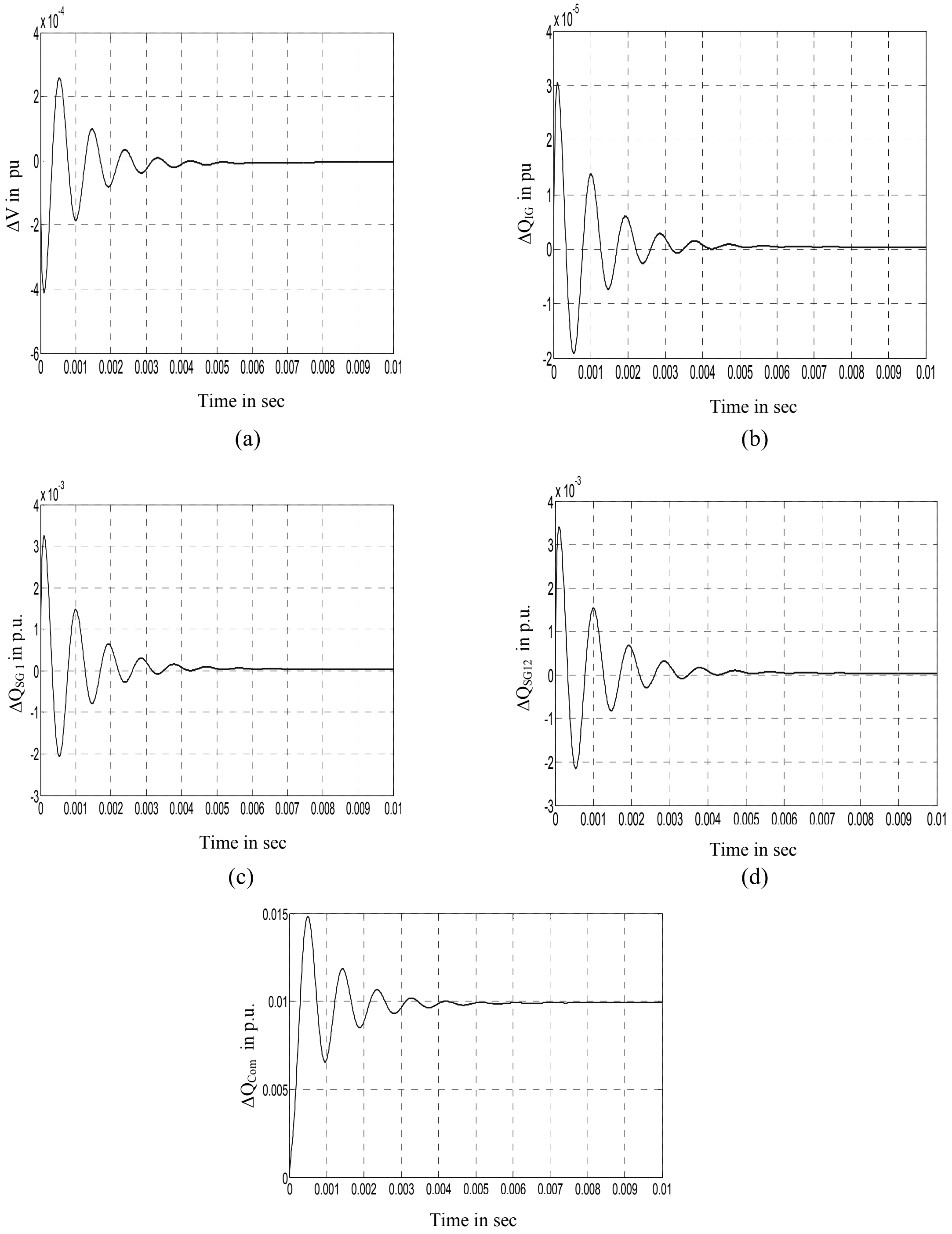


(a) (b)

(c) (d)

(e)

Figure 7. Transient responses of the single wind/multiple diesel hybrid power system for a 1% step increase load, and no increase in input wind power showing time vs (a) ΔV, (b) ΔQ_{IG}, (c) ΔQ_{SG1},(d) ΔQ_{SG2}, and (e) ΔQ_{com}



(a) (b)

(c) (d)

(e)

Figure 8. Transient responses of the single wind/multiple diesel hybrid power system for a 1% step increase load, and with 1% step increase in input wind power showing time vs (a) ΔV , (b) ΔQ_{IG} , (c) ΔQ_{SG1} ,(d) ΔQ_{SG2} , and (e) ΔQ_{com}

From Fig. 5-8, it is observed that the STATCOM provides the reactive power required by the load and the induction generator or induction generators under steady state condition, but initially the synchronous generator or synchronous generators is able to meet total demand. It has also been found that the increase in input wind power result in increased fluctuations in ΔQ_{IG}, without effecting the settling time of the transient responses as shown in Fig. 5 (b), 5(c), 6(b), 6(c), 7(b), 8(b). In the case of multi-wind/single diesel system, the STATCOM under steady state condition provides reactive required by the load and induction generator or induction generators due to 1% step increase in input wind power as shown in Fig. 6. In case of single wind / multi-diesel system, there is no change in the settling time of the responses, but initially both the synchronous generators satisfy the reactive power requirement by sharing according to their size and finally STATCOM provides the required power under steady state condition as shown in Fig. 8.

4. Conclusions

The reactive power control of the isolated wind-diesel hybrid power systems has been presented in this paper. Induction generator or induction generators has been considered for electric power generation from wind turbine and STATCOM for providing variable reactive power required by the system. The examples of the wind-diesel hybrid power systems considered in this paper are multi-wind/single diesel, and single wind/multi-diesel. A complete dynamic model of the system has been derived to study the effect of load disturbances and input wind power disturbances. In the case of multi-wind/single diesel system, the STATCOM under steady state condition provides reactive required by the load and the induction generator or induction generators due to the change in the slip. The deviations in $\Delta V, \Delta Q_{SG}$ become zero under steady state conditions. In case of single wind/multi-diesel system, there is no change in the settling time of the responses, but initially both the synchronous generator and synchronous generators satisfy the reactive power requirement by sharing according to their size and finally STATCOM provides the required power under steady state condition.

Nomenclature

E_M = Electromagnetic energy stored in the IG.

ΔE_M = Small change in the stored electromagnetic energy of IG.

ΔE_{fd} , ΔE_q , $\Delta E'_q$ = Small change in the voltages of the exciter, internal armature under steady state, and transient conditions, respectively.

K_A, K_E, K_F = Voltage regulator, exciter, stabilizer gain constants, respectively.

K_P, K_I = Proportional and integral controller gains of the STATCOM regulator, respectively.

P_{IG} , Q_{IG} = Real and reactive power generated by the IG.

P_{SG} , Q_{SG} = Real and reactive power generated by diesel set with synchronous generator.

P_L , Q_L = Real and reactive power of the load.

Q_{com} , Reactive power generated by compensator.

ΔV = Incremental change in the voltage.

$\Delta \alpha$ = Incremental change in the phase angle of STATCOM.

s = Slip of IG.

T'_{do} = Direct-axis open-circuit transient time constant.

V = System terminal voltage.

$\Delta V, \Delta V_a, \Delta V_f$ = Small changes in system terminal voltage, amplifier output voltage, and exciter feedback voltage, respectively.

X_d, X'_d = Direct-axis reactance of synchronous generator under steady-state and transient-state conditions, respectively.

Appendix

The data of the proposed hybrid power systems are given below:

S. No.	Systems	Wind 1 (kW)	Wind 2 (kW)	Diesel1 (kW)	Diesel2 (kW)	Load in kW
1.	Multi-Wind/Single diesel system	150	50	150	-	150+50+100=300
2.	Single Wind /Multi- diesel system	150	-	150	75	150+100+50=300

The data of the systems are as follows:

System Parameter	Multi-Wind/Single diesel system		Single Wind / Multi-diesel system	
Synchronous Generators	SG		SG1	SG2
P_{SG} (p.u. kW)	0.3333		0.3333	0.16667
Q_{SG} (p.u. kVAR)	0.161		0.161	0.0181
E_q (p.u.)	1.12418		1.12418	1.10826
E'_q (p.u.)	0.9804		0.9804	1.01
δ (degree)	17.24		17.24	6.91
X'_d (p.u.)	0.15		0.15	0.12
X_d (p.u.)	1.0		1.0	1.0
T'_{do} (seconds)	5.0		5.0	5.0
Induction Generators	IG1	IG2	IG	
P_{IG} (p.u. kW)	0.6	0.16666	0.5	
$Q_{IG,}$ (p.u. kVAR)	0.2906	0.08072	0.242161	
η (%)	90	90	90	
$r_1 = r'_2$ (p.u.)	0.19	0.55	0.19	
$x_1 = x'_2$ (p.u.)	0.56	1.6	0.56	
s (%)	-3.5	-3.4	-3.5	
Load				
P_L (p.u. kW)	1.0		1.0	

Q_L (p.u. kVAR) Power Factor	0.75 0.8	0.75 0.8
IEEE Type-1 Excitation System K_A K_E K_F T_A (seconds) S_F , T_E (seconds)	40 1.0 0.5 0.05 0, 0.55	40 1.0 0.5 0.05 0, 0.55
STATCOM T_1 (ms) T_α (ms) T_d (ms)	10-50 0.2-0.3 1.67	10-50 0.2-0.3 1.67
Reactive Power Data Q_{com} (p.u. kVAR) α (degree)	0.91736 53.32	0.81206 53.2

The data of generation capacity, the excitation control, and load and STATCOM model are given below,
Base power=250 kVA, Base Voltage=400 V.

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