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Reactive Power Compensation of Isolated Wind-Diesel Hybrid Power Systems with STATCOM and SVC

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Abstract: The use of the isolated hybrid power systems is being popular due to the continuous increasing gap between demand and supply of conventional energy sources and intermittent nature of non-conventional energy sources. Normally, the non-conventional energy source such as wind have induction generator to generate electricity but induction generators require reactive power for its operation and this demand is continuously changing by the variation of load and wind power. The synchronous generator used in hybrid system for generating power through diesel system is supplying reactive power to the system partially; therefore, another source of reactive power is required to fulfill this demand. In this paper, the static VAR compensator (SVC) and static synchronous compensator (STATCOM) using a proportional-integral controller (PI) are used as reactive power compensator. The dynamic performance of SVC and STATCOM are investigated for wind-diesel and wind-diesel-microhydro power systems ate constant slip operation of induction generators. The results show that the STATCOM is a better option than that of SVC for reactive power control of the hybrid system.

Key words: Isolated hybrid power system; conventional energy sources; induction generator; renewable energy sources; synchronous generator; SVC and 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 drawback is that they are intermittent in nature. To enhance the capacity and reliability of the power supply of local grids, the non-conventional energy sources like wind, mini/micro hydro, etc. are integrated with diesel system. This combination of conventional and renewable sources is called as isolated hybrid power system [1]-[2]. 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 [4]-[5]. Induction generators offer many advantages over synchronous generators in an isolated hybrid power system but require reactive power for their operation. Due to this 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 generator. Many papers have appeared in the literature, which suggest different methods using a bank of fixed capacitors for providing the reactive power under steady state conditions [7]-[8]. 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

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available those can supply fast and continuous reactive power [9-11]. Therefore, for standalone applications, and effective capacitive VAR controller has become central to the success of the induction generator system. Switched Capacitors, SVC, and 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 [13]. STATCOM [14] - [16] employs a voltage source inverter (VSC) that internally generates inductive/capacitive reactive power which has the advantages over the SVC scheme [17].

This paper presents dynamic stability study of wind-diesel and wind-diesel-microhydro systems with realistic load power disturbance. The realistic comprises 1% step increase plus band limited white noise signal. SVC and STATCOM are used for control of reactive power in the system. The gains of the controllers with SVC and STATCOM have been optimized and optimum transient responses are shown

2. Mathematical model of the System

The wind-diesel power system in general comprises induction generator, synchronous generator, electrical loads and reactive power compensator (SVC or STATCOM) and a control mechanism. A single line diagram of the system is shown in Figure 1. The active power demand of the load is fulfilled by the synchronous generator and the induction generator. The reactive

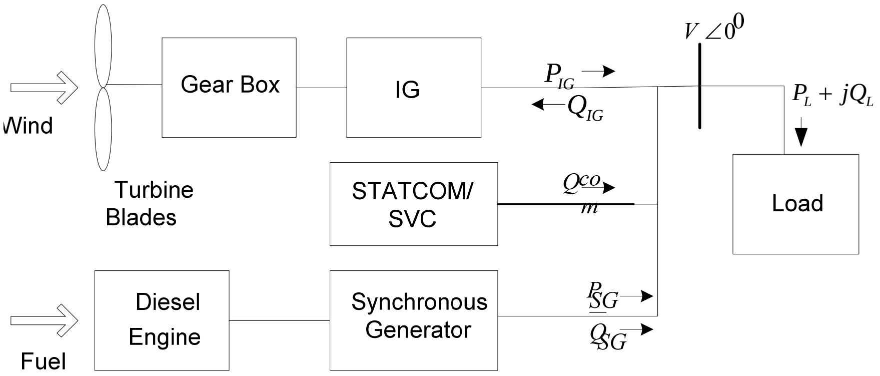


Figure 1. Single line diagram of an isolated wind diesel power system

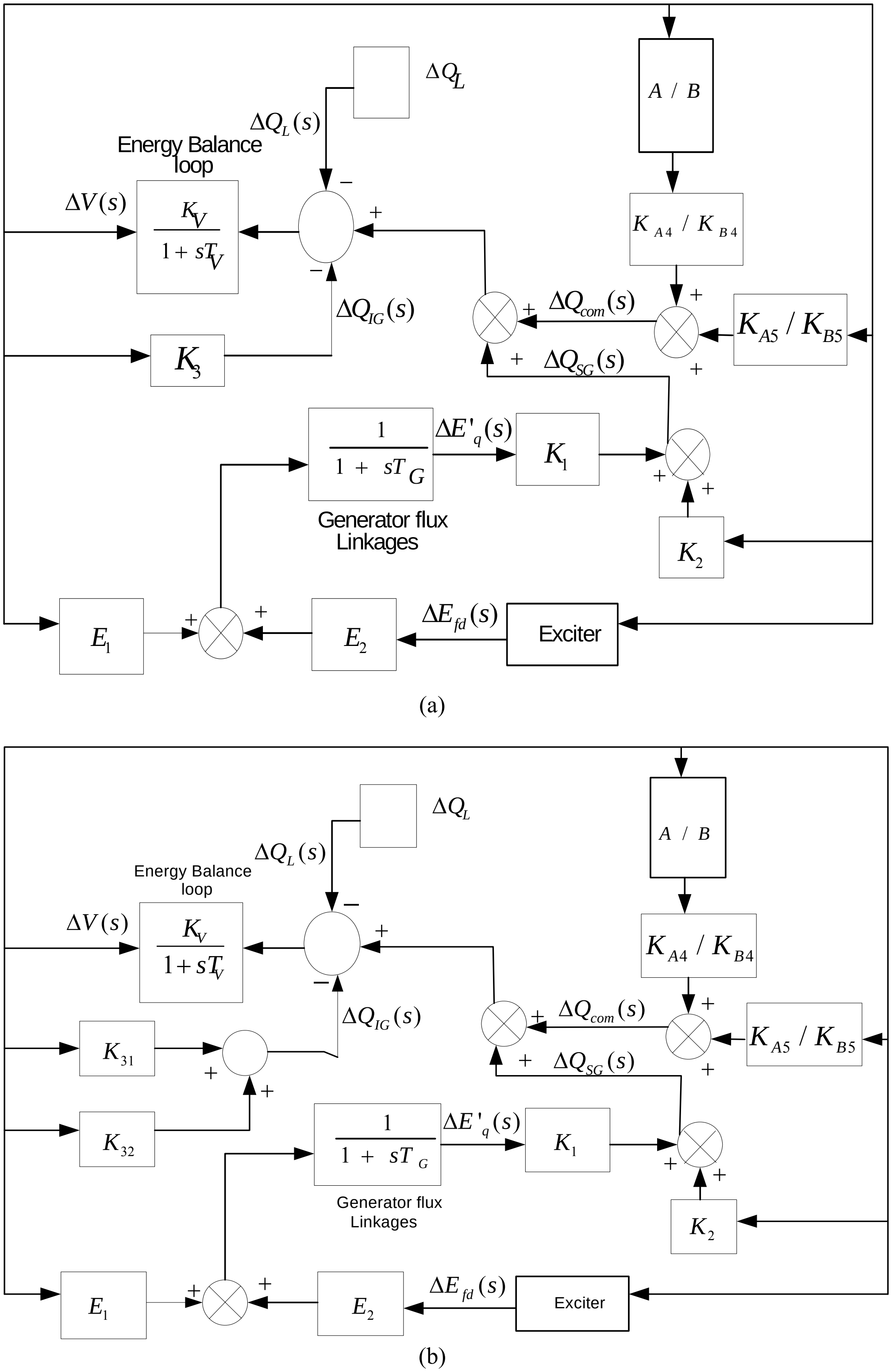
Power required for the operation of induction generator and load is provided by synchronous generator and SVC/STATCOM and equations for the system shown in Figureure1 is given by,

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

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

Due to disturbance in load reactive power ΔQ_L , the system voltage may change which results 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 voltage which will govern by the following transfer function equation.

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



(a)

(b)

Figure 2. Transfer function block diagrams for (a) isolated wind-diesel power system (b) wind-diesel-microhydro power system at constant slip operation (A: SVC, B: STATCOM)

The incremental change in reactive power of the synchronous generator ΔQ_{SG} in equation (3) depends upon $\Delta E_q'$ and ΔV . The corresponding transfer equation is given by,

$$\Delta Q_{SG}(s) = K_1 \Delta E_q'(s) + K_2 \Delta V(s) \tag{4}$$

The transfer function equation for the state variable $\Delta E_q'(s)$ is obtained from the flux linkage equation of the synchronous generator along with the excitation system (IEEE type-I) as given in reference [11]. The induction generator requires reactive power under constant slip condition and the incremental change in reactive power of induction generator, ΔQ_{IG} depends upon ΔV . The corresponding transfer function equation is given by,

$$\Delta Q_{IG}(s) = K_3 \Delta V(s) \tag{5}$$

The two simulink models separately using reactive power compensators SVC and STATCOM are designed. The proportional-integral (PI) controller scheme is used for control mechanism in both the compensators. For SVC, the incremental change in reactive power depends upon ΔV , ΔB_{SVC} while for STATCOM, the incremental change in reactive power depends upon ΔV , $\Delta \alpha$. The corresponding transfer equation of the SVC is given below

$$\Delta Q_{SVC} = K_{A4} \Delta B_{SVC} + K_{A5} \Delta V(s) \tag{6}$$

The STATCOM transfer equation is given by

$$\Delta Q_{STATCOM} = K_{B4} \Delta \alpha + K_{B5} \Delta V(s) \tag{7}$$

The transfer function block diagrams of the isolated wind-diesel power system conFigureurations for reactive power control at constant slip operation of the induction generator is shown in Figure 2. The details of all constants in equation (3) to (7) are given in the Appendix. The constant K_3 is replaced by K_{31} , and K_{32} in the case of wind-diesel-microhydro system as induction generators are used with wind and microhydro sources.

3. Simulation Results and Discussion

The wind-diesel system and wind-diesel-microhydro system has been simulated by using the system data as given in the Appendix. The gains K_P and K_I of the PI controllers of SVC and STATCOM have been optimized using integral square error (ISE) criterion. The optimum values obtained for the wind-diesel system are K_P = 233, K_I =10312 for SVC controller and K_P =35, K_I =5238 for STATCOM controller and the values for the wind-diesel-microhydro are K_P = 250 and K_I = 9642 for SVC controller and K_P = 40 and K_I = 5972 for STATCOM controller. The gains have been optimized for a realistic type of disturbance in reactive power load. The transient responses for realistic disturbance for wind-diesel system with SVC are shown in Figure 3. It has been observed that the system voltage decreases as the load increases. Initially, synchronous generator and the SVC supplies the reactive power required by the system. Finally, the voltage regulator of the synchronous generator maintains the voltage by eliminating the deviation in voltage. But the reactive power required by the load is supplied by the SVC under steady state conditions as shown in Figure 3 (d). It has been observed that the oscillations following the disturbance settle down in approximately 0.0225 seconds. Similarly, the transient responses for realistic disturbance in reactive power load for wind-diesel system with STATCOM are shown in Figure 4. Again it has been observed that the increase in reactive power load is supplied by the STATCOM under steady state conditions. Comparing Figure 3 and Figure 4, it has been observed that peak deviations in the system voltage are less in case of STATCOM than that of SVC. It has also been observed that the settling time of oscillations following the disturbance is approximately 0.01 seconds which is considerably less that of SVC.

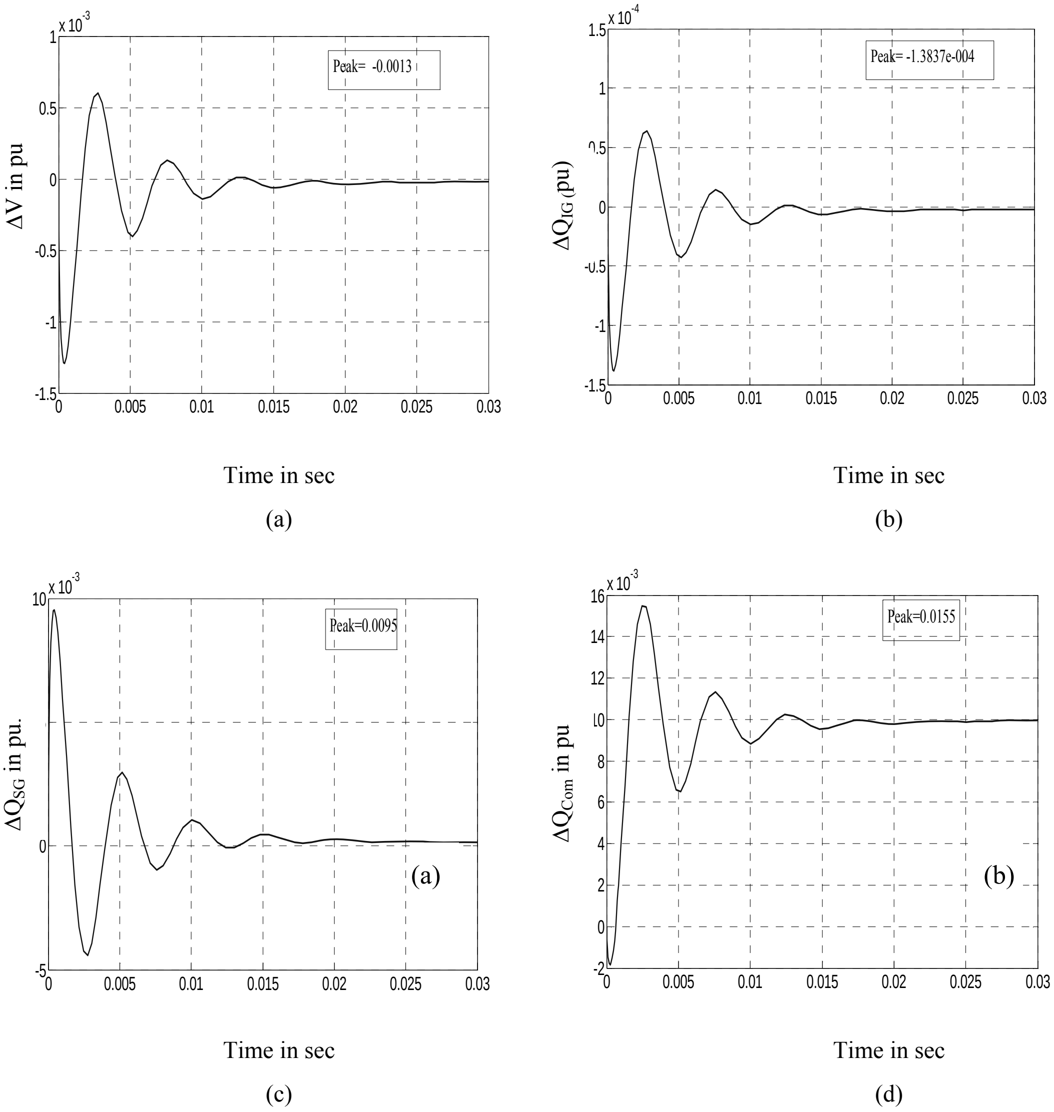
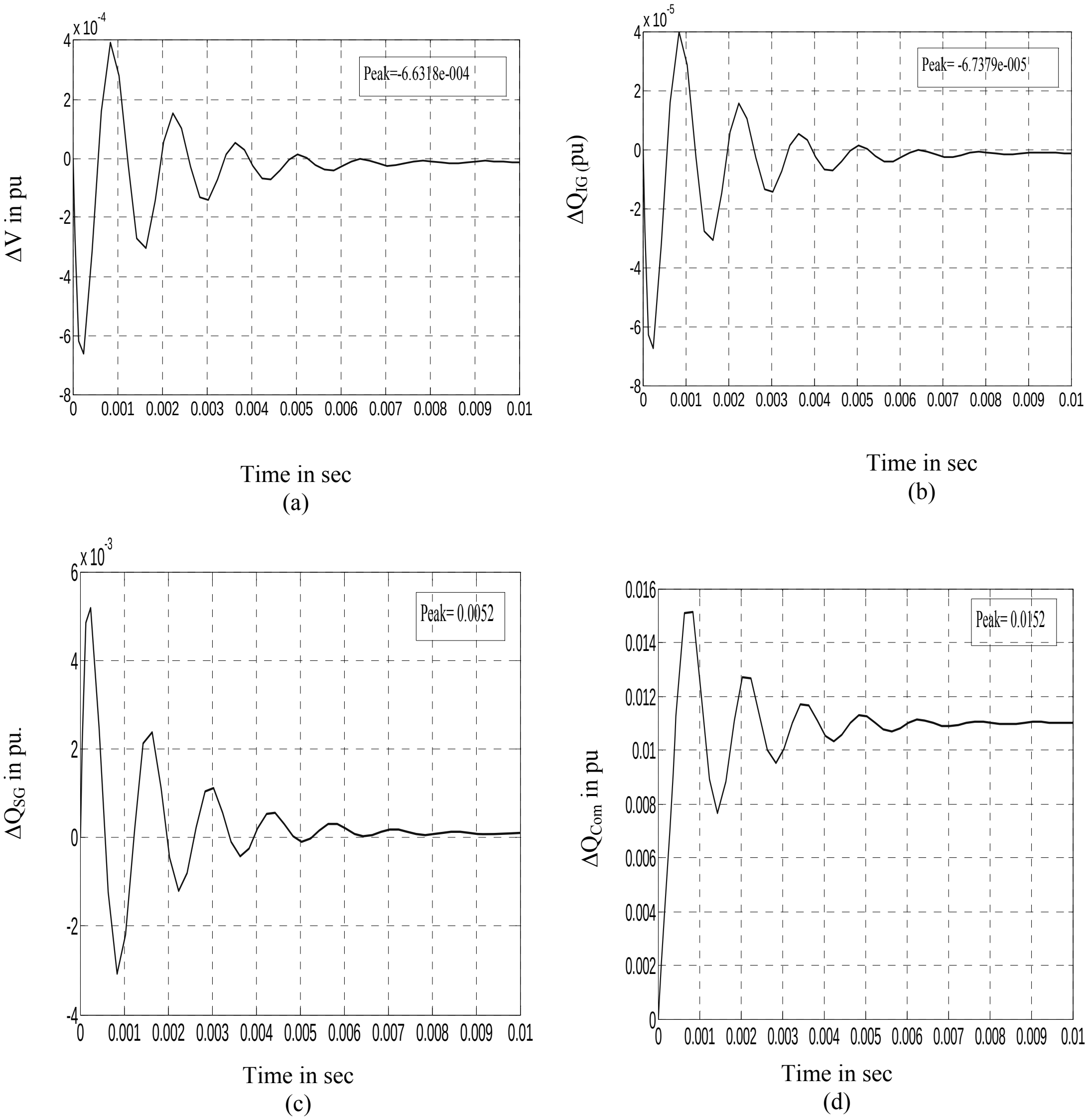


Figure 3. Transient responses of the *wind-diesel system with SVC* for realistic disturbances in reactive power load showing time vs. (a) ΔV , (b) ΔQ_{IG} , (c) ΔQ_{SG} , and (d) ΔQ_{com}



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

Figure 4. Transient responses of the *wind-diesel system with STATCOM* for realistic disturbances in reactive power load showing time vs (a) ΔV , (b) ΔQ_{IG} , (c) ΔQ_{SG} , and (d) ΔQ_{com}

The transient responses for realistic disturbance in reactive power load for wind-diesel-microhydro system with SVC is shown in Figure 5. Comparing Figure 3 and Figure 5, it has been observed that the peak deviations in voltage as well as the settling time are approximately same. The transient responses of the wind-diesel-microhydro system for realistic type of disturbance with STATCOM are shown in Figure 6. By comparing Figure 4 and Figure 6, it has been observed that the peak deviation in voltage, ΔV and the settling time are same for the wind-diesel and wind-diesel-mocrohydro systems. In general, the transient performance of the systems with STATCOM is better than with SVC.

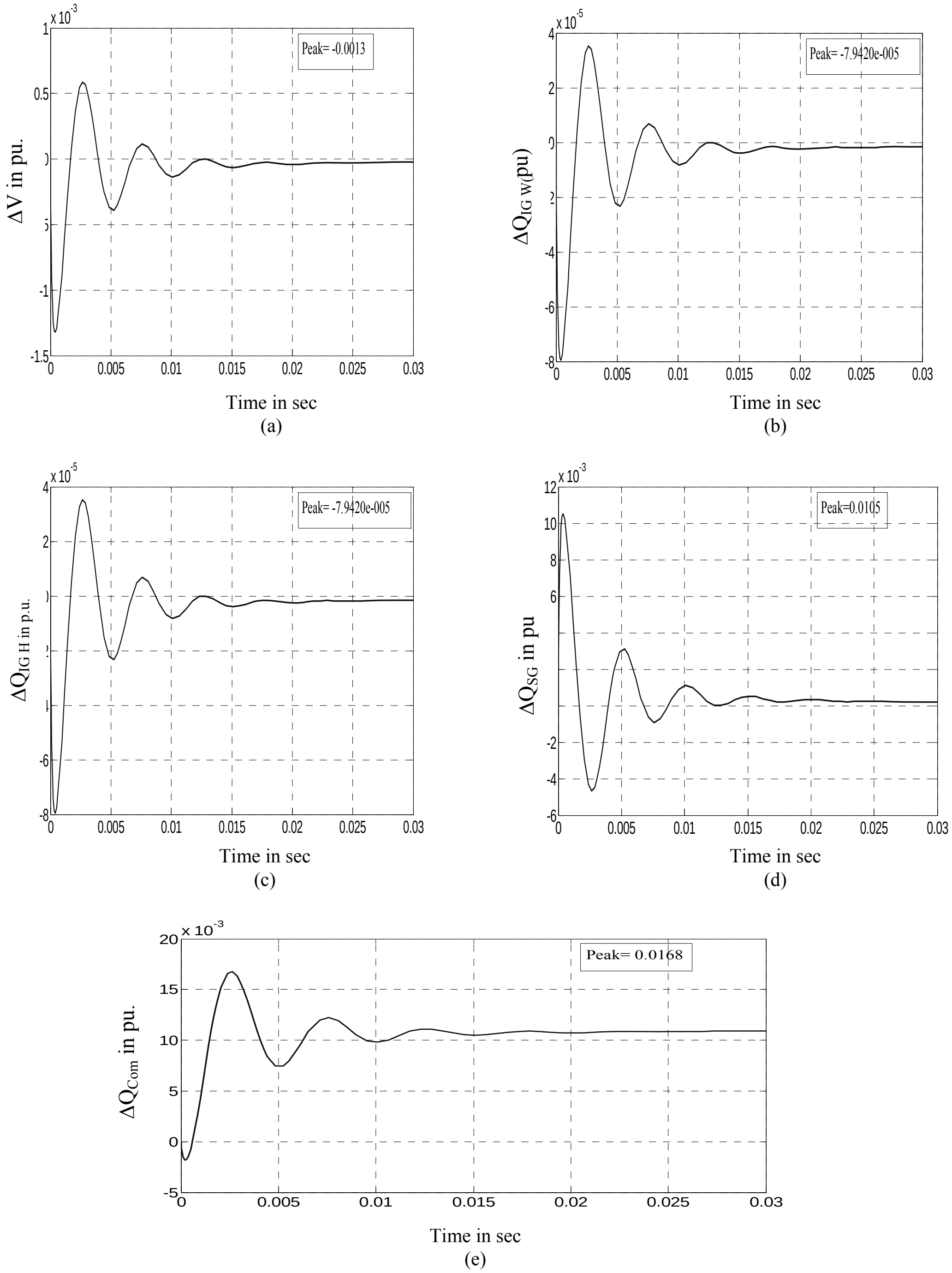


Figure 5. Transient response of the *wind-diesel-microhydro system with SVC* for realistic disturbances in the reactive power load showing time vs (a) ΔV , (b) ΔQ_{IGW} , (c) ΔQ_{IGH} ,(d) ΔQ_{SG} , and (e) ΔQ_{com}

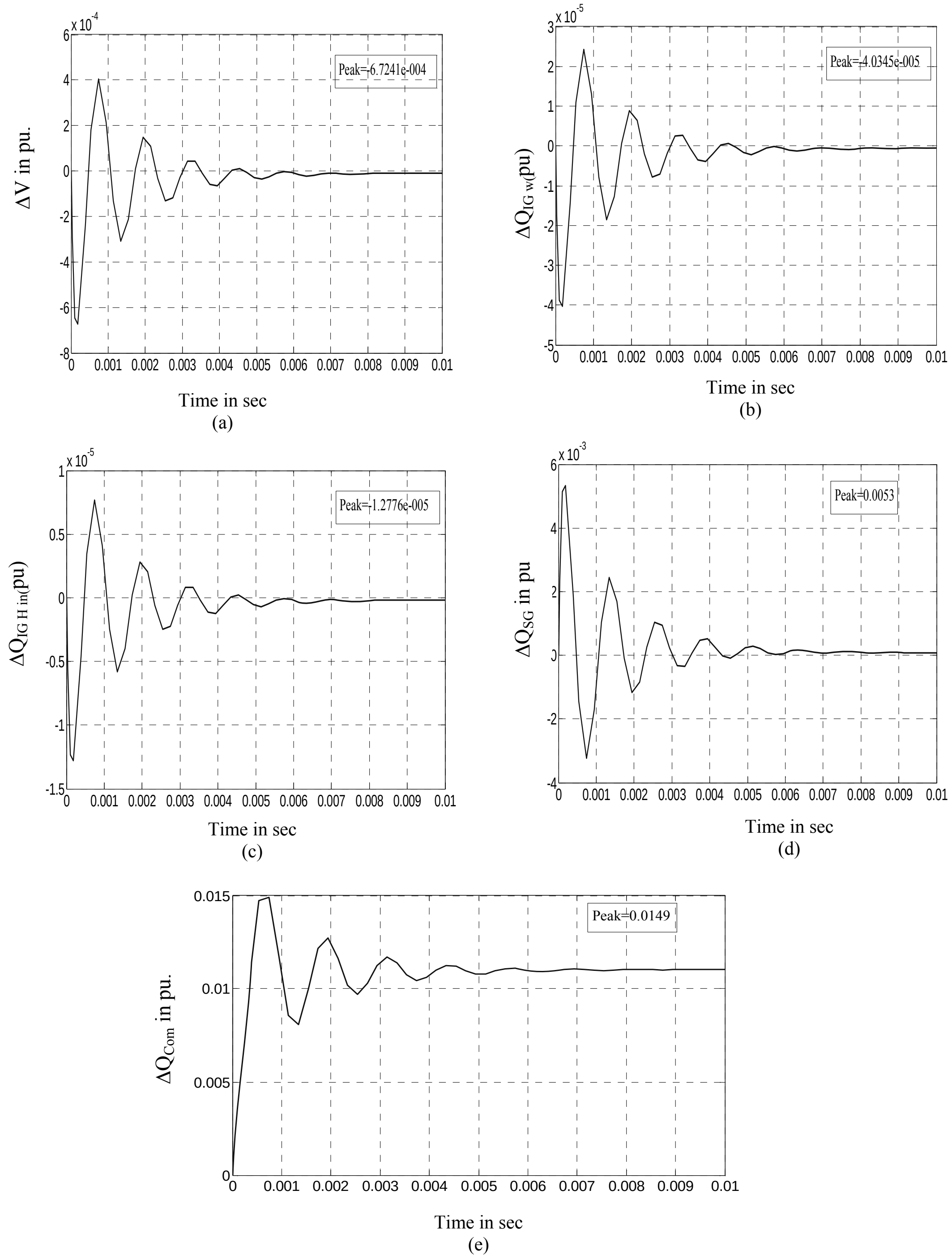


Figure 6. Transient response of the *wind-diesel-microhydro system with STATCOM* for realistic disturbances in the reactive power load showing time vs (a) ΔV , (b) ΔQ_{IGW} , (c) ΔQ_{IGH} ,(d) ΔQ_{SG} , and (e) ΔQ_{com}

4. Conclusions

The reactive power control of isolated wind-diesel and wind-diesel-microhydro systems has been investigated in this paper. The controlled reactive power has been investigated by using STATCOM and SVC. The system has been simulated by taking typical data and the gains of the controller have been optimized. A realistic disturbance i.e. 1% step increase in reactive power load plus band limited white noise has been considered. It has been shown that STATCOM is a better choice for damping transient oscillations due to disturbances in the system than the SVC.

Nomenclature

P_{IG} = Real power generated by wind system,

P_{SG} = Real power generated by diesel system,

P_L = Real power load demand,

Q_{SG} & ΔQ_{SG} = Reactive power & incremental change in reactive power generated by diesel generator respectively,

Q_{Com} & ΔQ_{Com} = Reactive power & incremental change in reactive power generated by compensator respectively, Q_L & ΔQ_L = Reactive power & incremental change in reactive power generated by load respectively,

Q_{IG} & ΔQ_{IG} = Reactive power & incremental change in reactive power generated induction generator respectively,

$\Delta E_q'$ = Incremental change in the internal armature e.m.f. proportional to the change in the direct axis field flux under transient condition,

ΔB_{SVC} = Incremental change in the susceptance of the SVC,

$\Delta \alpha$ = Incremental change in the phase angle at STATCOM output

ΔV = Incremental change in voltage at load, all the values are in p.u.

Appendix

The details of the constants used in the equations are:

$K_1 = V \cos\delta / X'_d$, $K_2 = \left[E' \cos\delta - 2V\right] / X'_d$, $K_3 = 2VX_{eq} / R_Y^2 + X_{eq}^2$,

$K_{A4} = V^2$,

$K_{A5} = 2VB_{SVC}$, $K_{B4} = kV_{dc}VB\ Sin\alpha$, $K_{B5} = -kV_{dc}B\cos\alpha$,

$E_1 = \left[\left(X_d - X'_d\right)\cos\delta\right] / X'_d$, $E_2 = X'_d / X_d$

The data of the wind-diesel system is given below:

Synchronous Generator	**Induction Generator**	**Load**	**SVC**	**STATCOM**
P_{SG} = 0.4 p.u. kW	P_{IG} = 0.6 p.u. kW	P_L = 1.0 p.u. kW	Q_{SVC} = 0.841 p.u. kVAR	$Q_{STATCOM}$ = 0.841 p.u. kVAR,
Q_{SG} = 0.2 pu kVAR	Q_{IG} = 0.291 p.u. kVAR	Q_L = 0.75 pu kVAR	α_{SVC} =138.8^0	$\alpha_{STATCOM} = 53.32^0$
E_q = 1.12418 pu	P_{in} = 0.667 pu kW	Power Factor = 0.8	-	$V_{dc} = 0.6410$ p.u.
δ = 17.2483	η =90%	-	-	$L_{a.c.}$ = 0.3173 mH
E'_q = 0.9804 p.u	Power Factor = 0.9	-	-	-
V = 1.0 pu	$r_1 = r_2' = 0.19\ p.u.$	-	-	-
X_d = 1.0 pu	$x_1 = x_2' = 0.56$ p.u.	-	-	-
X'_d = 0.15 pu	S = -3.5%	-	-	-
T'_{do} = 5.0 sec	-	-	-	-

The data of the wind-diesel-microhydro system is given below:

Synchronous Generator for diesel	Induction Generator for wind	Induction Generator for micro hydro	Load	SVC	STATCOM
P_{SG} = 0.3333 p.u. kW	P_{IG} = 0.5 p.u. kW	P_{IG} = 0.16666 p.u. kW	P_L = 1.0 p.u.kW	Q_{SVC} = 0.93 p.u. kVAR	$Q_{STATCOM}$ = 0.93p.u. kVAR
Q_{SG} = 0.161 p.u. kVAR	Q_{IG} = 0.242161 p.u. kVAR	Q_{IG} = 0.09 p.u. kVAR	Q_L = 0.75 pu kVAR	$\alpha_{SVC} = 138^0$	$\alpha_{STATCOM}$ = 53.2^0
E_q = 1.12418 p.u.	P_{in} = 0.555 pu kW	P_{in} = 0.186 pu kW	Power Factor = 0.8	-	V_{dc} =0.6410
δ = 17.2483	η =90%	η =90%	-	-	-
E'_q = 0.9804 p.u.	Power Factor = 0.9	Power Factor = 0.9	-	-	-
V = 1.0 pu	$r_1 = r_2' = 0.19\ p.u.$	$r_1 = r_2' = 0.55$ p.u.	-	-	-
X_d = 1.0 pu	$x_1 = x_2' = 0.56$ p.u.	$x_1 = x_2' = 1.6$ p.u.	-	-	-
X'_d = 0.15 pu	S = -3.5%	S = -3.4%	-	-	-
T'_{do} = 5.0 sec	-	-	-	-	-

The values of the constants in the equations are given as below:

$K_1 = 6.22178, K_2 = -7.8349, K_3 = 0.11, K_{31} = 0.0615, K_{32} = 0.0195, K_{A4} = 1.478, K_{A5} = 1.0$

$K_{B4} = 5.623, K_{B5} = -3.8285, , E_1 = 0.79 , E_2 = 0.15 ,$

$K_V = 6.667, T_V = 7.855E^{-04}$

References

[1] Ray Hunter, George Elliot, ‘Wind-Diesel Systems, A Guide to the Technology and its Implementation,’ (Cambridge University Press, 1994).

[2] H. Nacfaire, ‘Wind-Diesel and Wind Autonomous Energy Systems’, in (ed.), (Elsevier Applied Science, London, 1989).

[3] N. G. Hingorani , L. Gyugyi, ‘Understanding FACTs: Concepts and technology of Flexible AC Transmission Systems’, (*IEEE Power Eng. Soc., New York, 2000*).

[4] A. A. F. A1-Ademi, ‘Load-Frequency Control of Stand-Alone Hybrid Power Systems Based on Renewable Energy Sources’, Ph. D Thesis, Centre for Energy Studies, Indian Institute of Technology, Delhi (India), July 1996.

[5] R. C. Bansal, T. S. Bhatti, and D. P. Kothari, ‘A bibliographical survey on induction generators for application of non-conventional energy systems’, *IEEE Trans. Energy Convers.,* 18(2003)3, pp. 433–439.

[6] K. Tandon, S. S Murthy, and G. J. Berg, ‘Steady State Analysis of Capacitors Excited Induction Generators’, *IEEE Transactions on Power Apparatus and Systems*, 103 (1984)3.

[7] S. S. Murthy, O. P. Malik, and A. K. Tandon, ‘Analysis of Self-Excited Induction Generator’, *IEE Proceedings*, 129 (1982)6.

[8] B. T. Ooi, R. A. David, “Induction Generator/Synchronous Condenser System for Wind Turbine Power”, *Proceeding of IEE,* Vol. 126. No. 1, January 1979.

[9] M. A. Elsharkawic, S. S. Venkata, T. J. Williams, and N. G. Butlar, “An adaptive power factor controller for Three Phase Induction Generator”, *IEEE Transaction on Power Apparatus and Systems*, Vol. PAS-104, No. 7, July 1985.

[10] S. E. Haque, N. H. Malik, and W. Shepherd, “Operation of a Fixed Capacitor Thyristor Controlled Reactor (FC-TCR) Power Factor Compensator”, *IEEE Transaction on Power Apparatus and Systems,* Vol. PAS-104, No. 6, July 1985.

[11] E. Hammad, “Analysis of Power System Stability enhancement by Static VAR Compensators”, *IEEE Transactions on Power System,* Vol. PWRS-1, No. 4, November 1986.

[12] R. C. Bansal, “Automatic Reactive Power Control of Autonomous Hybrid Power System”, Ph.D. Thesis, Centre for Energy Studies, Indian Institute of Technology, Delhi, December 2002.

[13] Bhim Singh, S. S. Murthy, and Sushma Gupta, “Analysis and Design of STATCOM-based voltage regulator for self-excited induction generators,” *IEEE Transactions On Energy Conversion*, Vol. 19, No.4, 2004, pp.783-790.

[14] B. Singh, and L. B. Shilpakar, “Analysis of a novel solid state voltage regulator for a self-excited induction generator,” *Proc. Inst. Elect. Eng.,Gen., Transm*. Dist. Vol. 145, No.6, pp. 647-655, 1998.

[15] E.G. Marra, and J. A. Pomilio, “Self-excited induction generator controlled by a VS-PWM converter providing high power-factor current to a single-phase grid,” *Proc. Industrial Electronics Society Conf*, pp. 703-708, 1998.

[16] S. C. Kuo, and L. Wang, “Analysis of voltage control for a self-excited induction generator using a current-controlled voltage source inverter (CC-VSI),” *Proc. Inst. Elect. Eng., Gen., Transm. Distrib*, Vol.148, No.5, pp. 431–438, 2001.

[17] E. Larsen, N. Miller, S. Nilsson, and S. Lindgren, “Benefits of GTO-based compensation systems for electric utility applications,” *IEEE Trans. Power Delivery*, Vol.7, 1992; pp.2056–2063.

[18] B. Kouadri, Y. Tahir, “Power flow and transient stability modeling of a 12-pulse statcom, *Journal of Cybernetic and Informatics*,” Vo. 7, pp. 9-25, 2008.

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