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Small Signal Stability Enhancement for Hybrid Power Systems by SVC

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Abstract**—**In this paper an isolated wind-diesel hybrid power system has been considered for reactive power control study having an induction generator for wind power conversion and synchronous alternator with automatic voltage regulator (AVR) for diesel unit is presented. The dynamic voltage stability evaluation is dependent on small signal analysis considering a Static VAR Compensator (SVC) and IEEE type -I excitation system. It's shown that the variable reactive power source like SVC is crucial to meet the varying demand of reactive power by induction generator and load and to acquire an excellent voltage regulation of the system with minimum fluctuations. Integral square error (ISE) criterion can be used to evaluate the optimum setting of gain parameters. Finally the dynamic responses of the power systems considered with optimum gain setting will also be presented.

Keywords**—**SVC, Small Signal Stability, Reactive Power, Control, Hybrid System.

I. Introduction

RECENTLY, much emphasis has been placed on the squirrel cage induction machine since the electromechanical energy converter in generation schemes involving renewable energy sources [1]-[4]. The benefits of the induction generator within the synchronous generator are low cost, robustness, no moving contacts, i.e., slip- rings, no synchronization required and no requirement for dc excitation.

However the induction machine takes a reactive power support for the operation [5]-[10]. A large number of papers have appeared in the literature about them and several papers investigate the capacitance requirement of self-excited induction generator under steady state conditions only [1]-[10].

Its practical significance since it enables the design and operation engineers to choose the appropriate value of excitation capacitance for a certain machine. In a stand-alone hybrid power system, the reactive power device needs to fulfil the variable reactive power requirement of the induction generator and of the load. In the absence of proper reactive device and controls the system might be afflicted by large voltage fluctuations, which will be not desirable. The device employed for this function in conventional power systems is recognized as Static Var Compensator (SVC) [11]-[15] can be employed for the hybrid system.

In conventional power system the power is exported on transmission lines to load centres. The reactive power devices are employed in such a way to have minimum reactive power flow on the transmission lines so that maximum power can be exported with minimum transmission loses.

Developments in the field of high voltage power electronics have made possible the practical realization of FACTS controllers. The SVC is the most important FACTS device that has been used for a number of years to improve transmission line economics by resolving dynamic voltage problems. The accuracy, availability and fast response enable SVC's to provide high performance steady state and transient voltage control compared with classical shunt compensation. SVCs can perform the duty of providing rapidly controlled Vars more appropriately and thus, by maintaining the voltage, inherently improve transient stability.

In hybrid systems the load is directly linked to the generator terminals itself. Therefore the aim of the reactive power device in this case is to provide the reactive power required by the load and the induction machine under varying load conditions. The devices AVR and SVC have different functions but both operate on the voltage error signal caused by any disturbance in the system. The main function of the AVR is to maintain the voltage profile constant at the terminals. The alternator also provides partial reactive power to the load. Similarly the main function of SVC is to eradicate the mismatch of reactive power in the system.

The SVC also partially helps in voltage maintenance at the terminals. A new innovative scheme, namely, automatic reactive power control, similar to automatic generation control [12], [14] has been evolved. The scheme is applicable to isolated hybrid power systems. The system state equations have been derived with transfer function block diagram representation of the control system. The voltage deviation signal can be used as area reactive power control error to eliminate the reactive power mismatch in the system. The integral square error (ISE) criterion is employed to evaluate the optimum setting of gain parameters of the controller. Finally transient responses are shown for different disturbance conditions.

II. Reactive Power Balance Analysis

A wind-diesel system is considered for mathematical modeling, where diesel generator (DG) set acts as a local grid for the wind energy conversion system connected to it. The system also has a SVC to provide the required reactive power in addition to the reactive power generated by the synchronous generator. The reactive power balance equation of the system under steady state condition is

$$Q_{SG} + Q_{SVC} = Q_L + Q_{IG} \tag{1}$$

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where Q_{SG} = reactive power generated by diesel generator set, Q_{SVC} = reactive power generated by SVC, Q_L = reactive power load demand, and Q_{IG} = reactive power required by generator.

For the incremental reactive power balance analysis of the hybrid system, let the hybrid system experience a reactive power load change of magnitude ΔQ_L . Due to the action of the AVR and SVC controllers the system reactive power generation increases by an amount $\Delta Q_{SG} + \Delta Q_{SVC}$. The reactive power required by the system will also change due to change in voltage by ΔV. The net reactive power surplus in the system, therefore, equals $\Delta Q_{SG} + \Delta Q_{SVC} - \Delta Q_L - \Delta Q_{IG}$ and this power will increase the system voltage in two ways:

- by increasing the electromagnetic energy absorption E_M of the induction generator at the rate $d/dt(E_M)$,
- by an increased reactive load consumption of the system due to increase in voltage.

This can be expressed mathematically as

$$\Delta Q_{SG} + \Delta Q_{SVC} - Q_L + Q_{IG} = d/dt(\Delta E_M) + D_V \Delta V \tag{2}$$

The electromagnetic energy stored in the winding of the induction generator is given by

$$E_M = \frac{1}{2} L_M I_M^2 = \frac{1}{2} L_M (\frac{V}{X_M})^2 \tag{3}$$

where X_M is the magnetizing reactance of the induction generator. Equation (3) can be further written as

$$E_M = \frac{V^2}{(4\pi f X_M)} \tag{4}$$

From (4), ΔE_M can be written as

$$\Delta E_M = E_M - E_{M^\circ} = 2(\frac{E_{M^\circ}}{V^\circ})\Delta V \tag{5}$$

With increase in voltage all the connected loads experience an increase by $D_V = \frac{\partial Q_L}{\partial V}$ pu kVAR /pu kV. The parameter D_V can be found empirically. The composite loads are expressed in the exponential voltage form as

$$Q_L = C_1 V_q \tag{6}$$

where C_1 is the constant of the load and the exponent q depends upon the type of load. For small perturbations (6) can be written as

$$\Delta Q_L / \Delta V = q(\frac{Q_{L^\circ}}{V^\circ}) \tag{7}$$

In (2), D_V can be calculated empirically using (7). Let Q_R be the system reactive power rating. Using (5), (3) can be written as

$$\Delta Q_{SG} + \Delta Q_{SVC} - \Delta Q_L - \Delta Q_{IG} = \frac{2E_{M^\circ}}{(V^\circ Q_R)} \frac{d}{dt}(\Delta V) + D_V \Delta V \tag{8}$$

In (8) Q_R divides only one term as all the other terms are already in pu KVAR. The term $\frac{E_{M^\circ}}{Q_R}$ can be written as

$$\frac{E_{M^\circ}}{Q_R} = \frac{1}{(4\pi f k_R)} = H_R \tag{9}$$

where H_R is a constant of the system and its units are sec. and k_R is the ratio of system reactive power rating to rated magnetizing reactive power of induction generator. Substituting the value of $\frac{E_{M^\circ}}{Q_R}$ from (9) in (8) we get

$$\Delta Q_{SG} + \Delta Q_{SVC} - \Delta Q_L - \Delta Q_{IG} = (\frac{2H_R}{V^\circ}) \frac{d}{dt}(\Delta V) + D_V \Delta V \tag{10}$$

In Laplace form the state differential equation, from (10), can be written as

$$\Delta V(s) = \frac{K_V}{(1+sT_v)} [\Delta Q_{SG}(s) + \Delta Q_{SVC}(s) - \Delta Q_L(s) - \Delta Q_{IG}(s)] \tag{11}$$

Under transient condition Q_{SG} is given by

$$\Delta Q_{SG} = \frac{(E_q' V \cos\delta - V^2)}{X_d'} \tag{12}$$

where $\Delta E_q'$ = change in the internal armature emf proportional to the change in the direct axis field flux under transient condition. For small perturbation (12) can be written as

$$\Delta Q_{SG} = \frac{(V \cos\delta)}{X_d' \Delta E_q'} + \frac{(E_q' \cos\delta - 2V)}{X_d' \Delta V} \tag{13}$$

Taking Laplace transform of both sides we get

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

where

$$K_3 = \frac{V \cos\delta}{X_d'} \tag{15}$$

and

$$K_4 = \frac{(E_q' \cos\delta - 2V)}{X_d'} \tag{16}$$

The reactive power supplied by the SVC is given by

$$Q_{SVC} = V^2 B_{SVC} \tag{17}$$

For small perturbation (17), taking Laplace transform, can be written as

$$\Delta Q_{SVC} = K_6 \Delta V(s) + K_7 \Delta B_{SVC}(s) \tag{18}$$

where

$$K_6 = 2VB_{SVC} \quad and \quad K_7 = V^2 \tag{19}$$

III. The Flux Linkage Equation

The flux linkage equation of the round rotor synchronous machine for small perturbation is

$$d/dt(\Delta E_q') = (\Delta E_{fd} - \Delta E_q)/T_{do}' \tag{20}$$

where ΔE_q = change in the internal armature emf proportional to the change in the direct axis field flux under steady state condition. T_{do}' = direct axis open circuit transient time constant. In (20) is given by

$$E_q = (X_d - X_d')E_q' - (X_d - X_d')/X_d' \cos\delta \tag{21}$$

For small changes (20), using (21) and taking Laplace transform can be written as

$$(1 + sT_g)\Delta E_q'(s) = K_1 \Delta E_{fd}(s) + K_2 \Delta V(s) \tag{22}$$

where

$$T_g = \frac{X_d' T_{do}'}{X_d} \tag{23}$$

$$K_1 = \frac{X_d'}{X_d} \tag{24}$$

$$K_2 = \frac{(X_d - X_d')}{X_d} \cos\delta \tag{25}$$

IV. Mathematical Modeling of Wind/Diesel System

The block diagram of the system using the Laplace transfer function (11), (14), (18) and (22) with typical SVC scheme and IEEE type I excitation system is shown in Fig. 1. The state equations in a standard form can be written as

$$A\underline{x} + B\underline{u} + C\underline{p} \tag{26}$$

where x, u and p are state, control and disturbance vectors and A, B and C are system, control and disturbances matrices, respectively. The vectors are given by

$$x = [\Delta E_{fd}\ \Delta V_a\ \Delta V_f\ \Delta E_q'\ \Delta\alpha\ \Delta B_{svc}'\ \Delta B_{svc}\ \Delta V]^T \tag{27}$$

$$\underline{u} = [\Delta V_{ref}] \tag{28}$$

$$\underline{p} = [\Delta Q_L] \tag{29}$$

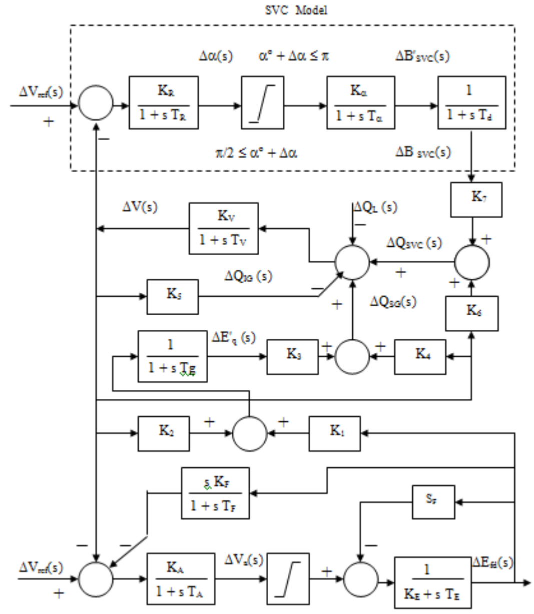


Fig. 1 Transfer function block diagram for reactive power control of wind/diesel hybrid power system

V. Simulation Results

The data of the wind-diesel power system considered for simulation is given in Appendix. The gains are optimized using the Lyapunov technique for continuous linear systems with the performance index based upon the integral square error criterion (ISE) and is given by

$$\eta = \int [\Delta V(t)]^2 dt \tag{30}$$

The optimum value of the parameters corresponds to the minimum value of the performance index. In the studies carried out in this paper η is evaluated over a time period of 2 seconds. The performance index curve for 1% step increase in reactive load demand is shown Fig. 2. The minimum value of the gain parameter obtained is $K_R = 337$.

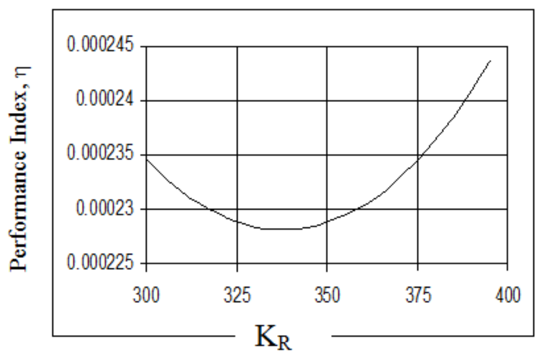
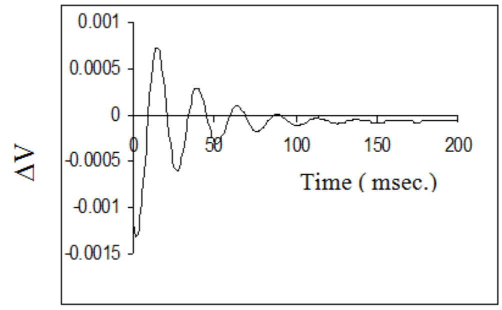


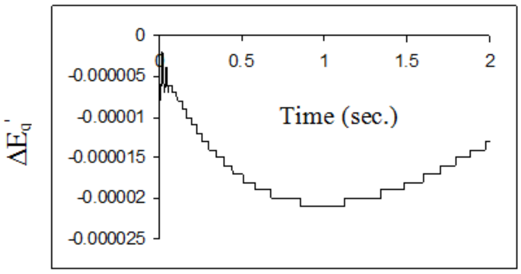
Fig. 2 Optimization of SVC amplifier

The transient response curves of the system for 1% step increase in reactive load for optimum gain settings are shown in Fig. 3. It is observed that the deviation in the system voltage and firing angle vanishes in 150 msec. The deviation in voltage behind transient reactance $\Delta E'_q$ takes maximum time of 3 sec. to vanish as shown in Fig. 3 (b). It is clear from the Fig. 3 that the reactive demand by load and induction generator $\Delta Q_L + \Delta Q_{IG}$ is met by reactive power ΔQ_{SVC} supplied by the SVC with negligible reactive power ΔQ_{SG} supplied by the synchronous generator. The system returns to steady state conditions in 7½ cycles of the supply frequency following a step load disturbance of 1%.

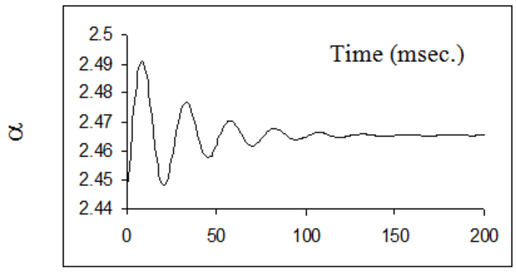
It indicates that AVR controls the voltage of the system and the SVC controls the reactive power of the system.



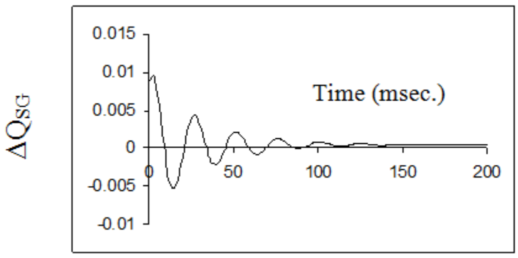
(a)



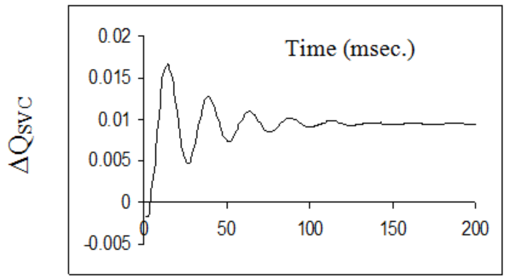
(b)



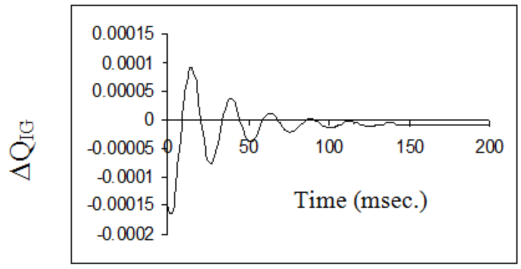
(c)



(d)



(e)



(f)

Fig. 3 Transient responses of the system for 1 % step disturbance in reactive power load

VI. Conclusion

A dynamic voltage stability study has been presented in this paper for the hybrid wind-diesel isolated power system considering transfer function model based on small signal analysis. The automatic reactive power control model using reactive power flow equations have been developed for the first time for hybrid systems. The integral square error criterion has been used to evaluate the optimum gain settings. It has been shown that SVC is essential for an isolated hybrid system to meet the varying demand of reactive power by induction generator and load and to have minimum voltage fluctuations. Finally some of the system transient responses have been shown for optimum gain settings.

Appendix

TABLE I
Ratings and Data of the Typical Example of the Isolated Power System Studied

Generation	Capacity (kW)	Load (kW)
Wind	150.0	150.0
Diesel	150.0	100.0
Total	300.0	250.0

TABLE II
System Parameters

$E_q = 1.1136$ pu	$\delta = 21.05°$	$X_d = 1.0$ pu
$X'_d = 0.15$ pu	$E'_q = 0.9603$ pu	$T'_{do} = 5.0$sec
$T_E = 0.55$ sec	$K_A = 40.0$	$T_F = 0.715$ sec
$K_F = 0.5$	$K_E = 1.0$	$K_R = 337.0$
$T_A = 0.05$ sec	$T_R = 0.05$ sec	$X_{eq} = 1.12$ pu
$Q_L = 0.75$ pu	$R_Y = 4.06415$ pu	$B_{SVC} = 0.73$ pu
$\alpha = 2.443985$	$q = 2.0$	$X_R = 1.0/0.85$ pu
$T_\alpha = 0.02/4$ sec	$T_d = 0.02/12$ sec	

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