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Full Length Research Paper

The investigation of dynamic performance of induction generator in different operational conditions and improving its behaviour using proper FACTS devices

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The object of this paper is to study the possibility of using of SVC and STATCOM in order to improve dynamic performance of induction generator. Also, these two devices have been compared with each other. Induction generators have many advantages in small wind-hydro power plants. On the other hand arising some problems including controlling of voltage and frequency oscillation due to dynamic oscillation of load and also power quality related problems causes us to study these generators widely. In most studies, the performance of generator has been estimated just in continuous mode and by each one the method of designing only one FACTS device has been described. Although in most studies design details and definition of various parameters of these devices have been considered but the behavior of generator with each of these devices, however, and their advantages to each other in different conditions has not been investigated yet. In this paper among comparing the above mentioned devices and clarifying their advantages to each other we show that employing both tools has significant impact on the quality of the produced energy from generators especially self excited ones and this approach would be useful for improving their loading characteristics.

Key words: Dynamic behavior, induction generator, FACTS.

INTRODUCTION

Employing squirrel cage capacitive actuation induction generator in small wind-hydro power plants has many advantages. These generators are inexpensive and strong and their maintenance activities are easy due to absence of ring, brush, commutator, battery and inverter. But they have not been widely employed in form of SEIG in small hydro power plants due to lack of a proper and inexpensive control system (Brazil, 1990; Freitas et al., 2000). When induction machine works as generator, it can supply its magnetic flux (reactive) in two ways. If it is connected to a grid, this flux is supplied through the grid and where it is operated in self excited form, this flux is supplied through capacitor banks. Of course existence of capacitor even in the first case can lead to current reduction of transfer lines which this also leads to reduction of losses and improvement of voltage regulation. The notable fact is that in generating mode the rate of drawn reactive power from grid by an induction machine, for every specific slip, is greater than motor mode and this rate will be increased by increasing generating active power and the minimum value would be at synchronous speed (Brazil, 1990; Marra and Pomilio, 2005).

It should be noted that sometimes the value of reactive power drawn from grid by an induction generator may exceed even than its generating active power. This is an undesirable parameter which may impose unnecessary overload to grid and relative connected synchronous units and as a result may weaken the system in terms of voltage adjusting. To remove this parameter, the necessary reactive power for every induction generator should be compensated locally. As the generation rate of reactive power through capacitor depends on the voltage of generator terminal and it is not possible to vary it

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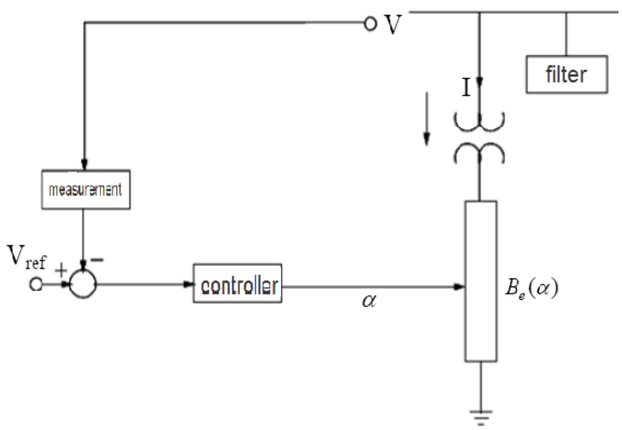

Figure 1. Dynamic model of SVC.

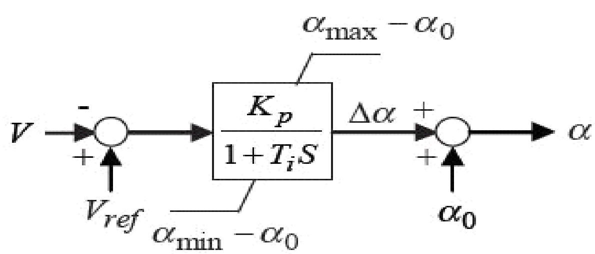

Figure 2. Controller block diagram for fire angle of TCR.

continuously, we need variable reactive power to stabilize the value of frequency and voltage range in different loading conditions which makes it essential to use variable reactive power sources such as FACTS devices.

Until today different papers have been published about this matter. Most of them have been estimated the performance of generator only in continuous mode and although in each one design details and definition of various parameters of these devices have been considered but the behavior of generator along with these devices, however, and their advantages to each other in different conditions has not been investigated.

In Markus (2003) SVC and DSATACOM capabilities in improving induction generators stability are compared. Thus, this paper try to estimate both SVC and DSATACOM and compare them so that preferring one to other in different conditions becomes reasonable. The rest of this paper is structured as follows. In the Modeling generator section, we present dynamic model of induction generator in dq axes and also generator and capacitor equations around these axes. We also discuss SVC and STATCOM models and their controllers. In Simulation section, the method of modeling these devices is presented. Simulation results is obtained by MATLAB software and the profile of voltage and its frequencies under load variation and symmetrical short circuit conditions are analyzed. In the final section offers tools to improve the dynamic bihavior of induction generator is presented.

MODELING GENERATOR

In this paper we use machine model within qd coordinate system (Wang and Deng, 1999). The volt-ampear presented in shows the equations to simplify the calculation of the voltage-flux at any point in time, only one operator is considered a derivative (Krause, 1986).

The relationships ultimately obtained in the form of the Equation (1)

$$\begin{aligned}
p\psi_{qs} &= \omega_b\left[v_{qs} - \frac{\omega}{\omega_b}\psi_{ds} + \frac{R_S}{X_{ls}}\left(\psi_{mq} - \psi_{qs}\right)\right] \\
p\psi_{ds} &= \omega_b\left[v_{ds} - \frac{\omega}{\omega_b}\psi_{qs} + \frac{R_S}{X_{ls}}\left(\psi_{md} - \psi_{ds}\right)\right] \\
p\psi_{qr} &= \omega_b\left[v_{qr} - \left(\frac{\omega-\omega_r}{\omega_b}\right)\psi_{dr} + \frac{R_r}{X_{lr}}\left(\psi_{mq} - \psi_{qr}\right)\right] \\
p\psi_{qr} &= \omega_b\left[v_{dr} - \left(\frac{\omega-\omega_r}{\omega_b}\right)\psi_{qr} + \frac{R_r}{X_{lr}}\left(\psi_{md} - \psi_{dr}\right)\right]
\end{aligned} \quad (1)$$

Velocity moment equation is also obtained by the Equation 2

$$T_e = 2H_P\frac{\omega_r}{\omega_b} + T_L \quad (2)$$

Where, H_P is the inertia constant of turbine and generator. The Equation (3) refers to active and reactive powers.

$$\begin{aligned}
P_e &= \frac{3}{2}(V_{qs}I_{qs} + V_{ds}I_{ds}) \\
Q_e &= \frac{3}{2}(-V_{qs}I_{ds} + V_{ds}I_{qs})
\end{aligned} \quad (3)$$

SVC

Figure 1 shows the dynamic model of SVC (Ahmad, 2004; Canizares, 1999). Since the employed 3 phase SVC reactors have no significant magnetic coupling with each other, their dq model, like capacitor, includes two similar elements in dq axes.

Where, α is firing delay angle and $\beta_e(\alpha)$ effective value according to firing delay.

(Figure 2) shows employed controller block diagram for controlling the fire angle of thyristor.

STATCOM

Dynamic model of STATCOM and its controllers are

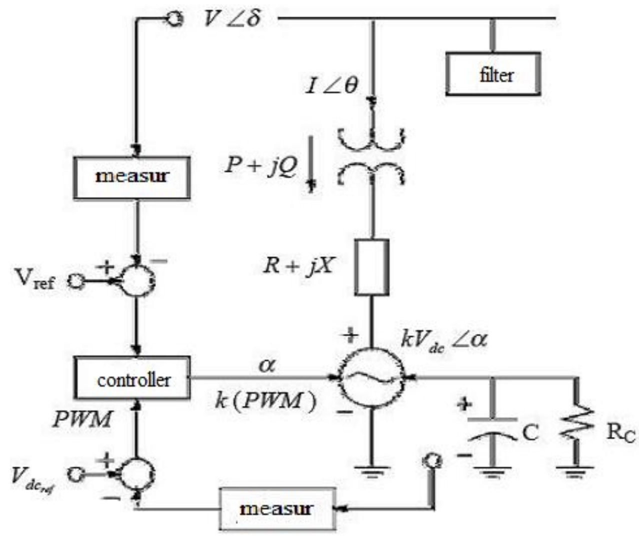

Figure 3. Dynamic model of STATCOM.

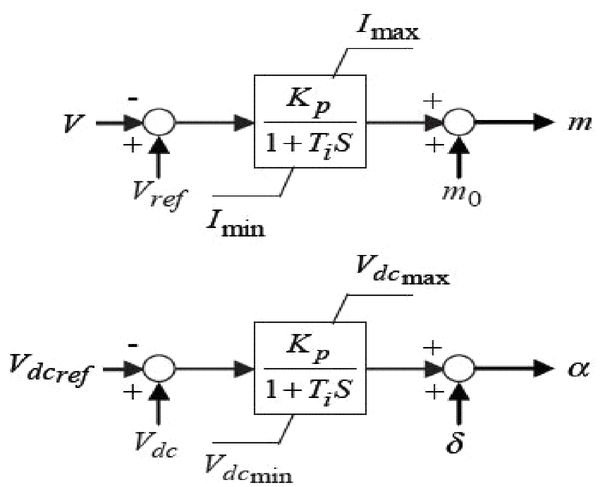

Figure 4. Dynamic model of STATCOM.

presented in (Figure 3) and (Figure 4) (.Canizares, 1999).

In (Figure 3) m is modulation index; δ is grid voltage angle and α is terminal voltage phase angle.

SIMULATION

State variables are qd axes fluxes and rotor speed and for the generator, a capacitor voltage is also considered along with capacitor itself. In SVC, state variable is variations of fire angle and for STATCOM these variables are DC bus voltage; modulation index PWM and the voltage angle of inverter. The equations of dq axes fluxes regarding to magnetic saturation phenomenon is presented in the Equation (4) where, function *f* is presented by the statemen (Krause, 1986; Sun-Chun and Wang, 2003) .

$$\psi_{mq} = X_{aq}\left(\frac{\psi_{qs}}{X_{ls}} + \frac{\psi_{qr}}{X_{lr}}\right) - \frac{X_{aq}}{X_M} f(\psi_{mq}) \qquad (4)$$

$$\psi_{md} = X_{ad}\left(\frac{\psi_{ds}}{X_{ls}} + \frac{\psi_{dr}}{X_{lr}}\right) - \frac{X_{ad}}{X_M} f(\psi_{md})$$

$$f(\psi_m) = \psi_m - \tan^{-1}(\psi_m) \qquad (5)$$

Capacitor voltage and current equations are as follows:

$$i_{qc} = \omega C v_{ds} + Cp v_{qs} \qquad (6)$$

$$i_{dc} = \omega C v_{qs} + Cp v_{ds}$$

The employed equations for simulation of SVC are as follows:

$$\alpha = \Delta\alpha + \frac{\pi}{2}$$

$$B_e = B_0\left[2 - \frac{(2\alpha - \sin 2\alpha)}{\pi}\right] \qquad (7)$$

$$p\Delta\alpha = \frac{k_p}{T_i}(V - V_{ref}) - \frac{\Delta\alpha}{T_i}$$

STATCOM model is obtained in every instant by the Equation (8) according to low of conservation of energy. Dc bus voltage within STATCOM is obtained by the Equation (9).

$$P_{ac} = P_{dc} + P_{loss} \qquad (8)$$

$$PV_{dc} = \frac{VI}{CV_{dc}}\cos(\delta - \theta) - \frac{G_c}{C}V_{dc} - \frac{RI^2}{CV_{dc}} \qquad (9)$$

The employed parameters within this equation are shown in (Figure 3).

We can obtain differential equations of modulation index and phase angle of STATCOM terminal voltage with regard to controller block shown in (Figure 4). These equations are shown in statements (10) and (11) as follows (Canizares, 1999)

$$P_m = \frac{K_p}{T_i}(V_{ref} - V) - \frac{\Delta m}{T_i} \qquad (10)$$

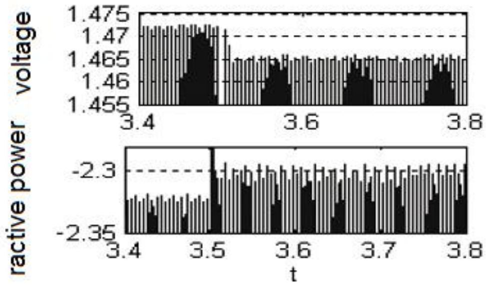

Figure 5. The performance of grid connected generator under over load condition.

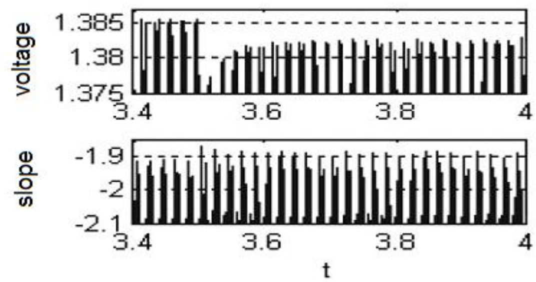

Figure 9. The performance of generator with STATCOM under over load condition.

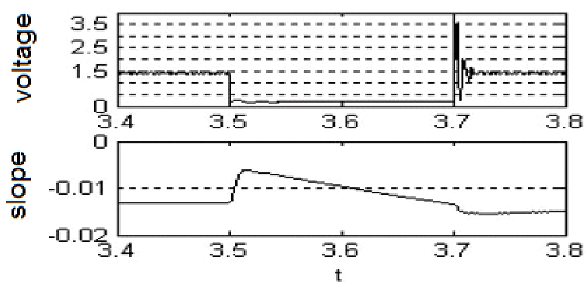

Figure 6. The performance of grid connected generator under short circuit condition.

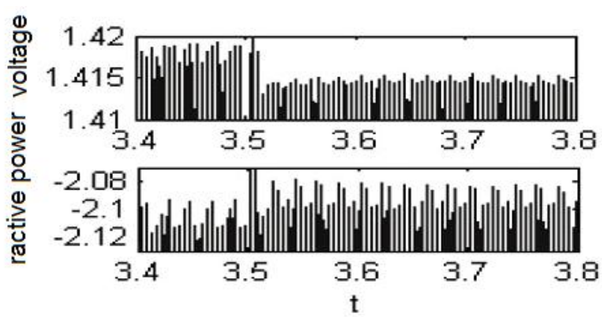

Figure 7. The performance of generator with SVC under over load condition.

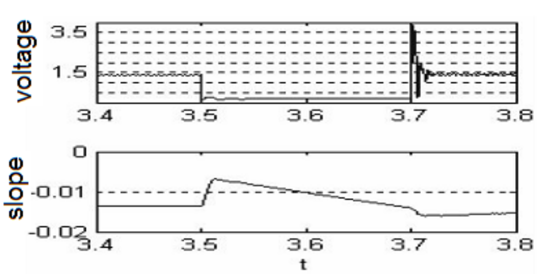

Figure 8. The performance of generator with SVC under short circuit condition.

$$P\Delta\alpha = \frac{K_P}{T_i}(V_{dcref} - V_{dc}) - \frac{\Delta\alpha}{T_i} \qquad (11)$$

SIMULATION RESULTS

In this section we discuss simulation of generator in states of grid connected and self excited respectively and in both of them we investigate employment of SVC and STATCOM under following dynamic conditions:

1-increasing of load by 25%
2-symmetrical short circuit
*point: All figures are in terms of units in the Perunit.

Grid connected induction generator (GCIG)

Generator without compensator: Figure 5 shows the shape of voltage wave and reactive power drawn from grid in t>3.5 s under increasing of load by 25% condiion. Voltage range before over load was 1.472 perunit and after that it has reached to 1.465 perunit. (Figure 6) shows the shape of voltage wave and slip curve under short circuit condition. This Figure shows that the speed of generator has been increased 0.002 per unit during 0.2 s short circuit condition between 3.5 s<t<3.7 s and reached to its permanent voltage level after 0.045 s.

Generator with SVC: In Figure 7, the performance of a grid connected machine with SVC is presented. Voltage range before over load was 1.419 and after over load it has reached to 1.415. (Figure 8) shows generator performance under short circuit condition. The speed of generator has been increased 0.0017 per unit during 0.2 s short circuit condition and reached to its permanent voltage level after 0.040 s.

Generator with STATCOM: Figure 9 shows the performance of grid connected generator with STATCOM.

The effective voltage value before over load was 1.385 and after over load it has reached to 1.382. (Figure 10)

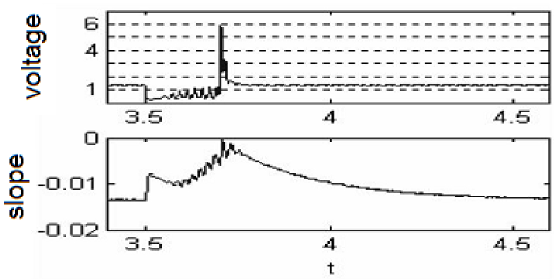

Figure 10. The performance of generator with STATCOM under short circuit condition.

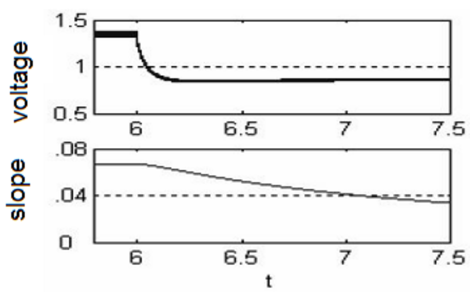

Figure 11. The performance of self excited generator under over load condition.

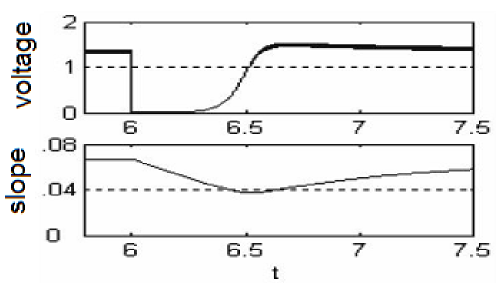

Figure 12. The performance of generator under short circuit condition.

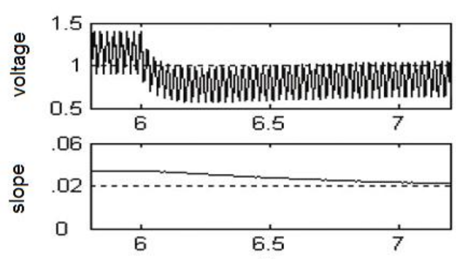

Figure 13. Performance of self excited generator with SVC under over load condition.

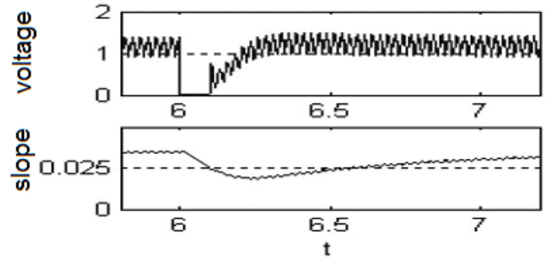

Figure 14. performance of self excited generatorwithSVC under short circuit condition.

shows the performance of the generator under short circuit condition. The speed of generator has been increased 0.0013 per unit during 0.02 s short circuit condition and reached to its permanent voltage level after 0.19 s.

Self excited induction generator

Generator without compensator: Figure 11 shows performance of generator under 25% over load condition in 6.0 <t. Voltage range was 1.35 before over load and it has reached to 0.855 after over load. The value of frequency before over load was 46.2 Hz and after over load it has reached to 48.5 Hz. So the generator is not responsible for this over load. Thus, load current has been reduced due to drop in terminal voltage. This resulted in reduction of stator current and resistance moment values and hence the frequency increased about 2.3 Hz. (Figure 12) shows the performance of generator under short circuit condition.

The speed of generator has been increased 0.03 per unit during 0.1 s short circuit condition between 6.0 s<t<6.1 s and reached to its permanent voltage level after 2.75 s. In this situation, since the speed of generator has been increased, the recovered voltage has a peak point in t = 6.65 s and its value is 0.15 and by reducing the speed of generator it has reached in t = 8.95 s to the value of before short circuit condition.

Generator with SVC: Figure 13 shows the performance of self excited generator with SVC. Voltage range before over load was 1.391 and after over load it has reached to 1.048.

Also, the value of frequency before over load is 47.5 Hz and after over load it has reached to 49 Hz. Figure 14 shows the performance of generator under short circuit condition. The speed of generator is increased 0.03 per unit during 0.1 s short circuit condition and reached to permanent voltage level after 0.31 s.

Generator with STATCOM: Figure 15 shows the performance of self excited generator with STATCOM.

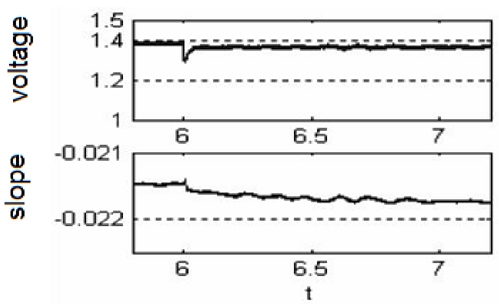

Figure 15. Performance of self excited generator with STATCOM under over load condition.

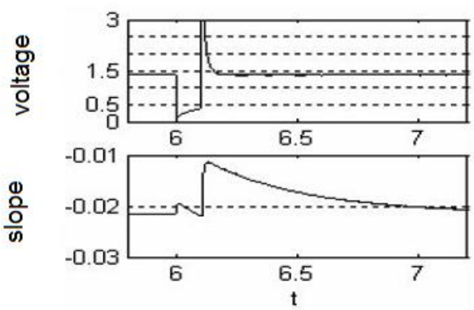

Figure 16. Performance of self excited generator with STATCOM short circuit condition.

Voltage range before overload was 1.3892 and after over load it has reached to 1.3738. Also, the value of frequency before over load was 48.94 Hz and after over load it has reached to 48.91 Hz.

Figure 16 shows the performance of generator with STATCOM under short circuit condition. The speed of generator has been increased 0.01 per unit during 0.1 s short circuit condition and reached to its permanent voltage level after 0.08 s.

CONCLUSION

Grid-connected case

In this situation, because the generator is connected to an infinite bus, the reactive power supply is no problem. FACTS equipment deployment is to stabilize the terminal voltage and capacitor banks. So, in GCIG case, SVC and STATCOM have no advantages to each other in terms of performance. Under short circuit condition, the above mentioned compensators has no significant effect on voltage build up process and SVC could only accelerate this process 0.005 s. (From 0.04 to 0.045) because during voltage build up process what is applied from SVC on the board is just fixed capacitors, whereas STATCOM causes 0.19 s delay because it needs to supply its DC bus charge.

Self excited case

FACTS devices has very significant role in this case. It has been shown that a SVC has significant role in controlling the voltage of generator and load oscillations in dynamic conditions and results in less reduction of generator voltage.

In this paper increased 25% to meet increased load is realized that SVC. Against STATCOM is added to the load imposed on the frequency response can be better established. As frequency problems of SEIG(s) arise due to voltage level stabilizing problems, using STATCOM and then SVC in a wind farm would be effectively helpful in producing energy with standard quality.

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Appendix. Basic values for conversion (pu). Base power: 660KVA; base voltage: 690 V.

Generator specifications		
Nominal power (KVA)	660	
Nominal voltage V	690	
Nominal frequency Hz	50	
Magnetizing reactance	13.8	
Stator resistance	0.087	
Stator reactance	0.302	
transmitted resistance to rotor in nominal frequency Ω	0.228	
transmitted reactance to rotor in nominal frequency Ω	0.302	
SVC values	X_c	X_L
GCIG case	1 pu	3 pu
SEIG case	3 pu	3 pu
STATCOM values		
Voltage of AC terminal connected to step up transformer	230 V	
DC bus voltage	400 V	
Nominal current	11.9 A	
DC bus capacitor	470 μF	
Moving transmission line specification		
resistance	0.015 pu	
reactance	0.15 pu	
Controller parameters	K_p	T_i
In all blocks	10	0.01