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Bulk Power System Low Frequency Oscillation Suppression By FACTS/ESS

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Virginia Tech   Tennessee Valley Authority   EPRI   Univ. of Missouri-Rolla

***Abstract*-- Low frequency oscillations in the interconnected power systems are observed all around the world. In this paper, the authors studied the inter-area mode low frequency oscillations by analyzing the phenomena in Nashville area of the Tennessee Valley Authority (TVA) system. Our study revealed 4 dynamic groups of generators in this area. Within each group, generators swing together and have the same dynamic trend. Generators from different dynamic groups swing against each other. The authors studied the possibility of using a FACTS/ESS controller to damp the low frequency oscillations in Nashville area. The active power is controlled to damp the low frequency oscillation while the reactive power is controlled to keep the local bus voltage at a constant level. The simulation results of the actual TVA system showed that the energy storage devices can be used for power system low frequency oscillation damping. The study also showed that the wide area measurements could be used as inputs for improved FACTS/ESS control.**

***Index Terms*-- energy storage system, FACTS, low frequency oscillation, damping, power system simulation, PSS/E.**

I. INTRODUCTION

Containing large amount of different dynamic devices, low frequency oscillations in some parts or between parts of the interconnected power systems are commonly experienced in modern power systems. The low frequency oscillations in power systems take place as the synchronous generators swing against each other. The frequency range of these oscillations is from 0.1 to 2.5 Hz. It is related to the dynamic power transfer between areas. At times, the oscillations may continue to grow causing the instability of power systems. There are two types of such oscillations referred to as local mode and inter-area mode, corresponding to a single-machine-to-infinite-bus structure, and those occurs in interconnected power systems respectively [1-3].

Although a number of ways are available for damping the low frequency oscillations in power system, the power system stabilizer (PSS) is the most commonly used one. It operates by generating an electric torque in phase with the rotor speed. In most cases, the PSS works well in damping oscillations. However, because the parameters of PSS is tuned by the original system parameters, its control has less flexibility, which means the control results is far from idea if the operating conditions and/or structures of the system change [2].

Other modern controllers used to damp the power system oscillation may include high-voltage dc (HVDC) lines, static var compensators (SVCs), thyristor-controlled series capacitors (TCSCs), and other such flexible ac transmission system (FACTS) equipments. FACTS devices have the advantage of flexibility of being located at the most suitable places to achieve the best control results [2,4-7].

FACTS/ESS technology has the advantages in both energy storage ability and flexibility of its power electronics interface. FACTS/ESS technology offers an alternative way in damping low frequency oscillations. FACTS/ESS has been employed due to its capability to work as active and reactive power generation and absorption systems. Besides the task of voltage control, it may also be applied to improve the transmission capability and system stability [11,12, 16-19].

In this paper, the authors analyzed the low frequency oscillation phenomena in Nashville area of the TVA system. The oscillation observed behaves like an inter-area mode oscillation. There are 4 different dynamic groups of generators. Generators swing against others in different groups. In the same group, generators do not swing against each other. They have the same dynamic trends. The authors designed a FACTS/ESS controller and used it to damp the low frequency oscillation in Nashville area. The active and reactive power controls of FACTS/ESS are independent. The active power of FACTS/ESS is controlled to damp the low frequency oscillation and the reactive power of FACTS/ESS is controlled to keep the local voltage at a standard level. The active power control signal is actually taken remotely for better sensitivity and control results.

II. ANALYSIS OF LOW FREQUENCY OSCILLATION IN BULK POWER SYSTEM

This section will study the oscillation mode of the system. The dynamic equation of the one-machine-to-infinite-bus system in Fig. 1 is given as follows [8].

$$\begin{cases} M\dfrac{d\omega}{dt} = P_m - P_e - D(\omega - 1) \\ \dfrac{d\delta}{dt} = \omega - 1 \end{cases} \tag{1}$$

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In which, M is generator inertia, D is the damping factor, δ and ω are the generator angle and speed respectively. The generator active power output is give as:

$$P_e = \frac{E'U}{X_\Sigma}\sin\delta \tag{2}$$

where X_Σ contains X_d' and the impedance of transformer and line.

The standard eigenfunction of equation (1) follows when $\Delta P_m = 0$.

$$p^2 + 2\xi\omega_n p + \omega_n^2 = 0 \tag{3}$$

where,

$$\omega_n = \sqrt{\frac{K}{M}} \tag{4}$$

which is the natural oscillation frequency when there is no damping (D=0). In (4), the synchronizing factor K is defined as

$$K = \frac{E'U}{X_\Sigma}\cos\delta_0 \tag{5}$$

here δ_0 is the generator angle.

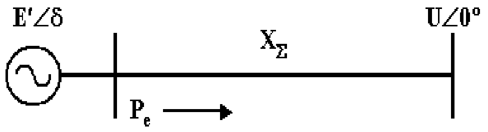


Fig. 1. One-machine-to-infinite-bus system.

The above equations indicate the generator rotor angle deviation $\Delta\delta$ will oscillate against the infinite system at the frequency ω_n during the dynamic period after the disturbance. The oscillation will decrease if there is damping (e.g. D≠0).

If we simplified a multi-machine power system to the following quasi-second-order system shown in Fig. 2, we can have the following similar dynamic equations. Here p is d/dt in Fig. 2.

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{D} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} \tag{6}$$

Where $\mathbf{K} = \frac{\partial P_e}{\partial \delta} = \mathbf{K}_1$, called synchronous torque factor matrix. $\mathbf{I}$ is the unit matrix. $\mathbf{M}$ and $\mathbf{D}$ are the inertia and damping factor matrix respectively.

The standard eigenfunction of (6) will be given in (7).

$$\mathbf{M}\Delta\ddot{\delta} + \mathbf{D}\Delta\dot{\delta} + \mathbf{K}\Delta\delta = \mathbf{0} \tag{7}$$

We can roughly analyze the low frequency oscillation in a multi-machine system the same way as in the above one-machine-to-infinite-bus system. But for a very detailed analysis, the whole system linearized state equation must be used. Analysis schemes such as SMA (selective modal analysis) and AESOPS (analysis of essential spontaneous oscillation in power systems) may be necessary [8].

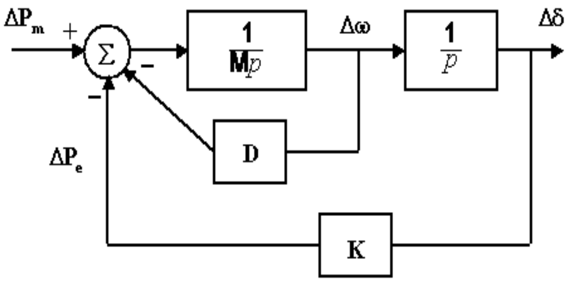


Fig. 2. Simplified multi-machine power system function.

In equation (2), when X_Σ is small, then K in equation (5) is large, then the ω_n value in (4) will be high. That means if the electrical distance between generators is small, the generators will oscillation at a high frequency. Generally, if the oscillation frequency is higher than 1Hz, it could be viewed as generator oscillation within a same area, or local mode (plant mode). If the oscillation frequency is low (around 0.2~0.5 Hz), it is classified as inter-area oscillation mode.

In this study, we use the Eastern U.S. System model. The system buses from 765 kV to distribution level. There are about 2313 generators and 10808 buses in the system data. The capacity of the whole system is about 60.8 GVA, with 59.2 GW active generation and 13.7 GVAR reactive generation. The load of the whole system is about 58.5 GW active load and 20.4 GVAR reactive load. The researched Nashville area is within the TVA system shown in Fig. 3. In this area, there are about 4 dynamic generator groups located at Cumberland, Gallatin, Kingston, and Wilson. Low frequency oscillation has been monitored among these generator groups after a disturbance. We select one generator from each dynamic cluster (group) as a representative, which are unit 1 at Cumberland, unit 2 at Gallatin, unit 3 at Kingston, and unit 4 at Wilson. The disturbance in this study is a 5 cycles three-phase short circuit fault at north Nashville (see Fig. 3). During the fault, there is no bypass of the FACTS/ESS devices.

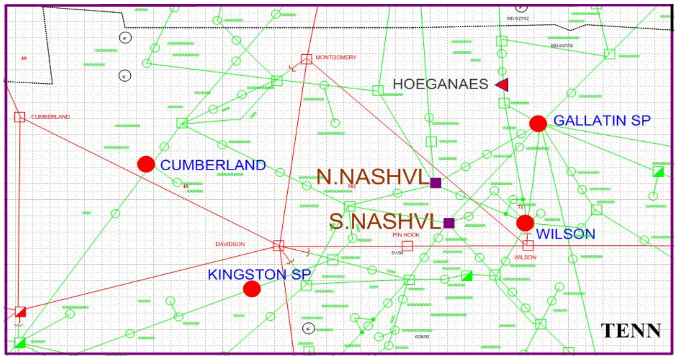


Fig. 3. TVA system one-line-diagram at Nashville area.

As an example, Fig. 4 shows the generator angle oscillations of the 4 generator-units at the 4 locations after a disturbance. The oscillation frequency is about 0.6 Hz.

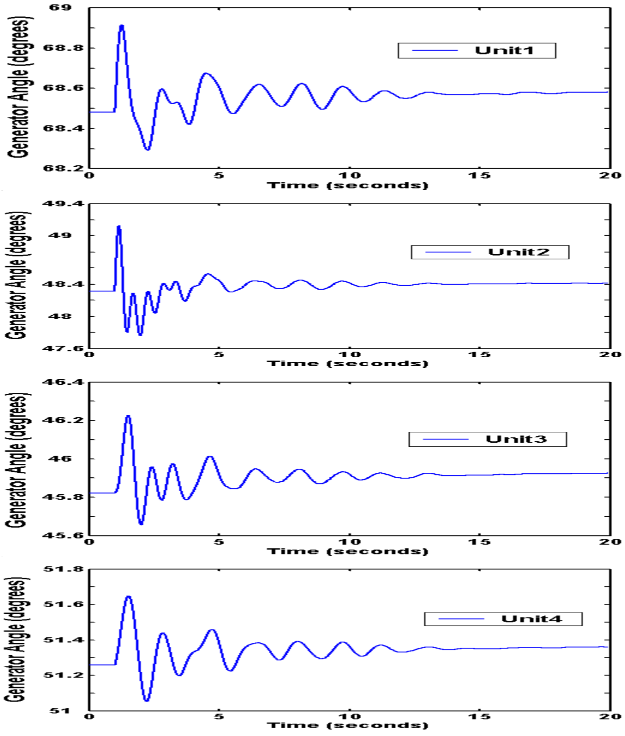


Fig. 4. Generator angle oscillations in the 4 different areas.

Fig. 5 is the relative angle of the generators in other three areas (Unit1, Unit2 and Unit3) against the one in Wilson area (unit4). Low frequency oscillation phenomena are found in these figures.

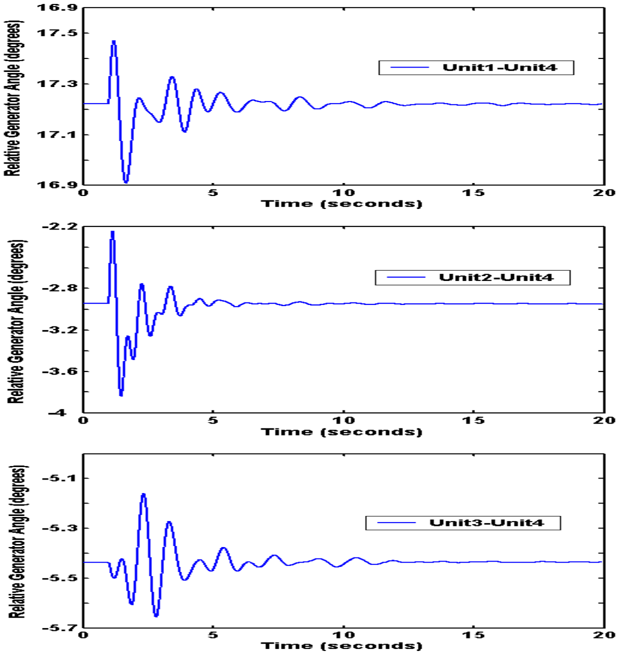


Fig. 5. Relative generator angle of Unit 1 (Cumberland), Unit 2 (Gallatin), and Unit 3 (Kingston) against Unit 4 (Wilson).

In the same group, generators have no relative oscillation against each other as shown in Fig. 6. We selected 4 generators in the group at Wilson name them Gen1, Gen2, Gen3 and Gen4. Fig. 6 is the relative generator angle of the above 4 generators against Unit4 in the same group. We can see that there is no relative oscillation. The generators from different area groups have low frequency oscillation against each other after a disturbance.

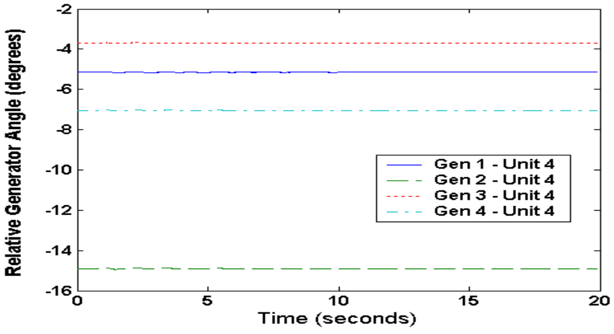


Fig. 6. Relative generator angle against Unit 4 the group No. 4 at Wilson.

Fig. 7 is the oscillation in generator active power output. Dynamics of inter-area power transfer are observed. Of course, the active power of generator oscillates at the same frequency of that of generator angle which is about 0.6 Hz. Fig. 8 is the reactive power output of the four generator-units. There is no oscillation of the generator reactive power. The reason lies in that the terminal voltage of each one does not change violently. The reactive power of Unit1 and Unit2 changes a little to control the local voltage during and after the fault. Reactive power of Unit3 and Unit4 has no change either during or after the fault which means the local voltage does not change much at all.

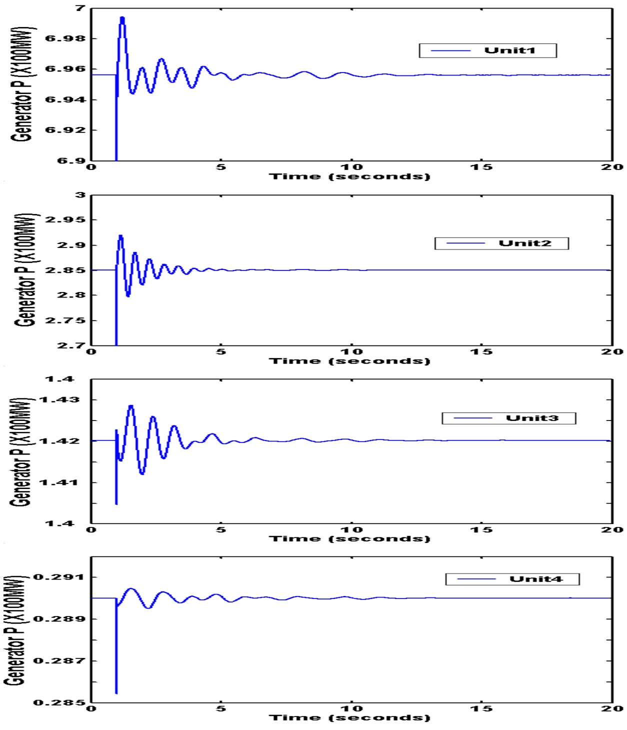


Fig. 7. Generator output active power oscillation.

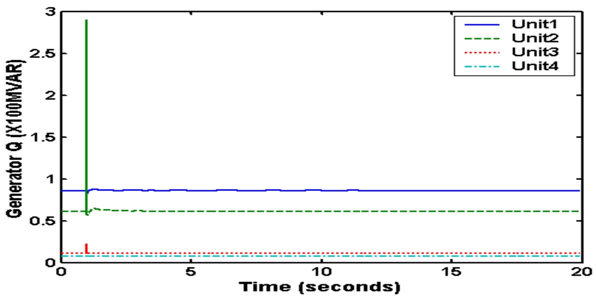


Fig. 8. Generator output reactive power.

Fig. 9 is the low frequency oscillation distribution of 17 generators. We chose several generators in each group at the 4 different locations: No.1 and No.2 are located at Cumberland (there are two generators in this area), No.3~No.7 are located at Gallatin, No.8~No.12 are at Kingston, and No.13~No.17 are at Wilson. We can see that generators in Gallatin oscillate more violently than those in the other groups.

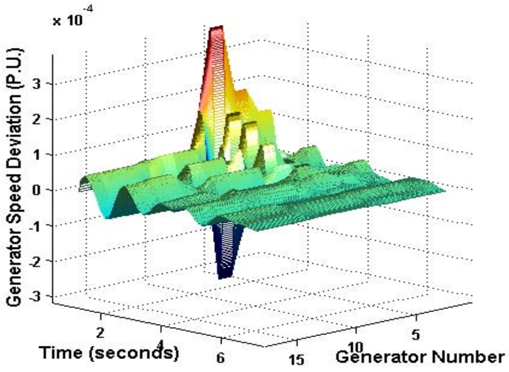


Fig. 9. Low frequency oscillation distribution within the research area.

In the past, a great deal of attention has been given to local mode of low frequency oscillations. However, due to the increasing complexity and the need of detailed representation of the entire system, knowledge about the characteristics of inter-area modes and associated control methods are still lacking and warrant further study [1]. Nashville case is a typical inter-area mode oscillation in a complex bulk power system. As the above figures show, the oscillation mode of Nashville is complex. The oscillation does not happen only between two areas, but among several different areas.

III. POWER SYSTEM LOW FREQUENCY OSCILLATION DAMPING BY FACTS/ESS

FACTS (without ESS) devices can only utilize and/or redirect the power and energy available on the ac system and consequently are limited in the degree of freedom and sustained action to the power grid. Adding ESS to FACTS is able to rapidly inject or absorb active and reactive power, as a result, will increase the effectiveness of the overall control. Thus, functions such as system stability, transmission capacity, and the overall supply quality provided by power electronic devices, including FACTS devices, can be significantly enhanced by the ability of the ESS to support the actions associated with active power control [9, 16-19].

The configuration of FACTS/ESS in this study consists of three main parts shown in Fig. 10: an energy storage system such as battery energy storage system (BESS) or superconducting magnetic energy storage system (SMES), a power converter, and a transformer. The converter produces a three-phase voltage at the secondary winding of the transformer. This voltage can be varied in magnitude and phase with respect to the voltage on the high side of the transformer. The reactive power exchange between the converter and the ac system is controlled by varying the phase of the secondary voltage, the converter, effectively, a STATCOM that has the added feature of facilitating active power flow between its dc and the ac side.

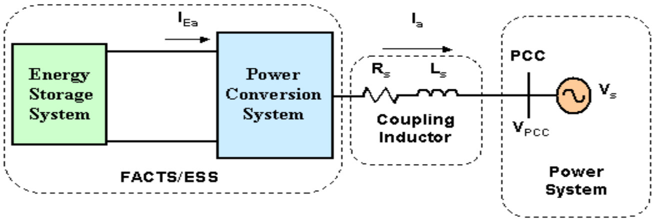
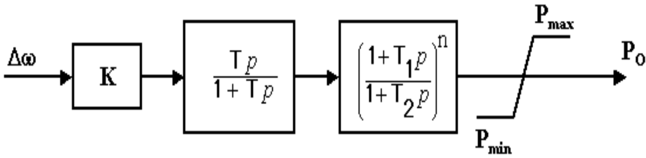
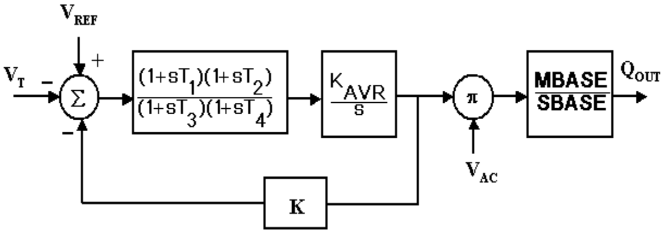


Fig. 10. The configuration of FACTS/ESS.

The control functions of the FACTS/ESS have two parallel independent parts for active power control and reactive power control. The active power control is to control the active power output of FACTS/ESS to suppress the generator rotor oscillation [8]. The reactive power control is to keep the terminal voltage at the reference value [10]. Fig. 11 is the control blocks of the two parts. In Fig. 11 (a), the K in the first block is the multiplying factor. The second block is the resetting block which makes P_{out} zero when t → ∞. The third block is a phase compensation block which will make P_{out} be synchronous with $\Delta\omega$. In Fig. 11 (b), K_{AVR}, T_1, T_2, T_3, and T_4 are the gain and time constants of the automatic voltage regulator. K is the negative feed back factor. In our case, there is no phase shift with n=0.



(a) Active power control function of FACTS/ESS



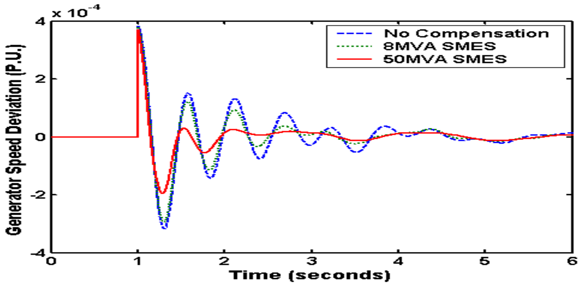
(b) Reactive power control function of FACTS/ESS

Fig. 11. Control function chart of FACTS/ESS controller.

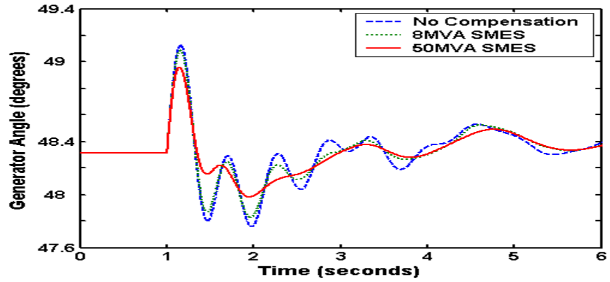
In this study, the FACTS/ESS is located at the Hoeganaes substation near Gallatin (as planned by TVA) to damp the generator rotor oscillation in Gallatin Steam Plant (Unit 2). The control signal Δω (generator rotor speed deviation of Unit 2 at Gallatin) is used as input to control the active power of ESS which is assumed available from synchronized wide area measurement. The reason to choose it as the input signal is two fold. The generator speed deviation Δω of Unit2 at Gallatin is the largest one within the whole system (Fig. 9) and the two places are nearby.

Either the size of 8MVA or 50MVA FACTS/ESS at Hoeganaes substation are studied in the simulation. Fig. 12 to Fig.15 are the simulation results with the FACTS/SMES as the example. Fig.16 shows that the FACTS/BESS has the same control effect as the FACTS/SMES.

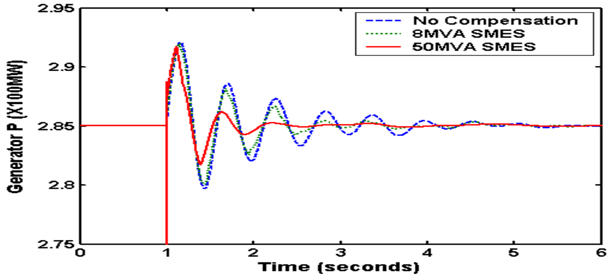
Fig 12 is the Unit 2 (at Gallatin) generator rotor speed control effects by different capacity FACTS/SMES, including the generator speed, angle, and active power output. The results show that the 50MVA FACTS/SMES has reasonably good control result. The effect of the 8MVA FACTS/SMES is obviously much less effective then the 50MVA. However, it seems to be working well after 2-3 cycles, when the oscillation magnitude has dropped to a lower level.



(a) Unit2 (Gallatin) generator rotor speed deviation.



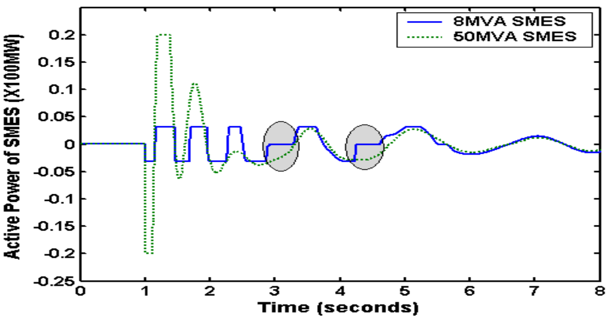
(b) Unit2 (Gallatin) generator angle.



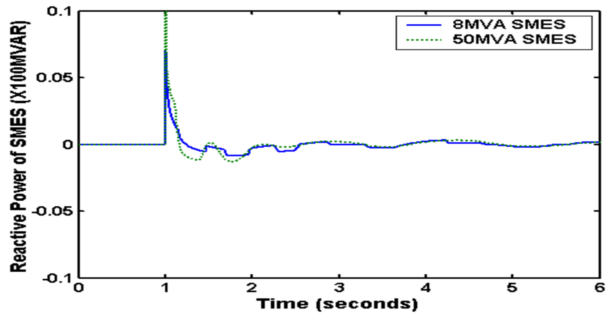
(c) Unit2 (Gallatin) generator active power output.

Fig. 12. Unit2 (at Gallatin) control effects by different capacity FACTS/SMES located at Hoeganaes.

Fig. 13 is the FACTS/SMES output active and reactive power. We can find that in Fig. 13 (a), both the 50MVA and 8MVA FACTS/SMES have the maximum active power output for some periods of time because of the high K control scheme. The output active power of 8MVA FACTS/SMES is zero for some periods of time (shaded areas) because it cannot absorb enough active power with its capacity limit. The reactive power outputs in Fig. 13 (b) are almost the same.



(a) FACTS/SMES output active power.



(b) FACTS/ESS output reactive power.

Fig. 13. FACTS/SMES output active and reactive power.

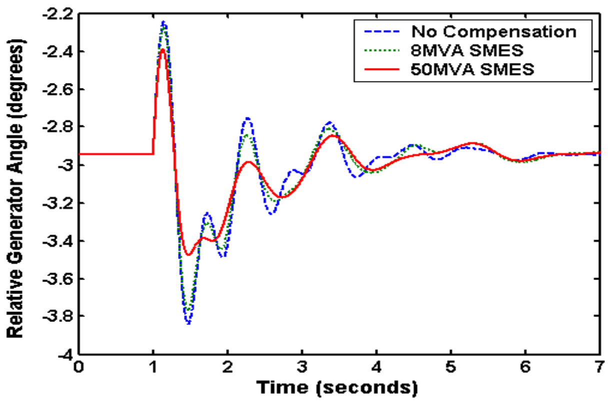
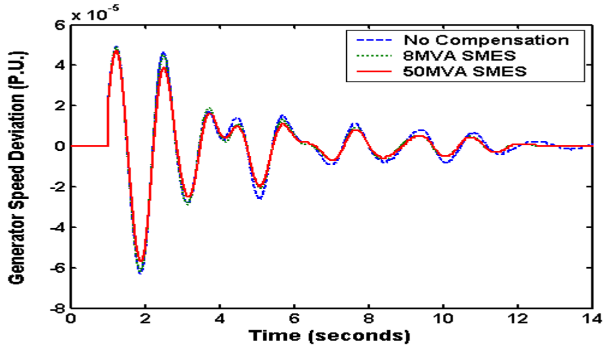


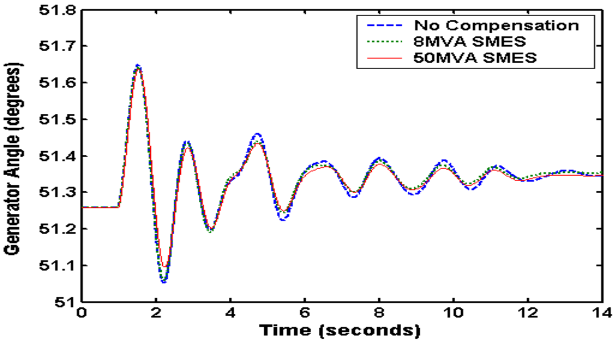
Fig. 14. The relative angle oscillation between Unit 2 (Gallatin) and Unit 4 (Wilson).

Fig. 14 is the relative angle oscillation between Unit 2 (Gallatin) and Unit 4 (Wilson). We can see that the 50MVA FACTS/SMES has better control result than the 8MVA one.

The damping result for the Unit 4 generator (at Wilson) is not obvious in Fig. 15 because the FACTS/ESS device is located quite some distance from Wilson.



(a) Unit 4 (Wilson) generator speed deviation.



(b) Unit 4 (Wilson) generator angle.

Fig. 15. Unit4 (at Wilson) control effects by different capacity FACTS/SMES located at Hoeganaes.

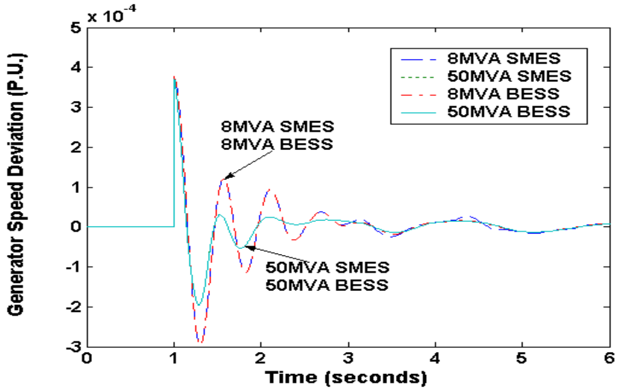
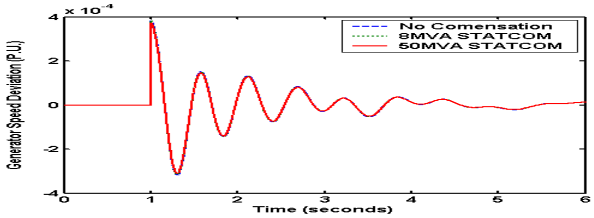
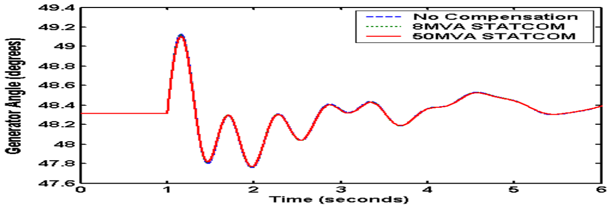


Fig. 16. Comparison of the control effect of FACTS/BESS and FACTS/SMES (Unit 2 at Gallatin).

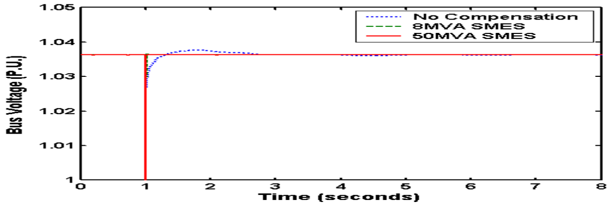
We also look at the STATCOM in our study case. 8MVA and 50MVA STATCOM are installed at the same location in Hoeganaes. The control scheme of STATCOM is the same as that used for reactive power control of FACTS/ESS shown in Fig. 11 (b). The STATCOM is to control its local terminal voltage during and after the fault. As we see in Fig. 17, the local terminal voltage of STATCOM does not have much change soon after the fault. The reactive power output of the STATCOM drops down to almost zero in response to the slight change of the local voltage after fault. For the above reason, STATCOM under this control mode has little effect on damping the oscillation as shown in Fig. 17 (a) and (b).



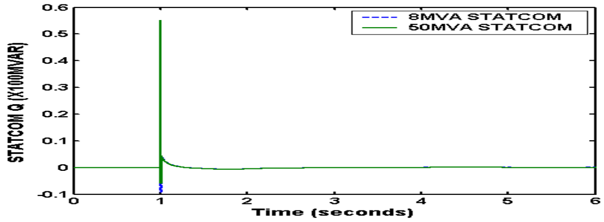
(a) Unit2 (Gallatin) generator rotor speed.



(b) Unit2 (Gallatin) generator angle.



(c) Local terminal bus voltage at Hoeganaes.



(d) Reactive power output of different capacity STATCOM.

Fig. 17. Control effects of different capacity STATCOM.

Fig. 18 is the control effects of the whole research area by 50MVA FACTS/EES. Comparing with Fig. 9, we can see that the oscillation in Group No.2 at Gallatin has been damped to a very low level soon after fault. But the damping results for the generators in the other three areas are not very obvious. That is the limit by the location of the FACTS/ESS unit.

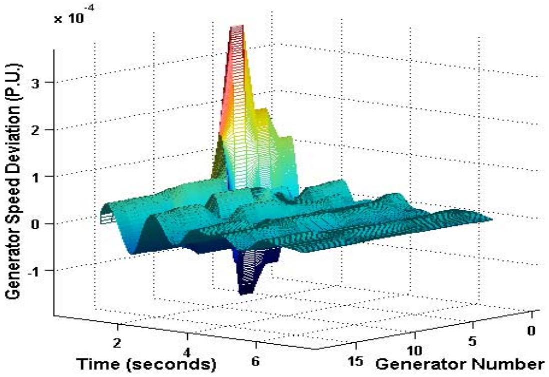


Fig. 18. Low frequency oscillation control results by 50MVA FACTS/SMES.

IV. DISTRIBUTED FACTS/ESS CONTROL SCHEME

As we seen from the previous FACTS/ESS control results, the concentrated allocation FACTS/ESS device cannot damp low frequency oscillation in all four area generator groups. It can only successfully damp local low frequency oscillations.

For the inter-area oscillation mode of a wide area, we tested the distributed location scheme in which we divided the 50MVA FACTS/ESS into 4 equal 12.5MVA parts located in the four areas: Cumberland, Gallatin, Kingston, and Wilson. Table 1 listed the maximum generator speed deviation of the 4 generator units from each area for (a) no compensation, (b) 50MVA concentrated FACTS/ESS located at Hoeganaes and (c) distributed compensation by 4 one of the 12.5 MVA devices located in 4 areas. The result of the distributed scheme is better that the concentrated one.

Table1 is the comparison of the control results for the above tow different control schemes. Even though the concentrated FACTS/ESS control scheme can damp the local low frequency oscillation to a lower level than that of the distributed one, but the distributed FACTS/ESS control has a better control results from the power of view of wide-area control results.

TABLE1 COMPARISON OF THE CONTROL RESULTS

	Maximum Generator Speed Deviation (x10^{-4} P.U.)		
	No Compensation	Concentrated FACTS/ESS	Distributed FACTS/ESS
Unit1	0.647	0.56	0.512
Unit2	3.234	1.93	2.74
Unit3	0.857	0.809	0.512
Unit4	0.639	0.566	0.485

Fig. 19 is the control effect of the distributed compensation scheme. The oscillation in the four area generator groups has been suppressed to a lower level and the oscillation duration is shorter than that shown in Fig. 18.

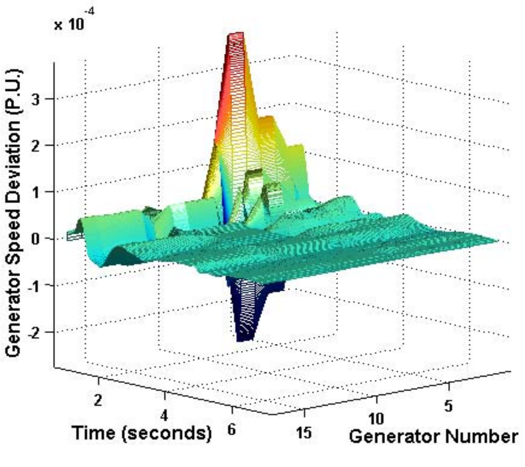


Fig. 19. Low frequency oscillation control results by 12.5MVA distributed FACTS/SMES.

V. CONCLUSION

The authors studied the inter-area mode power system low frequency oscillations by analyzing the low frequency oscillation phenomena in Nashville area of the TVA system. There are 4 dynamic groups of generators that oscillate against each other. The authors designed a FACTS/ESS controller and use remote generator speed deviation as one of the control inputs to damp the low frequency oscillations in Nashville area. While the active power of FACTS/ESS is controlled to damp the Gallatin local low frequency oscillation, the reactive power of FACTS/ESS is controlled to keep the local voltage at a constant level.

The study results show that FACTS/ESS can be used to damp the low frequency oscillations. The damping in the generator where the FACTS/ESS is installed is very effective. The damping effect in the other generators located at some distance away from the FACTS/ESS unit are very limited. In our study, the 50MVA FACTS/ESS has the best control effects due to its relative large size. The effect of the 8MVA unit is only more observable about 2-3 cycles after the fault. The 8 MVA unit could obviously help shorten the oscillation. When the 50 MVA unit was divided into 4 equal parts and the results show the "distributed" scheme has better overall effect.

For comparison, the authors also studied the effect of STATCOM without energy storage device. The results show that STATCOM has almost no effect in damping the low frequency oscillations in this particular case. This does not imply that STATCOM cannot be used to damp the low frequency oscillation in general.

More efforts will be taken on the research of damping the low frequency oscillations for the area using the ESS in the future.

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