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The Effect of a Fault Neutralizer on the Torsional Vibrations of Turbine-Generator Shafts and Blades

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Abstract: The operating life of a steam turbine is closely related to the operating conditions of a power system. The three-phase-to-ground fault leads to the most onerous impact on turbine-generator mechanism. However, numerous turbine generators even do not encounter such a fault during their operation life times. Since, the single line-to-ground fault has the largest occurrence probability among power system faults, it may be the main cause of fatigue life loss on turbine-generator mechanism due to power system faults. During single line-to-ground fault, the positive-, negative- and zero-sequence networks are in series. For the purpose of limiting fault current, the fault neutralizer is employed to magnify the zero-sequence impedance. This study analyzes the effect of such a resonant reactance connected between the neutral of the wye side of the transformer and the ground in a single-machine-infinite-bus system. From the simulation results, it is found that the neutralizer functioned with parallel resonance not only depresses the torsional vibrations on turbine mechanisms but also enhances the transient stability due to the successful limitation of the fault current. Besides the stresses on power utilities are reduced.

Key words: Torsional vibration, fault neutralizer, turbine generator, shaft, blade

INTRODUCTION

The torsional vibrations induced by power system faults inflict torsional stressing on the shafts and blades and even cause fatigue damage concerns (Masrur *et al*., 1991; Faried *et al*., 1996; Lin and Tsao, 2001). To alleviate these vibrations, many countermeasures have been proposed such as Power System Stabilizer (PSS) (El-Serafi *et al*., 1986), Static VAR Compensator (SVC) (Padiyar and Varma, 1991), Thyristor Controlled Series Capacitor (TCSC) (Perkins and Iravani, 1987), fast phase shifter (Wang *et al*., 1997), braking resistor (Wasynezak, 1981), superconductive energy storage system (Lee and Wu, 1991) and HVDC (Hsu and Wang, 1989) etc. Almost all of them are based on the modulation of either effective or reactive powers to bring supplementary damping into the system. However, the critical fatigue life expenditure is mostly cumulated from initially peak vibration torques within several cycles after fault inception. The objective for instantly reducing initial torisonal torques cannot be achieved by the feedback controllers for the aforementioned devices.

Based on the investigation in Table 1 conducted by the GE Corporation, many turbine generators might be never subjected to a three-phase to ground fault during their operational life according to the low occurrence probability of 3%. In contrast, a single line-to-ground fault contributes more than 90% possibility. Therefore, the possible life loss accumulated in turbine mechanism arising from power system faults is believed to be excited by the single line-to-ground fault.

Table 1: Probability of various faults

Fault type	Occurrence (%)	Temporary (%)
3P-G	3	60
2P-G	3	60
P-P	<4	87
1P-G	>90	87

Note: 4 faults/year in average for a 100 miles line

Resonant reactance grounding is used in 'distribution systems' in Europe, parts of Asia and a few areas of United States (IEEE, 1996). In most of the reported studies concerning interaction of the resonant grounding with generating stations, attention has been concentrated on the steady-state effect on either unit-connected generators or cogenerators (Fulczyk and Bertsch, 2002; Rifaat, 1997). However, no attempt has been made to consider its transient performance with large-scale turbine-generators. The main objective of this study, is to investigate the effects of resonant grounding on the

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torsional torques in turbine shafts and blades during transmission line faults. Aimed at restricting initial vibrations instead of augmenting system damping, this method adds additional advantages as follows:

- The fault neutralizer is not a resistance but a pure inductance. This means it consumes no real power and has no heating loss problem.
- The neutralizer is connected to the neutral of the wye transformer and can directly substitute solid ground without modifying any components. Neither an additional circuit breaker nor a controller is required. The very simple and inexpensive property reveals its superiority.
- Based on the peak fault current being weakened, the stress impact on all the generation and transmission utilities can be reduced. The benefits for prolonging life and enhancing power reliability can be obtained.
- Since most line faults start from single line-to-ground, some progress quickly to a line-to-line fault if fault site energy is high and the fault current is not interrupted in time. Therefore, this neutralizer can contribute indirectly to a reduction in the number of occurrences on line-to-line faults by reducing the energy available at the location of the line to ground fault.

The validity and effectiveness of the scheme as well as parameter variations are carried out through time-domain simulation studies using the Matlab-Power System Blockset (PSB) (Mathwork Inc, 2001).

THE DESIGN OF RESONANT GROUNDING REACTANCE

Under the normal operation of a balance system, there is only positive-sequence network, without negative- and zero-sequence ones. During the period between fault inception and fault clearing, the corresponding three sequence networks as plotted in Fig. 1 are in series due to a single line-to-ground fault (Grainger and Stevenson, 1994). The fault current of injecting to ground is 3 times of the zero-sequence currents as give by

$$I_f^{"} = 3I_{a0} \tag{1}$$

Consider a double circuit transmission line represented as the pi model and connected to the output of the step-up transformers with generally delta-wye configuration as in Fig. 2, the corresponding zero-sequence network with the fault neutralizer in service be plotted in Fig. 3. Figure 4 gives the simplified equivalent

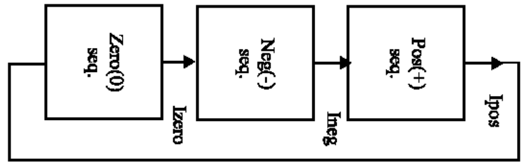

Fig. 1: The sequence network configuration during single line-to-ground fault

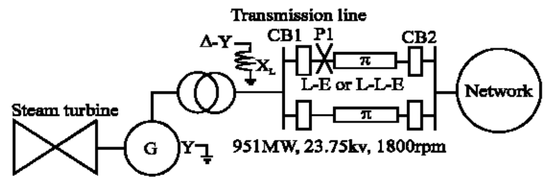

Fig. 2: Studied system

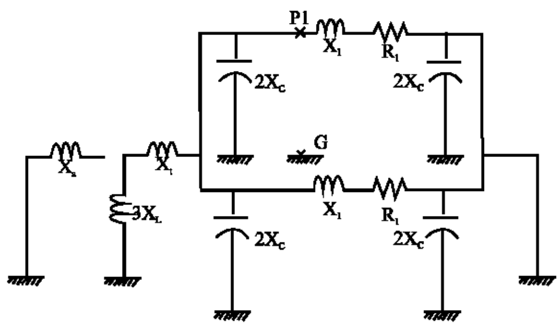

Fig. 3: The zero-sequence network circuit during single line-to-ground fault

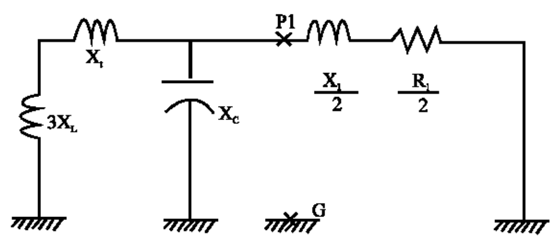

Fig. 4: The simplified circuit of Fig. 3

circuit and then the impedance equation on the left path of the P1 fault point can be described as:

$$(3X_L+X_t)//X_C=0 \tag{2}$$

Where, X_L, X_t is the neutral reactance and transformer reactance, X_C is the reactance of line-to-ground capacitor C. From the Eq. 2, the series X_t could be omitted because it has the quite smaller value than $3X_L$. Thus, when the neutral inductance L_L is:

$$L_L = \frac{1}{3\omega^2 C} \tag{3}$$

the parallel resonant effect will be made and provide open-circuit impedance on this path. This will increase the net impedance of zero-sequence network and restrict the fault current. This neutral resonance inductance is then defined as fault neutralizer.

SYSTEM UNDER STUDY

Figure 2 schematically shows the electromechanical system for the present study. The practical steam turbine unit, including a high-pressure stage and two low-pressure stage steam turbines, analysed in this study is a close-coupled and cross-compound reheat unit that operations at a rotational speed of 1800 rpm. The rated capacitor of the generator, which was installed in 1984, is 951MW. Each of the low-pressure steam turbines has A and B spindles and uses the shrunk-on rotor. There are eleven rows of blades in the LP steam turbine. The first nine rows of blades are shrouded.

The typical model of a long blade on the mechanical model of the turbine-generator is quite complicated. The flexural, axial and torsional modes vibrate in the same direction as rotation, perpendicular to the rotation direction and in a twist direction, respectively. Among them, the flexural mode has lower resonant frequency and is usually chosen to investigate the vibration mode shapes of blades. The simulation electrical and mechanical data are given in Table 2. All of the parameters of this system are in the per unit system, based on generator ratings.

For time-domain simulation investigations, the entire studied system is modeled by PSB program. The synchronous generator is represented by a six-order state-space d-q-0 model. The step-up transformer with delta-wye (3 phase-4 wire) configuration is represented by lumped model transformers. Each transmission line is modeled by one PI section line. Each network source is treated as an infinite bus modeled by a fixed amplitude sinusoidal voltage source at nominal frequency. Each circuit-breaker is represented as an ideal switch which is able to open at the current zero crossings. Dynamics of the excitation systems are included in the T-G model. A mass-damping-spring model is adopted for turbine model representation.

FREQUENCY DOMAIN ANALYSIS

It is well known that the E/M disturbing torque (E/M torque) due to power system fault consists of these three components, a unidirectional component (<2 Hz), a system-frequency component and double system-frequency component, which correspond to the generator delivering power swing, the unsymmetrical fault current (DC component) and the negative-sequence armature current (Lin and Tsao, 2001). These three frequency types of E/M torques are the main excitation sources to stress turbine mechanism, which dominate the vibration behaviors of turbine shafts and blades. This study analyzes the torque responses of turbine mechanism by frequency-scanning method. Suppose that the terminal of generator rotor is a shaker with one per-unit excitation, the frequency-scanning inspects the natural frequencies of steam turbines from 0.01-140 Hz with interval of 0.01 Hz.

The scanning results of the essential shaft LP2R-GEN and blade LP2R are shown in Fig. 5. In the figure, nine vibration modes are then present in the turbine system, which are summarized in Table 3. All the modes have been avoided from the forbidden frequency bands defined as 60Hz ±5% and 120Hz ±5%. Aimed at the excitations of aforementioned three frequency component of E/M torque, it is clearly compared that the most considerable blade torque response is excited by double system-frequency component (-29.6db at 120Hz). This will impose Supersynchronous Oscillations (SPSO) in turbine

Table 2: 951MW turbine-generator system parameters

	Generator (1057MVA, 24kV)			Mechanical data			
	60Hz	X_d=1.574	R_s=0.00359	Mass	Inertia,H	Damping, C	Stiffness, K
	4 poles	X_q=1.490	R_{fd}=0.00070	HP	0.1787	0.00180	
	P_0=0.90	X_{fdl}=0.168	R_{kd}=0.02571	LP1F	0.6546	0.00023	144.15
	Q_0=0.2334	X_l=0.190	R_{kq}=0.02571	LP1R	0.6486	0.00021	1595.0
	V_t=1.03	X_{kd}=0.110	X_{kq}=0.490	LP2F	0.6575	0.00021	206.0
				LP2R	0.6676	0.00021	1584.9
	Step-up transformer 1057MVA			GEN	1.1616	0.00012	325.28
	24/345kV X_t= 0.14304		R_t=0.00192	REC	0.00344	0	117.16
				EXC	0.00236	0	1.61
	PI transm. line 1057MVA/345kV			Blade	0.0344	0.00004	220.127
	X_1=0.3112	R_1=0.0369	X_C=43.78				
	Fault neutralizer X_L= 14.59						
	Torque distribution (%)						
HP 31	LP1F 14.45	LP2F	14.45	B1F	2.8	B2F	2.8
	LP1R 14.45	LP2R	14.45	B1R	2.8	B2R	2.8

Table 3: Vibration modes

Mode	1	2	3	4	5	6	7	8	9
Hz	19.40	37.40	40.25	47.02	101.80	104.11	127.05	133.25	134.25

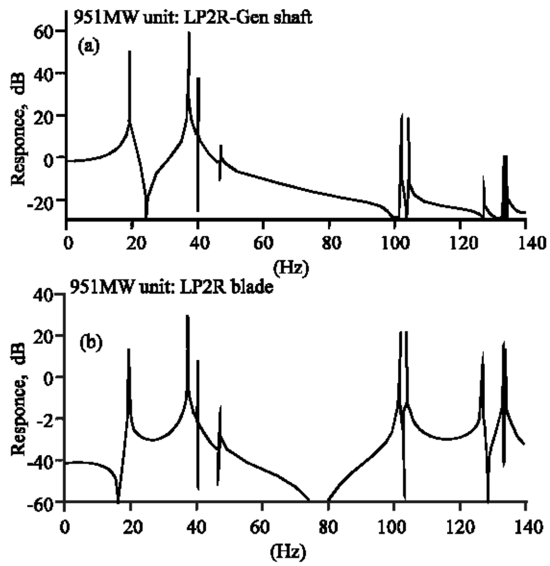

Fig. 5: The frequency scanning response of the main shaft and blade

blades. However, such an effect cannot be found in turbine shafts due to their low response (<-25dB at 120Hz). The shaft is more sensitive to the excitation of unidirectional component while the blade is not. Both the blade and the shaft have minor sensitivity to the excitation of system frequency component.

RESULTS AND DISCUSSION

Maximum faults in EHV transmission lines are single line-to-ground faults. They are caused mainly due to lightning and over voltage created on the line by switching and other phenomena. In the following cases, assume that a line fault is applied to P1 which is one end of the double transmission lines near the step-up transformer. The resonant reactance is designed as deduced in this study.

Single line-to-ground fault: It is assumed that a single line-to-ground fault is applied at 0.1 s and cleared at 0.23 s for the worst case. The subsequent auto- reclosing is unsuccessful at 0.79 s and re-clearing at 0.92 s, which is the worst reclosing case in the later studies. Based on the neutralizer being in service or out of service Fig. 6a and b comparatively show that the transient behaviors of the E/M torque, the turbine shaft and blade torsional torques, fault currents flowing at the CB1, the negative- and zero-sequence currents on the secondary side of the transformer. As can be seen, four times of torsional impact respectively, occurs at fault inception, clearing, unsuccessful reclosing and re-clearing. They lead to the new variation of E/M torque which induces turbine torsional torque amplifications with phase addition effect. During not only the fault period but also the unsuccessful reclosing period, the reduced DC component of the fault current shown in middle subfigure of Fig. 6b weakens the system frequency component of the E/M torque which suppresses the main torsional torque in turbine shafts and blades. The effect of the supersynchronous oscillations for turbine blades is also diminished owing to the depressed negative-sequence currents. The effectiveness of applying fault neutralizer can be clearly depicted in the third and fourth column of Table 4. On average, there is about a 20% reduction in peak-to-peak torques (the torque deviations between the maximum and the minimum). It is worth noting that a relatively modest reduction in the amplitudes of the torsional torques has a very significant impact on decreasing the induced fatigue loss in the material property of shafts or blades.

Due to the ability on limiting fault current for the fault neutralizer, the stresses on all the utilities and the generator could be alleviated. This also results in less delivering power swing which causes less shaft torsional torque of unidirectional component, less acceleration and less angle swing in the turbine-generator rotor as demonstrated in Fig. 6 and 7, respectively. Thus the power system stability has been enhanced. In addition, it is emphasized that the fault neutralizer cannot completely eliminate the fault current to be zero because the zero-sequence network between the P1 and the ground G has two main impedance paths as given in Fig. 4. One (in left side) can be open by parallel resonance effect which results in reducing the zero-sequence current of this path to be about zero as shown in the next-to-final subfigure of Fig. 6b. However, the other path (in right side) composed of pure transmission lines cannot be removed so that there would be still a minimum for the net impedances of zero-sequence network. The voltage and current rating of the designed fault neutralizer should be taken into consideration as depicted in the last two subfigures of Fig. 6b. The neutralizer voltage fluctuation is acceptable even though the neutralizer is parallel resonant.

Effect of neutral reactance: The suppressing effect of the reactance of fault neutralizer to the torsional torques on each shaft and blade has been studied. Reactance ranging from 0 pu (solid ground) to 14.59 pu (nominal fault neutralizer ground) is adopted for simulations. The result

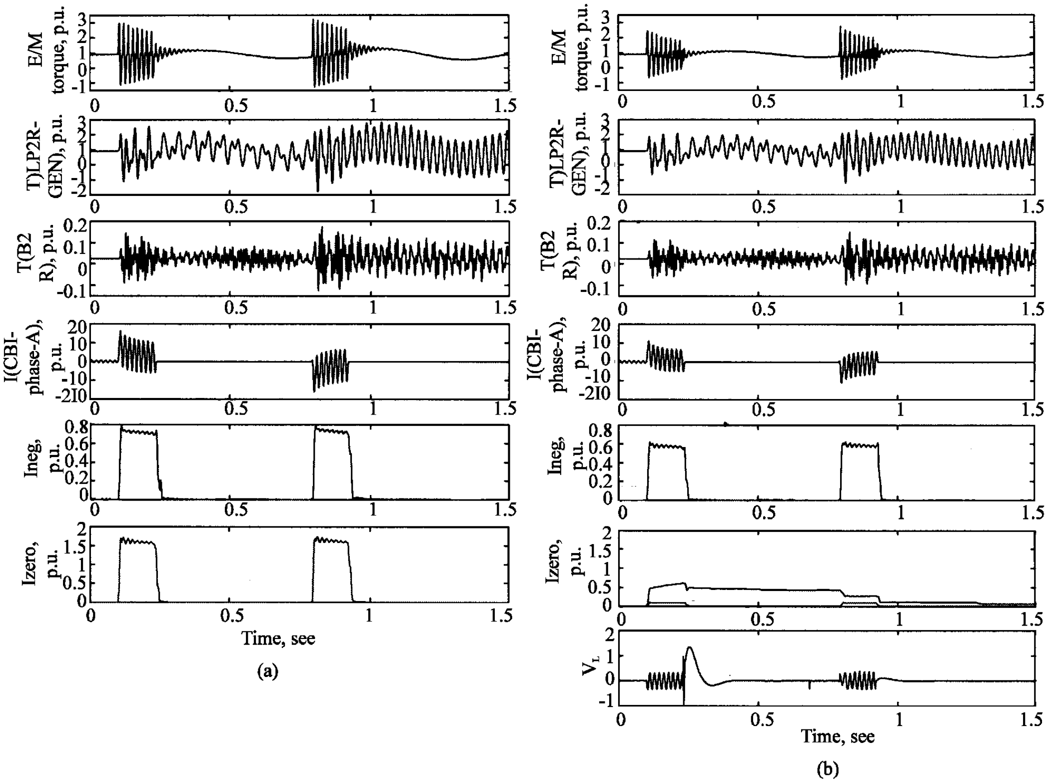

Fig. 6: The transient responses due to unsuccessful reclosing single line-to-ground fault solid ground, (b) fault neutralizer ground

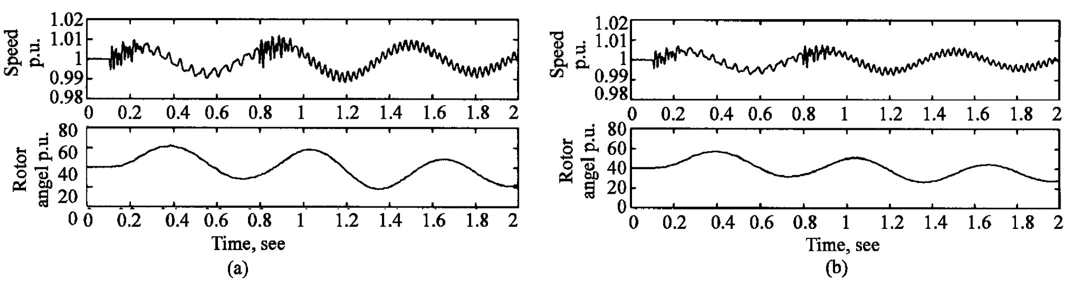

Fig. 7: The transient stability responses due to unsuccessful reclosing single line-to-ground fault, (a) solid ground, (b) fault neutralizer ground

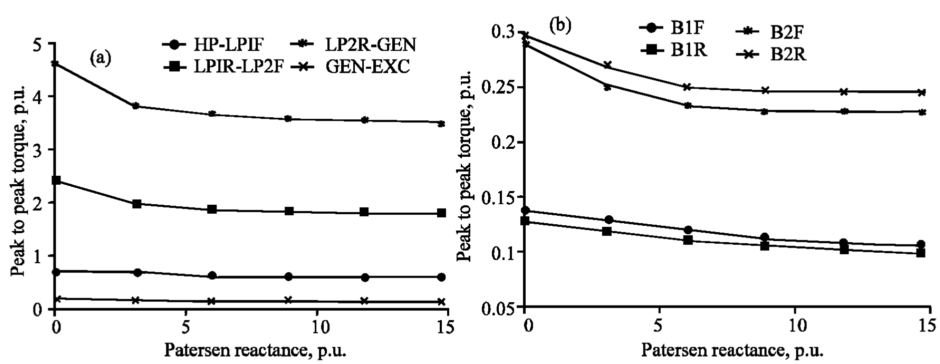

Fig. 8: Influence of the arc suppression reactance on torsional torques of shafts and blades for unsuccessful reclosing single line-to-ground fault

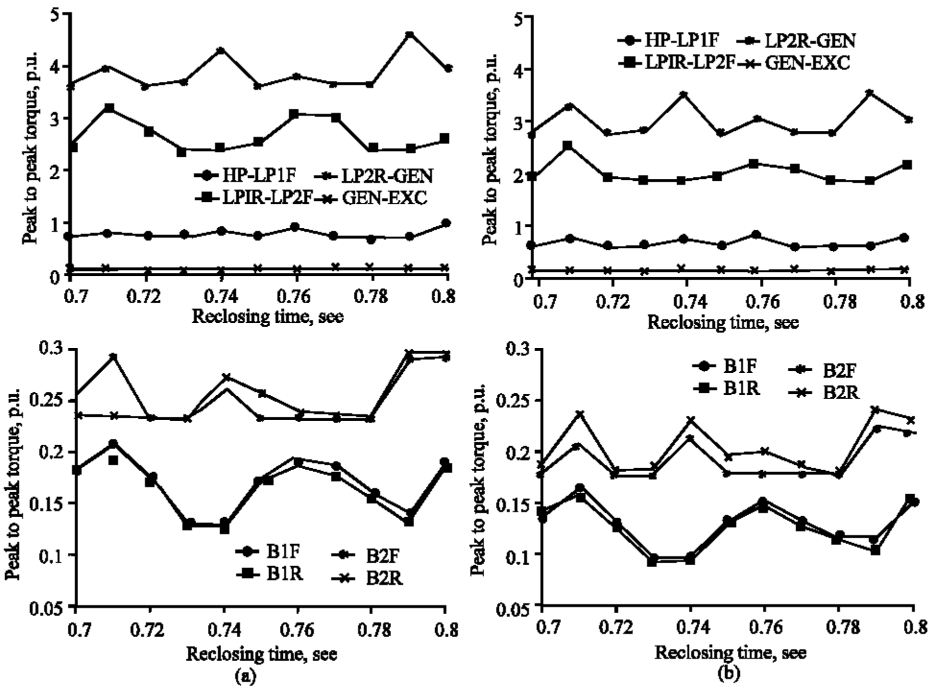

Fig. 9: Relationship between reclosing time and torsional torques of shafts and blades for unsuccessful reclosing single line-to-ground fault (a) solid ground, (b) fault neutralizer ground

due to the same fault disturbance is demonstrated in Fig. 8. It is shown that the torsional vibrations can be significantly reduced just by small amount of neutral reactance. This is because the net zero-sequence impedance has considerably been reduced as illustrated from Fig. 4. Consequently, it is unnecessary to design very precise value of the resonant reactance because the effectiveness is nearly similar and limited.

Effect of auto-reclosing time: The auto-reclosing operation may cause even more serious vibrations on turbine mechanism than clearing operation. To illustrate the effect of the fault neutralizer at different auto-reclosing time, the following fault and switching sequence is studied. A single line-to-ground fault occurs at 0.1 s. Clearance of fault is initiated 0.13 s after fault inception. After an interval of time, which accounts for the recovery time and the reclosing time of the circuit breaker, the line is reclosed onto the same fault. After an additional time interval of 0.13 s, the line is again cleared without subsequent reclosing. The relationship between the reclosing time and the peak-to-peak torque on each of the shaft sections are shown in Fig. 9. It is satisfyingly found that there are about 22% reductions in peak-to-peak torques of turbine shafts and blades.

Effect of double line-to-ground faults: Because the zero-sequence impedance can be magnified by the fault neutralizer, the double line-to-ground fault should be studied because its fault current also equals 3 times of zero-sequence currents (Grainger and Stevenson, 1994). Assume that the fault is applied to the same place at 0.1 s and cleared at 0.24 s without reclosure. In general, the reclosure for multi-phase fault in power systems is not allowed. Figure 10a and b give all the transient behaviors for the case of the solid ground and for the case of fault neutralizer ground, respectively. The system stability is also improved from comparing to their responses of the rotor speed and the angle. The main shaft torsional torques is depressed due to the reduced system frequency component of E/M torque by decreasing DC component of fault currents. However, the corresponding negative-sequence current does not reduce but amplifies. This is because the negative-sequence network gains more currents as a result of the parallel configuration of the positive, negative and zero-sequence networks during such a fault (Grainger and Stevenson, 1994). Therefore, the double system-frequency component of E/M torque shown in the first subfigure of Fig. 10(b) is raised and then induces more supersynchronous oscillations in blades. The different results of torque improvements between shafts and

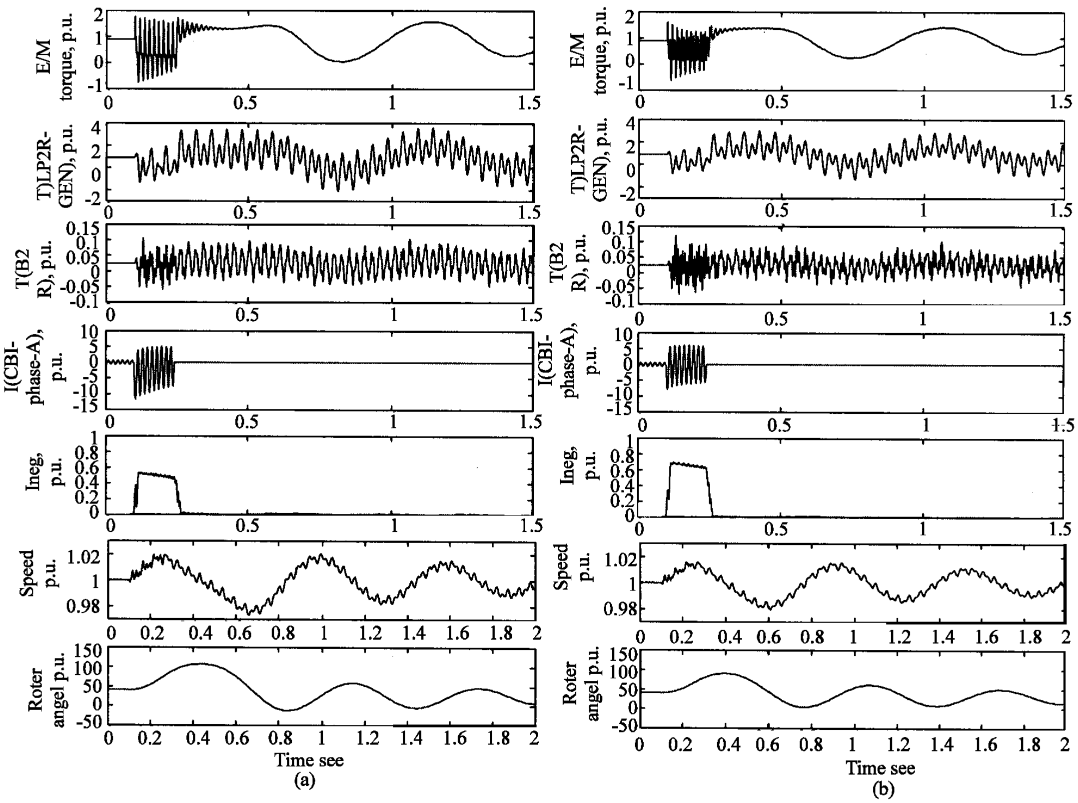

Fig. 10: The transient responses due to double line-to-ground fault (a) solid ground, (b) fault neutralizer ground

Table 4: The peak-to-peak value of the simulation transient responses (pu)

	Case A*	Case A**	Impr%	Case B*	Case B**	Impr%
T(E/M torque)	4.493	3.518	21.694	2.533	2.208	12.829
T(HP-LP1F)	0.711	0.564	20.667	0.897	0.673	24.961
T(LP1R-LP2F)	2.380	1.795	24.557	3.636	2.758	24.170
T(LP2R-GEN)	4.608	3.494	24.181	5.667	4.304	24.064
T(GEN-REC)	0.147	0.134	8.961	0.102	0.084	17.896
T(B1F)	0.138	0.105	23.529	0.104	0.109	-4.123
T(B1R)	0.127	0.098	22.555	0.093	0.103	-10.441
T(B2F)	0.290	0.226	22.172	0.164	0.165	-0.610
T(B2R)	0.296	0.245	17.252	0.165	0.188	-13.973
Speed	0.024	0.015	36.170	0.048	0.036	24.000
Rotor angle, deg.	43.504	30.903	28.965	119.811	87.011	27.377

Remark: *: Fault neutralizer out of service, **: Fault neutralizer in service, Impr: the improvement percentage

blades are demonstrated in the 7th column of Table 4. Fortunately, this might not be a concern because blade torsional torques are still smaller than those for case A and a double line-to-ground fault is not frequently encountered as listed in Table 1.

Effect of other types of line faults: Since the zero-sequence current is no related to the fault current due to either Line-to-Line fault (L-L) or three-phase-to-ground fault (L-L-L-E), the overall transient behaviors and torsional responses between solid ground and fault neutralizer ground are nearly invariant from the simulation results though they are not shown.

Effect of different grounding locations: Since the neutral of step-up transformer with delta-wye connection is usually solidly grounded and the generator neutral is never connected directly to ground (IEEE, 1996) the net zero-sequence impedance shown in Fig. 3 cannot be effectively changed by generator grounding impedance (Delta side of the transformer). From the results of simulation study, it is found that the generator resonant grounding is futile for the purpose of reducing single line-to-ground fault current or torsional vibrations. This suggests that the resonant grounding be employed at the neutral of step-up transformer instead of the large-scale generator.

CONCLUSION

This study presents the fault neutralizer approach to restrict turbine-generator torsional torques and enhance power system stability. From the results of these studies, the following conclusions can be summarized:

- The built-in generator neutral impedance cannot reduce line fault current. For the large-scale generating station, the grounding fault neutralizer should be treated as a built-in device at the neutral of the step-up transformer.
- During the normal balanced operation, the fault neutralizer grounded is like a short-circuited component that operates the function of solid ground. During the faulty period, the neutralizer reflects net large impedance to the zero-sequence network just as a high impedance ground. This will help alleviate the fault current.
- Since the fault current was effectively reduced, the less stress impact increases the life expectancy on all the utilities of the generation and the transmission. In addition, it is possible in the planning and designing stage of a turbine-generator system and the utilities to be designed with smaller strength.
- The torsional vibrations on turbine shafts and blades can be suppressed due to the majority of line faults because the single line-to-ground represents up to 90% of transmission line faults.

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