THE STUDY OF TORSIONAL IMPACT ON TURBINE-GENERATOR SHAFT USING EMTP AND SUPPLEMENTARY PROGRAMS

Yongzhuang Li
Electric Power Research Institute
Beijing, P.R.China, 100085

ABSTRACT: In order to study the torsional impact due to transmission line fault and subsequent switch operation on turbine-generator shaft, EMTP is adopted with supplementary programs for shaft analysis, shaft equivalent reduction and estimation of torsional fatigue. Statistics switch of EMTP is used to simulate the superimposition of successive torsional impulses. Some examples are given in this paper.

INTRODUCTION

Following two shaft failures caused by subsynchronous resonance in 1970 and 1971, it was suggested that system switching events, particularly high speed reclosing could also be detrimental to the turbine generator shaft system. The reason was found to tie in the superimposition of successive torsional impulses due to the fault in the transmission system and the ensuing clearing by switching off the faulted line. Superimposition of an additional torsional shock on the still oscillating shaft system can lead to either attenuation or amplification of the vibration amplitudes depending on the instant of superimposition. The question whether high speed reclosing can be utilized in East Chine power system safely was raised in Chine when the first 600 MW turbine generator manufactured in Harbin was going to be installed in Pingwei power plant in 1986. Since then, several cases have been studied such as the 350 MW unit in Fuzhou power plant of Fujian Province and the 900 MW unit in Daya Bay Nuclear power plant in Guangtong Province.

EMTP is adopted for the digital simulation of the simultaneous interaction of power system and the generator combination with the mechanical system of turbine-generator. All the important machines and the system performances such as the electrical torque and the torsional torque at various location along the shaft can be calculated and plotted precisely with its sophistic modeling and simulation techniques[1]. The statistics switch of EMTP is used for the probability of different severity level of torsional duty and resulting degree of shaft fatigue.

One supplementary program developed to cooperate with EMTP is for the torsional shaft analysis. Fundamental of the study of turbine-generator shaft torsional oscillation is the calculation of the torsional natural frequencies and the associated mode shapes. A new model for shaft torsional oscillation is presented on this paper. Rather than to calculate the eigenvalue and eigenvector of a lumped mass system, a two point boundary value problem is used to solve a second order differential equation for a distributed mass shaft in order to get the natural frequency and their mode shape accurately.

The results are then used to develop a reduced equivalent lumped-mass model with a sufficient number of discrete masses to yield for the shaft regions of interest an accurate torsional simulation with the correct natural frequencies and with the coupling location between two adjacent rotors along with the shaft unchanged. This equivalent model can then be employed into EMTP for studying the torsional impact of all electrical transients.

Another program developed is for torsional fatigue expenditure estimation. The torsional torque in time domain calculated from EMTP is processed to be the alternative torsional stressed on the shaft regions of interest and the total fatigue caused by an operational incident involving one or more successive electrical transients by Rain flow counting method.

Some examples of the torsional impact by electrical disturbances and switching events are given in this paper.

TURBINE GENERATOR SHAFT ANALYSIS

The shaft torsional system model plays an important role for the torsional response which causes complex stress along the shaft. Different techniques of modeling the shaft torsional system of a turbine-generator are often used as the simple lumped mass model and multi-mass model. The multi-mass model is such a precise modeling of a complete shaft system that allows the torsional natural frequencies of the turbine-generator to be determined with great accuracy. A program is developed to calculate the natural frequencies using multi-mass model based on the new model as follows [2].

New shaft model using multi-mass parameters

Consider a non-uniform shaft of length L. Let ζ and z be variables along the shaft ($0 < \zeta < z < L$). The shaft is treated as a free body from the origin to position z. The angular momentum equation is as follows in the case of neglecting the damping,

$$M(\zeta,t) = J(\zeta)\frac{\partial}{\partial t}\theta(\zeta,t) \qquad (1)$$

$$T(z,t) = K(z)\frac{\partial}{\partial z}\theta(z,t) \qquad (2)$$

$$\frac{\partial}{\partial t}\int_0^z M(\zeta,t)dt = \int_0^z \tau(\zeta,t)d\zeta + T(z,t) \qquad (3)$$

where $M(\zeta,t)$ -- Shaft rotational momentum per length at position ζ and t.

$J(\zeta)$-Shaft rotational inertia per length at position ζ.

$\theta(\zeta,t)$ -- Shaft rotational angle at ζ and t.

$K(z)$ - Shaft stiffness-length at position z.

$\tau(\zeta,t)$ -- Applied torque per length at position ζ.

$T(z,t)$--The torque carried internally by shaft material at position z and time t.

Substituting Eq. (1) and Eq. (2) into Eq. (3), then differentiate the two sides with respect to z, the result will be :

$$J(z)\frac{\partial^2}{\partial t^2}\theta(z,t) = \tau(z,t) + \frac{\partial}{\partial z}K(z)\frac{\partial}{\partial z}\theta(z,t) \qquad (4)$$

With the boundary conditions for Eq. (4) :

$$\frac{\partial}{\partial z}\theta(0,t) = 0 \qquad \frac{\partial}{\partial z}\theta(L,t) = 0 \qquad (5)$$

Consider the case that there is no applied torque on the shaft , Eq. (4) and its boundary condition Eq. (5) are one dimension wave equations. The solution to these equations can be assumed as :

$$\theta(z,t) = \theta_0 + \omega t + \sum_{n=1}^{\infty} A_n(z)[\alpha_n \sin\lambda_n t + \beta_n \cos\lambda_n t] \qquad (6)$$

Eq.(4), (5) can be written as :

$$\frac{d}{dz}[K(z)\frac{d}{dz}A_n(z)] + \lambda_n{}^2 A_n(z)J(z) = 0 \qquad (7)$$

$$\frac{d}{dz}A_n(0) = 0 \qquad \frac{d}{dz}A_n(L) = 0 \qquad (8)$$

Constant λ_n is the n-th mode frequency and An(z) is its associated mode shape along the shaft. The mode shape An(z) obeys the boundary condition, its slope at both ends is zero. Eq. (7) could be solved with a fourth Runge-Kutta method or the piesewise-analysis. Guessing a value of λ_n first, Eq. (7) is integrated from z = 0 to z = L. If λ_n is the mode frequency, then boundary condition is satisfactory. If not ,λ_n must be reguessed with a smaller step size $\Delta\lambda_n$ until the correct λ_n is found. The associated function An(z) is the mode shape, its zero-crossing equals to the order of λ_n .The next guessed value λ_{n+1} is higher than λ_n . In this way, the natural frequency is calculated one after the other from the lowest order to which wanted.

The digital program based on the above method is developed. The natural torsional frequency and its mode shapes are analyzed for a 900 MW unit in Daya Bay nuclear power station from 282 discrete sections, the results is listed in TABLE 1, Fig. 1 shows the first 3 mode shapes.

TABLE 1 The torsional modes of 900MW unit

	number of section		
mode order	282	50	1
1	13.24	13.19	13.16
2	23.48	23.31	23.14
3	31.32	30.82	30.78
4	35.16	34.94	34.53
5	43.30	42.82	42.33
6	81.54	80.29	80.42

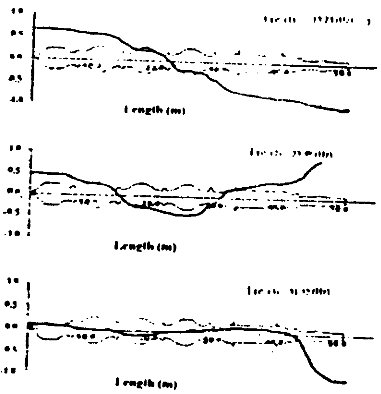


Fig 1. Mode shape of 900 MW unit

Shaft System Equivalent Reduction

The multi-mass model is accurate for the natural frequency and its mode shapes, but hardly to be adopted into EMTP. The simple lumped model is adequate for routine investigation of the torsional impact of most electrical disturbances and for evaluating different machine configuration, but the parameters of that is hard to get in some cases or the remaining natural frequencies are not enough to reflect the twice of power frequency with only five or six sections. A method to develop a reduced equivalent lumped-mass model is introduced as follows^3.

A torsional system is shown as Fig. 2. The i-th shaft and the i-th mass are taken into account. The movement equation of i-mass with torsional resonance at the frequency ω is:

$$J_i\frac{\partial^2}{\partial t^2}\theta_i = T_{i+1} - T_i \qquad (9)$$

$$\theta_i = \theta_i \sin(\omega t - \alpha) \qquad (10)$$

it is obtained that:

$$T_{i+1} = T_i - J_i\omega^2\theta_i \qquad (11)$$

The θ and T are defined as the variables, the letter R or L is to dedicating the right or left end, Eq. (12) is obtained for the i-th mass in matrix form then.

$$\begin{vmatrix} \theta \\ T \end{vmatrix}_i^R = \begin{vmatrix} 1 & 0 \\ -\omega^2 J & 1 \end{vmatrix}_i \begin{vmatrix} \theta \\ T \end{vmatrix}_i^L \qquad (12)$$

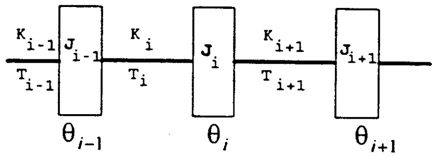


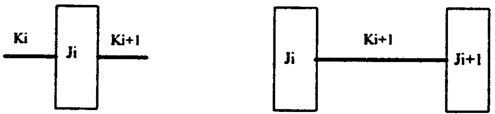
Fig. 2 A section of torsional shaft

For the i-th shaft,

$$T_i = T_{i-1}$$
$$\theta_i - \theta_{i-1} = \frac{T_{i-1}}{K_i} \qquad (13)$$

Eq. (14) is for the i-th shaft in the matrix form,

$$\begin{vmatrix} \theta \\ T \end{vmatrix}_i^L = \begin{vmatrix} 1 & \frac{1}{K} \\ 0 & 1 \end{vmatrix}_i \begin{vmatrix} \theta \\ T \end{vmatrix}_{i-1}^R \qquad (14)$$



(a) Type A (b) Type B

Fig. 3 Types of unit

For a unit of type A with two shafts and a mass as shown in Fig. 3(a), the relation between the two ends of the unit is as Eq. 15,

$$\begin{vmatrix} \theta \\ T \end{vmatrix}_{i+1}^L = \begin{vmatrix} 1-\frac{\omega^2 J_i}{K_{i+1}} & (\frac{1}{K_i}+\frac{1}{K_{i+1}})(1-\frac{\omega^2}{n_a^2}) \\ -\omega^2 J_i & 1-\frac{\omega^2 J_i}{K_i} \end{vmatrix} \begin{vmatrix} \theta \\ T \end{vmatrix}_{i-1}^R \qquad (15)$$

where $n_a^2 = \frac{K_i + K_{i+1}}{J_i}$

For a unit of type B with two masses and a shaft as shown in Fig. 3(b), the relation between the two ends of unit is as

$$\begin{vmatrix} \theta \\ T \end{vmatrix}_{i+1}^R = \begin{vmatrix} 1-\frac{\omega^2 J_i}{K_{i+1}} & \frac{1}{K_{i+1}} \\ -\omega^2 (J_i + J_{i+1})(1-\frac{\omega^2}{n_b^2}) & 1-\frac{\omega^2 J_{i+1}}{K_{i+1}} \end{vmatrix} \begin{vmatrix} \theta \\ T \end{vmatrix}_i^L \qquad (16)$$

where $n_b^2 = K_{i+1}(\frac{1}{J_i}+\frac{1}{J_{i+1}})$

The type A unit with the parameters of K_i, K_{i+1} and J_i can be converted into type B unit with the parameters of J_i', J_{i+1}' and K_{i+1}' as Eq. (17) in the condition that $\omega^2 << (K_i + K_{i+1})\frac{1}{J_i}$

$$\begin{cases} J_i' = \frac{K_i}{K_i + K_{i+1}} J_i \\ J_{i+1}' = \frac{K_{i+1}}{K_i + K_{i+1}} J_i \\ K_{i+1}' = \frac{K_i K_{i+1}}{K_i + K_{i+1}} \end{cases} \qquad (17)$$

The type B unit with the parameters of J_i, J_{i+1} and K_{i+1} can be converted into type B unit with the parameters of K_i', K_{i+1}' and J_i' as Eq. (18) in the condition that $\omega^2 << (\frac{1}{J_i}+\frac{1}{J_{i+1}})K_i$

$$\begin{cases} J_i' = J_i + J_{i+1} \\ K_i' = \frac{J_i + J_{i+1}}{J_{i+1}} K_{i+1} \\ K_{i+1}' = \frac{J_i + J_{i+1}}{J_i} K_{i+1} \end{cases} \qquad (18)$$

the multi-mass model is reduced in this way with the restriction that the coupling location between two adjacent rotors unchanged. The reduction process will stopped to have a curtain number masses which still keep the natural frequencies interested correct.

The reduced equivalent shaft model with 50 and 13 sections keeps the first six lower nature frequencies unchanged as shown in TABLE 1 with associated mode shapes agreed with those in Fig. 1.

THE ASSESSMENT OF TORSIONAL FATIGUE

Fatigue Model

Fatigue is a cumulative process where additional events add to previous fatigue life expenditure. It is extremely difficult to calculate accurately the fatigue life expenditure of a shaft system even though the electrical torque and torsional torque on various location of a turbine generator shaft system are calculated with accuracy. Metallurgical effects are not amenable to a rigorous theory for precise quantitative analysis. Fatigue models in the large part are based upon empirical data resulted on specimens of shaft steel. The material stress life characteristics derived from such experimental results usually takes the form of S-N curve. The S-N curve used here is calculated from equations recommended by Westinghouse Electric Corporation which takes the theoretical stress concentration factor and other factors into consideration[4].

Rain Flow Method

A cycle counting technique which is currently considered to be the best available is known as the Rain-flow cycle counting method. The alternating torsional stresses are converted into closed stress strain cycles with its accompanying stress- strain plane as the basis for counting cycles in Rain flow method. Once these values of alternating stress and mean stress have been determined using rain flow method, an "equivalent stress" is obtained by Goodmen line and used to find the life expenditure from S-N curve.

The linear damage accumulation rule is used to calculate loss of life for a sequence of stress variations. The individual increments of shaft fatigue are summated to obtain the total fatigue caused by an operational incident involving one or more successive electrical transients.

TORSIONAL IMPACT BY SWITCHING EVENTS

System Diagram for Study

Three cases are studied for investigation of the torsional impact of high speed reclosing on turbine generator shaft as a 600MW unit in Pingwei power plant, a 350MW unit in Fujian Huaneng plant and a 900MW unit in Daya Bay nuclear power plant. The power system diagram for the study is shown in Fig. 4. Fig. 4(a) and 4(b) show two different network operating configurations with different circuits between the step-up transformer and power system.

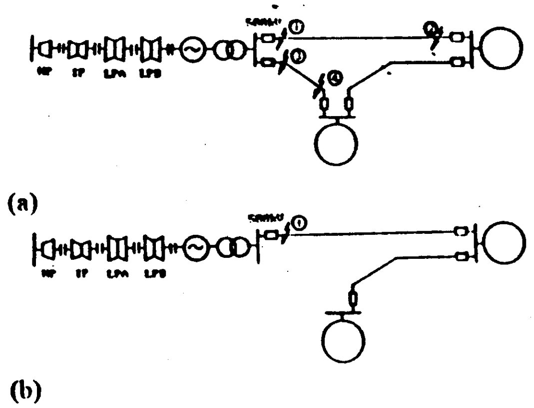
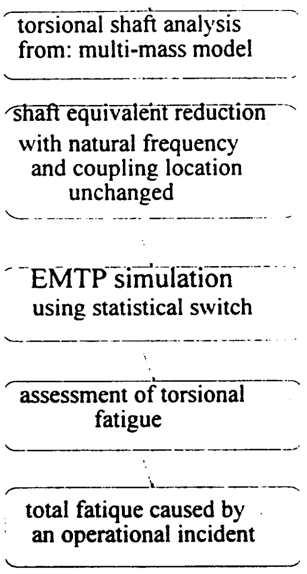


Fig. 4 Power system diagram

Simulation process



Unit Short Circuit

The terminal to terminal unit short circuit and three phase unit short circuit for the three cased are studied since the turbine generator have been designed for decades to withstand this kind of disturbances which are considered as a single torsional excitation. It is shown from the study that the maximum torque caused by unit short circuit are largely depending on the generator parameters and the actual timing of fault. The systematic switch of EMTP is used to make the short circuit sampling 20 times in a half circle evenly. The statistical maximum torque at the location between low pressure rotor and generator $T_{L\text{-}G,max}$ are listed in Table 2. Figure 5 shows the influence of fault timing on the maximum electrical air gap torque T_e and $T_{L\text{-}G,max}$ of 600MW unit .

TABLE 2 $T_{L\text{-}G,max}$ (pu) from Unit Terminal Short Circuit

kind of fault	unit capacity		
	350MW	600MW	900MW
2-phase short circuit	1.26	4.17	6.2
at high voltage side		2.23	2.4
3-phase short circuit	3.28	3.79	4.5
at high voltage side	1.78		

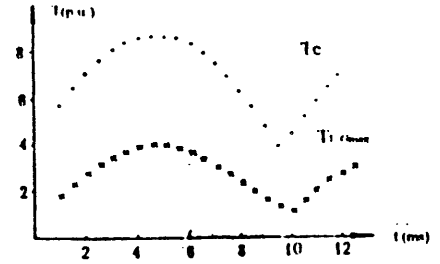


Fig. 5 Maximum torque T_e and $T_{L\text{-}G,max}$ as a function of fault timing for terminal to terminal fault of 600MW unit

Single Pole Reclosing

According to the statistics about the investigation of line fault in China by EPRI, 90% of faults in transmission line of 220kV is line to ground fault which is temporary in nature. So the single pole reclosing plays an important role not only to eliminate temporary line to ground fault, but also to keep the integrity of the whole system. Automatic reclosing is considered as multi torsional excitation, so statistical analysis is carried out to simulate the torque superimposition by either statistical or systematically switches in EMTP. A large number of simulations are calculated for the three cases as the condition that the fault is in different distance of the line from the generator high voltage bus of the system and that the fault timing is random sampled on the voltage wave form as even distribution. The fault clearing time of 0.1s is selected for the simulations. The switch opening on the two ends of the faulted line is successful as soon as the switch current has gone through zero. The reclosing time is 1.0s with a small variation taking account of the switch operation deviation by random sampling of even distribution. Figure 6 shows the influence of fault time on the maximum electrical air gap torque T_e and $T_{L-G,max}$ of 600MW unit.

TABLE 3 Statistics of T_e and $T_{L-G,max}$ for Single Pole Reclosing

fault position: at the sending end		
fault nature	temporary	permanent
maximum $T_{L-G,max}$	2.2	3.03
minimum $T_{L-G,max}$	1.17	1.24

fault position: at the sending end		
fault nature	temporary	permanent
maximum $T_{L-G,max}$	1.9	2.31
minimum $T_{L-G,max}$	1.17	1.20

An statistical result of the maximum torque T_{L-G} between the low pressure rotor and generator from single pole reclosing of the system in Fig. 4(a) is listed in Table 3.

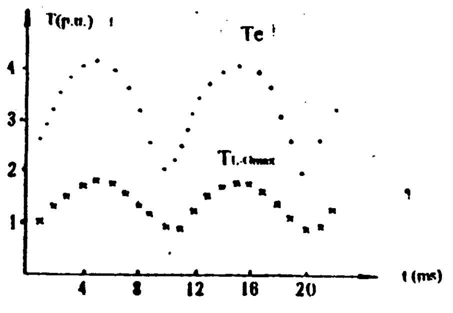
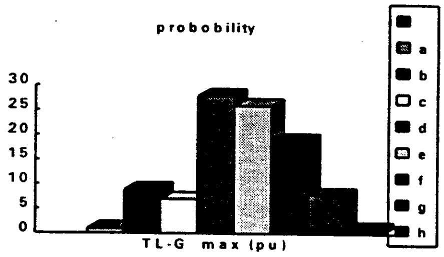
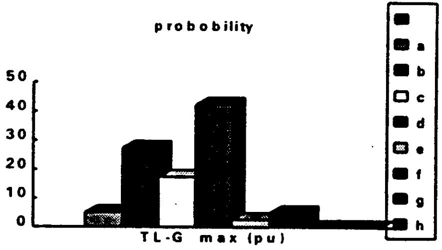


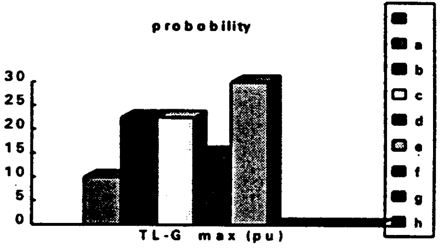
Fig. 6 Maximum torque T_e and T_{L-G} as a function of fault timing for line to ground fault of 600MW unit



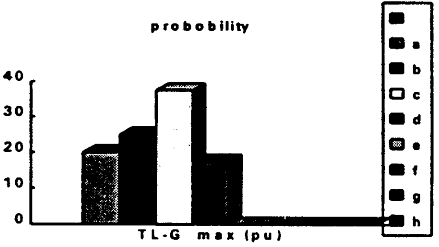
(a) unsuccessful reclosing for fault at sending end



(b) successful reclosing for fault at sending end



(c) unsuccessful reclosing for fault at receiving end



(d) successful reclosing for fault at receiving end

Fig. 7 Probability distribution of $T_{L-G,max}$ of 900MW unit for single pole reclosing

The probability distribution of $T_{L-G,max}$ of 900MW unit resulting from successful and unsuccessful single pole reclosing are shown in Fig. 7. The simulation results show that the severity of impact on the shaft are effected by several facts, It is to be considered as unfavorable when the system fault occurs closer to the generator high voltage bus. The results are also shown clearly that the unfavorable superimposition of successive torsional impulses due to the fault, fault clearing and reclosing time and the unsimultanuos operation of the switching on the two ends of the line.

Triple Pole Reclosing

Triple pole reclosing as the result of line to ground fault or three phase fault at different place of the line is studied for both the systems as Fig. 4(a) and 4(b). Triple pole opening for the fault clearing on a system of Fig. 4(a) caused the disconnection of the generator from the system, the generator will be accelerating after the full load rejection resulting from fault clearing. Consequent reclosing constitutes malsynchronization which inevitably excites severe torsional oscillation especially with successful reclosing even for the line to ground fault. Fig. 8 and Fig. 9 show the electrical air gap torque T_e and $T_{L\text{-}G}$ of 600MW unit from triple pole reclosing for line to ground fault and three phase fault respectively. It is clearly from the figures that three pole reclosing in unfavorable time combination will induce severe torsional oscillation even with line to ground fault.

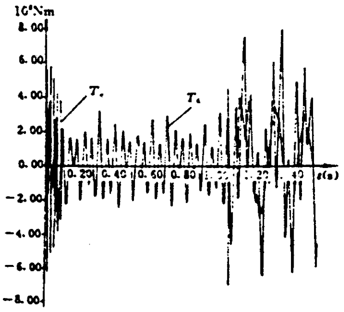


Fig. 8 Successful triple pole reclosing for line to ground fault of system in Fig . 4(b)

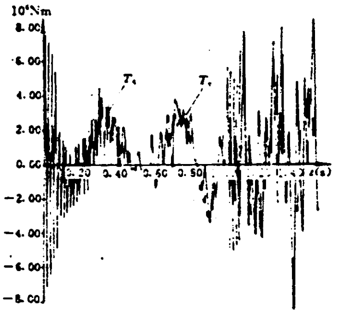


Fig. 9 Unsuccessful triple pole reclosing for three phase fault of system in Fig. 4(a)

CONCLUSION

The new shaft model using multi-mass parameters is presented in this paper. Rather than to calculate the eiganvalue and eigenvactor, a two point boundary value problem is used to get the natural frequency and its mode shapes from the lowest order until the one wanted. Using the method introduced in this paper for shaft system equivalent reduction, a lumped-mass shaft with a sufficient number of discrete masses is obtained for EMTP simulation. A program for the assessment of torsional fatigue is used to process the output from EMTP. Some examples are given in this paper.

References

1. Dommel, H.W., EMTP Theory Book, University of British Columbia.

2. Lambrecht, D., Evaluation of the Torsional Impact of accumulated Failure Combination on Turbine Generator Shaft as basis of Design Guidelines, CIGRE 1984 11-06.

3. Mathematics Models used for Shaft Torsional Oscillation study of Turbine Generator, Report of EPRI, China, 1990.5.

4. Turbine Generator Rotors Sample Calculation of S-N Curves. Westinghouse Electric Corporation.

5. Dunlop, R.D., Horowitz, S.H., Joyce, J.S., Lambrecht, D., Torsional oscillations and Fatigue of Steam Turbine Generator Shafts cursed by System Disturbances and Switching Events. CIGRE 1980 11-06,