Sensitivity Analysis on Turbine-Generator Shaft Torque in 154kV Transmission System

Ji-Kyung Park, Yun-Sik Oh, Hun-Chul Seo, Chul-Hwan Kim

***Abstract*—The torsional stress is caused by interaction between electrical transient air-gap torque by electrical disturbances and mechanical torque of turbine-generator shaft system. If a transient shaft torque exceeds a certain threshold, the loss of fatigue life occurs and in the end it is possible to happen shaft failure. This paper discusses that which factors can damage to turbine-generator shaft and how those factors cause transient shaft torque. For the study, we conducted sensitivity analysis for turbine-generator shaft system to assess torsional stress. We carried out various simulations by using ElectroMagnetic Transient Program (EMTP) based on actual Korea 154kV transmission system. Based on simulation results, this paper provides Zone of Vulnerability (ZoV) considering fault types and locations. Therefore, system operators need to study those factors that may result in torsional stress in detail, especially within ZoV.**

***Keywords*: electromagnetic transient program, fault type, fault distance, lumped-mass model, residual voltage, sensitivity analysis, shaft torque, turbine-generator torsional interaction, zone of vulnerability.**

I. Introduction

Many studies that are discussed relation between turbine-generator shaft and electrical network have been reported since 1970's. Especially, mechanical damage of turbine-generator shaft due to changes in transient shaft torque amplitudes from electrical faults has been mainly discussed. Electrical transient phenomena caused by electrical faults, such as rapid electrical power fluctuation, cause the changes in electromechanical forces. This relation makes a response of the turbine-generator shaft system. Sometimes, it leads to shaft failure when the mechanical damages are accumulated by transient shaft torques, exceeding a certain threshold [1]-[8].

In this paper, we conducted sensitivity analysis to assess the impacts of transient shaft torque according to various fault types and locations with normal clearing time, 0.3s, by using Electro Magnetic Transient Program (EMTP) based on actual 154kV transmission system in Korea. Furthermore, through above sensitivity analysis, we derived the Zone of Vulnerability (ZoV) of actual 154kV power system to determine the geographical range of potential risk to turbine-generator shaft system according to fault types and locations.

II. Turbine-Generator Shaft Torsional Interaction

A. Torsional Interaction and Lumped-mass Model

Network electrical disturbances, including tripping and reclosing of circuit breaker, result in transient air-gap torque through variation in generator stator current. If a resonance between air-gap torque frequency and natural frequency of mechanical shaft system happens, transient torque amplification will be developed in turbine-generator shaft system [8].

Turbine-generator shaft can be divided into several masses depending on its physical structure in Fig. 1. Therefore, when turbine-generator shaft oscillates, different shaft torques occur in different shaft sections according to their moment of inertia and spring constants. Usually, shaft torque between low pressure turbine and generator shaft, here Tm4, is most severe, since generator shaft directly faces to external power system impacts.

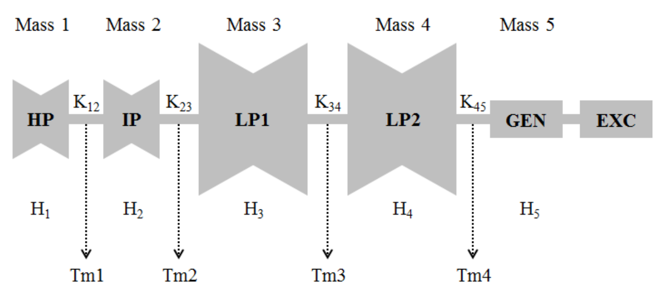

Fig. 1. Lumped-mass model of turbine-generator shaft.

B. Zone of Vulnerability

The ZoV concept is presented by EPRI to estimate whether maximum transient shaft torque due to electrical disturbance near the power plant potentially can make damages to turbine-generator shaft system. Generally, turbine-generator should be designed to withstand a terminal fault at least once in its lifetime. In other words, generator's end windings can withstand the electromagnetic forces imposed by a generator terminal short circuit. Thus, we can assume that maximum torque caused by terminal fault is a reference torque to determine ZoV [9]-[11].

The ZoV is a kind of geographical boundaries that system operator should study the risk of torsional interaction according to fault types and locations within this ZoV

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thoroughly. For example, if the transient shaft torque of a certain fault location is larger than that of three-phase terminal fault, we can consider that fault location is within ZoV. In addition, it may result in mechanical damage of turbine-generator, leading to significant loss of shaft fatigue life.

Defining ZoV is a useful method to estimate shaft damage in the absence of specific shaft fatigue data. Based on detailed studies, system operator can establish more precise power system protection scheme.

C. Sensitivity Analysis

Prior to determination of the ZoV, sensitivity analysis is required to evaluate the impacts of torsional interaction due to electrical disturbances for turbine-generator shaft system. There are various factors that influence to transient shaft torque such as fault locations, fault duration time, fault clearing time, generator loading, high speed reclosing, and etc. as Fig. 2 [7]-[9]. Each factors causes different risk of torsional interaction. In this paper, we mainly discussed the factors such as fault types and locations with normal clearing time.

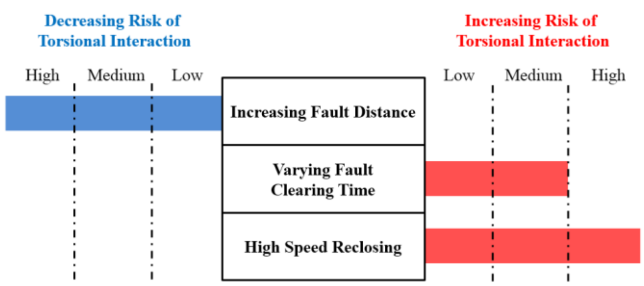

Fig. 2. Factors that affect the risk of torsional interaction.

III. Simulations

A. System and Simulation Conditions

We considered actual 154kV transmission system to assess transient shaft torque due to fault types and locations as Fig. 3. This system has two synchronous generators modeled by lumped-mass structure and three infinite equivalent sources, representing large interconnected power system. In addition, each EHV buses is connected through a double circuit. Thus, there are totally 10 transmission lines in modeled system.

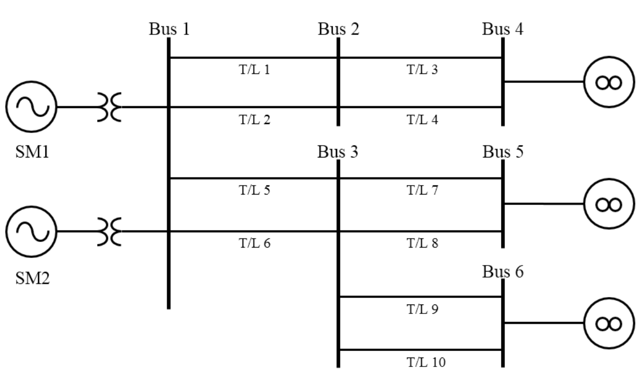

Fig. 3. Actual 154kV power system in Korea.

We assumed that both of synchronous generators, SM1 and SM2, have same mechanical characteristics. Both actual turbine-generator shafts are composed of five masses such as high, intermediate, low pressure turbine, generator rotor and exciter, as shown Fig. 1. Mechanical data such as moment of inertia and spring constant of both synchronous generators are presented in Table I.

TABLE I
MECHANICAL DATA FOR TURBINE-GENERATOR SHAFT IN 154KV THERMAL POWER PLANT

	Moment of Inertia [kgm^2/rad]		Spring Constant [Nm/rad]	
Mass1	H_1	380.6094744	K_{12}	14897722.21
Mass2	H_2	637.5798657	K_{23}	26957718.48
Mass3	H_3	3517.856391	K_{34}	40162024.68
Mass4	H_4	3622.785265	K_{45}	54686897.09
Mass5	H_5	3558.310896		

We assumed that a fault occurs at 0.2s and it is cleared at 0.3s, which passes 6 cycles after fault inception time. After a secondary arc extinction and dead time, the leader circuit breaker recloses at 0.6s and the follower end is reclosed at 2.4s by synchronism check as shown in Fig. 4.

This sequence is currently applied to protection scheme in Korea 154kV system. A circuit breaker of 154kV system in Korea is operated based on three-pole tripping and reclosing. Based on this sequence, we measured maximum shaft torque in time-domain. Its values are represented in per unit to compare their amplitude easily in whole simulation results.

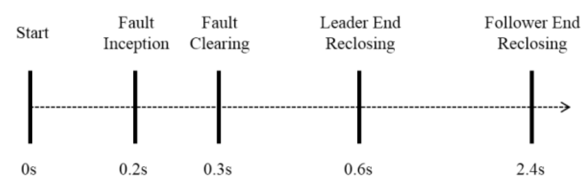

Fig. 4. Simulation sequence for 154kV protection scheme in Korea.

B. Analysis of Shaft Torque according to Generator Terminal Fault

Before going on sensitivity analysis of turbine-generator shaft, it is required to decide how much torsional stress may result in physical damages to turbine-generator shaft. Therefore, we need to find maximum shaft torque as a reference torque. Generator should be designed to be capable of withstanding, without any mechanical damages, any type of short circuit which may result in considerable transient torque in turbine-generator shaft [10]. For that reason, maximum shaft torque due to generator terminal fault is considered as a reference torque to conduct sensitivity analysis of turbine-generator shaft system.

Maximum shaft torque values for SM1 and SM2 due to each generator's terminal fault are shown in Table II and Table III, respectively. We can conclude that the worse fault occurs, the larger shaft torque is caused in turbine-generator shaft. In addition, unbalanced fault, such as single line-to-ground and double line-to-ground cause almost same maximum shaft torque in the same fault type. Based on these results, we can determine the maximum shaft torque, which is caused by three-phase fault, as a reference torque.

TABLE II
MAXIMUM SHAFT TORQUE FOR SM1 DUE TO EACH TERMINAL FAULT

Fault Type	Fault Location	Maximum Shaft Torque for SM1 (p.u.)			
		Tm1	Tm2	Tm3	Tm4
1LG_A	SM1 Terminal	0.352	0.657	0.925	1.125
1LG_B		0.352	0.657	0.926	1.126
1LG_C		0.352	0.657	0.925	1.125
2LG_AB		0.357	0.667	0.956	1.159
2LG_BC		0.357	0.667	0.956	1.159
2LG_CA		0.357	0.667	0.955	1.157
3LG		0.363	0.679	0.991	1.196

TABLE III
MAXIMUM SHAFT TORQUE FOR SM2 DUE TO EACH TERMINAL FAULT

Fault Type	Fault Location	Maximum Shaft Torque for SM2 (p.u.)			
		Tm1	Tm2	Tm3	Tm4
1LG_A	SM2 Terminal	0.356	0.665	0.938	1.141
1LG_B		0.356	0.665	0.939	1.142
1LG_C		0.356	0.665	0.938	1.141
2LG_AB		0.361	0.676	0.971	1.177
2LG_BC		0.362	0.676	0.972	1.177
2LG_CA		0.361	0.676	0.970	1.176
3LG		0.368	0.689	1.009	1.217

C. Analysis of Shaft Torque according to Fault Types and Locations in Transmission Line

We conducted a hundred simulation cases to assess shaft torque, which is measured after fault tripping, due to fault types and locations in all of transmission lines in modeled 154kV system. Table IV shows that three-phase fault causes larger maximum shaft torque than single phase-to-ground fault at 10, 30, 50, 70 and 90% of fault locations. Electrical transient phenomena such as fault current are directly related with air-gap torque in synchronous generator. Therefore, severe fault causes sudden alternation of air-gap torque which affects critical torsional interaction of turbine-generator shaft.

TABLE IV
MAXIMUM SHAFT TORQUE FOR SM1 AND SM2
ACCORDING TO FAULT TYPE IN T/L 1

Fault Type	Fault Location	Maximum Shaft Torque (p.u.)							
		SM1				SM2			
		Tm1	Tm2	Tm3	Tm4	Tm1	Tm2	Tm3	Tm4
1LG	10%	0.375	0.701	1.070	1.258	0.377	0.706	1.075	1.260
3LG		0.573	1.081	1.811	2.019	0.590	1.121	1.893	2.103
1LG	30%	0.358	0.669	1.001	1.189	0.360	0.673	1.005	1.186
3LG		0.536	1.010	1.678	1.894	0.548	1.039	1.737	1.945
1LG	50%	0.350	0.654	0.969	1.156	0.352	0.658	0.972	1.153
3LG		0.517	0.972	1.607	1.823	0.526	0.996	1.655	1.860
1LG	70%	0.347	0.647	0.955	1.142	0.348	0.651	0.958	1.139
3LG		0.510	0.959	1.584	1.798	0.519	0.982	1.629	1.831
1LG	90%	0.347	0.648	0.955	1.143	0.349	0.652	0.959	1.140
3LG		0.518	0.975	1.617	1.827	0.527	0.999	1.666	1.865

Moreover, we carried out detailed simulations according to fault locations from 1% to 90% in every transmission lines. The result of maximum shaft torque according to various fault locations in T/L 1 is shown in Table V and Fig. 5 as a representative. As fault location gets further from generation side, the maximum shaft torque decreases. This trend can be found every transmission lines in modeled 154kV system.

TABLE V
MAXIMUM SHAFT TORQUE FOR SM1 AND SM2
ACCORDING TO DETAILED FAULT LOCATIONS IN T/L 1

Fault Type	Fault Location	Maximum Shaft Torque (p.u.)							
		SM1				SM2			
		Tm1	Tm2	Tm3	Tm4	Tm1	Tm2	Tm3	Tm4
T/L 1 3LG	1%	0.597	1.129	1.899	2.101	0.618	1.178	1.999	2.206
	10%	0.573	1.081	1.811	2.019	0.590	1.121	1.893	2.103
	20%	0.552	1.040	1.735	1.949	0.566	1.074	1.803	2.013
	30%	0.536	1.010	1.678	1.894	0.548	1.039	1.737	1.945
	40%	0.525	0.987	1.636	1.852	0.535	1.013	1.688	1.895
	50%	0.517	0.972	1.607	1.823	0.526	0.996	1.655	1.860
	60%	0.512	0.963	1.589	1.805	0.520	0.985	1.635	1.838
	70%	0.510	0.959	1.584	1.798	0.519	0.982	1.629	1.831
	80%	0.512	0.963	1.592	1.805	0.520	0.986	1.638	1.839
	90%	0.518	0.975	1.617	1.827	0.527	0.999	1.666	1.865

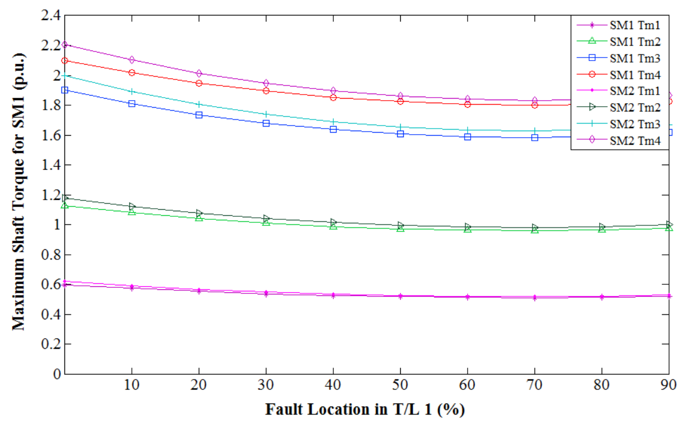

Fig. 5. Maximum shaft torque according to fault locations in T/L 1.

We can explain this trend with residual voltage at Bus 1. Although fault occurs in transmission line, bus voltage, which is connected by faulted line, does not drop to zero. Generally, substations are strongly interconnected with others by single or double circuit.

In modeled system, Bus 1 is connected with Bus 2 and 3 as double circuit. Therefore, its bus voltage can be sustained and the residual voltage of phase A can be shown in Fig. 6. After fault inception at 0.2s, the voltage experiences sudden transient voltage drop and it is maintained with residual voltage. Since then, bus voltage experiences one more sudden transient voltage rise by fault tripping operation at 0.3s.

Generally, the lower residual voltage remains, the greater alternation of bus voltage is caused by fault inception and clearing. Therefore, sudden voltage variation stimulates and amplifies the transient air-gap torque in synchronous generator.

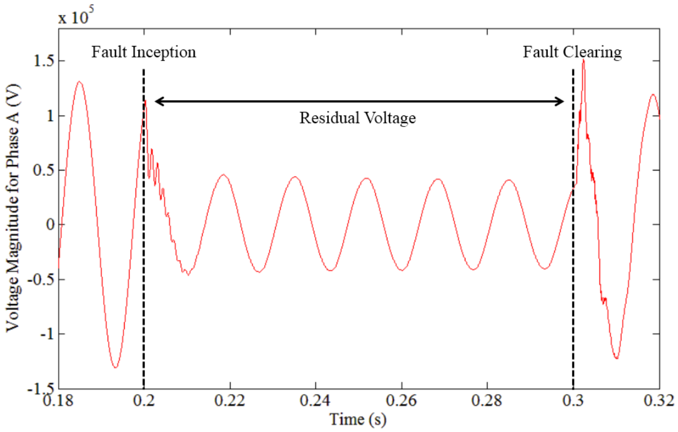

Fig. 6. Voltage magnitude for phase A due to fault inception and clearing.

Fault location is highly related with reactance, from substation to fault location in transmission line. In other words, if fault location is far from generation side, the reactance from substation to fault location is large. This large reactance supports substation to maintain its voltage relatively high comparing to small reactance by close in fault location. Fig. 7 shows the residual voltage of phase A in Bus 1.

As we discussed above, further fault location has larger residual voltage which results in less shaft torque. Therefore, we can simply know that if we flip Fig. 5 upside down, same trend plot will be derived as Fig. 7.

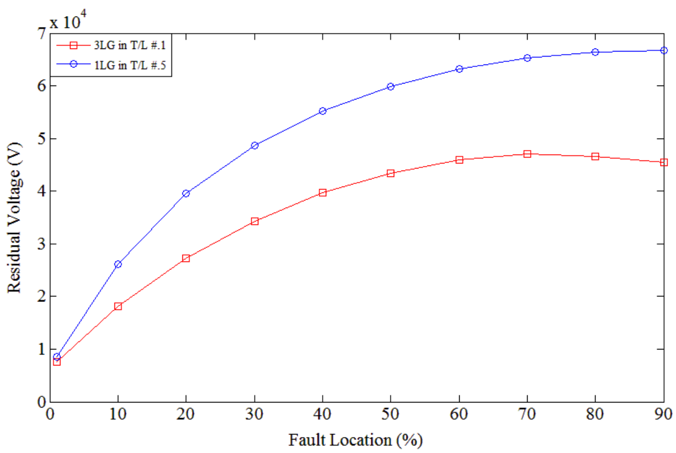

Fig. 7. Residual voltage at Bus 1 according to fault locations.

D. *Zone of Vulnerability of actual 154kV system*

We studied maximum shaft torque due to generator terminal fault to decide reference torque which is caused by three-phase fault and then, we compared every maximum shaft torque according to various fault types and locations in every transmission lines to determine ZoV. The ZoV for each individual synchronous generator can be derived and classified by fault types. Therefore, we derived ZoV of 154kV system considering three-phase and single phase-to-ground fault in SM1 aspects as Fig. 8 and Fig. 9, respectively.

This paper does not include the ZoV in SM2 aspects, but it can be derived easily by same method in Fig.8 and Fig.9. We can expect that it will be similar with ZoV in SM1 aspects, since SM1 and SM2 are connected with same substation and have same mechanical data.

The most frequent fault type in transmission line is single phase-to-ground fault and three-phase fault rarely happens. However, as we can see in Fig. 8, once a three-phase fault and bus faults happen within highlighted ZoV area in modeled 154kV system, turbine-generator shaft surely will be damaged by exceeding reference shaft torque and this damage will be accumulated causing shaft failure in the end. In addition, since three-phase fault causes most severe transient electrical torque, all of zone including extra high voltage buses in modeled 154kV system are within ZoV. Therefore, it is required to conduct research for reducing torsional interaction within ZoV for three-phase fault.

In ZoV case for single phase-to-ground fault in Fig. 9, we also considered faults in transmission line and bus faults. The results is that only fault which is proximity to generation side exceeds the reference torque, since single phase-to-ground fault causes less electrical transient torque comparing to three-phase fault. Although ZoV area of single phase-to-ground fault is smaller that of three-phase fault, it is also required to establish countermeasures for torsional stress.

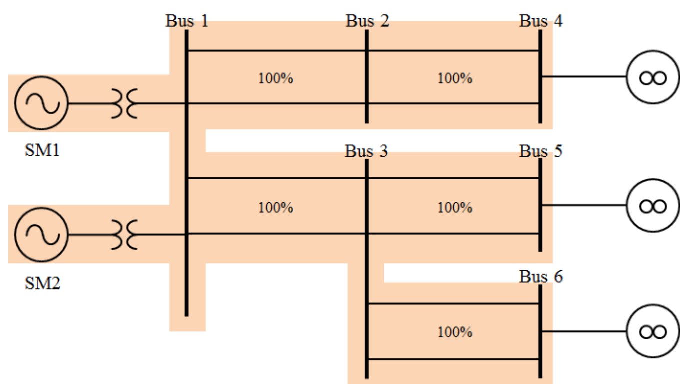

Fig. 8. ZoV of actual 154kV system considering 3LG and bus fault.

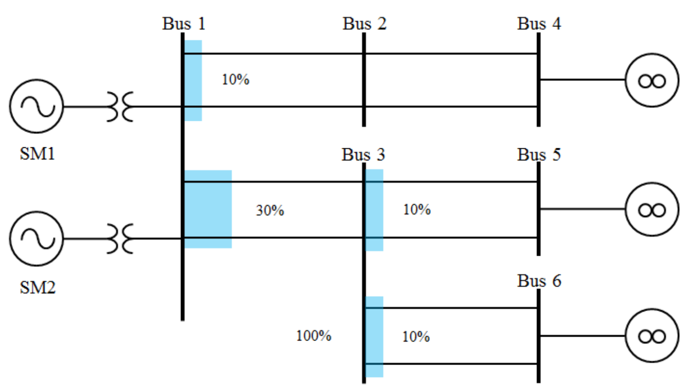

Fig. 9. ZoV of actual 154kV system considering 1LG fault.

In this way, system operator can anticipate which transmission line area is vulnerable to torsional interaction which is caused by fault types and locations. Moreover, considering other sensitivity analysis factors for turbine-generator shaft, it will be possible to optimize the system protection scheme.

IV. Conclusion

Generally, it is hard to assess torsional stress which may result in mechanical damages to turbine-generator shaft system, because of difficulty of obtaining mechanical data and shaft fatigue data from turbine-generator manufacturer or system operator. Therefore, we introduced the ZoV concept to assess the extent of torsional interaction. Based on maximum shaft torque caused by generator terminal fault as a reference torque, we conducted sensitivity analysis according to fault types and locations.

In brief summary, three-phase fault inception and clearing cause substantial change of generator stator current and air-gap torque comparing to other fault types. Therefore, it causes larger maximum turbine-generator shaft torque. In addition, the further fault location is, the smaller shaft torque is caused because of residual voltage effects at substations.

Based on these sensitivity analysis data, we derived ZoV for fault types and locations. This will be a helpful to expect torsional stress which may result in shaft failure. Moreover, it will be possible to enhance and establish the optimal 154kV protection scheme based on ZoV. In the future, we will study about torsional interaction due to variable fault clearing time, successful or unsuccessful reclosing, and etc.

V. References

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