Initiation Time Influence of Voltage Sag on Dispersed Generator Shaft Torque

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Abstract - **It has become popular for large industrial customers to have in-house generation systems for feeding their own loads. Especially the co-generation systems have been introduced to many customers such as hotels and hospitals. The non-utility generator is often connected to the utility power systems to supplement the electric power to the loads or to have higher reliability than the isolated operations. However, when a fault occurs on the utility transmission lines due to lightning etc., the voltage at the customer's bus drops until the fault clearance. This voltage sag might affect the customer's voltage sensitive loads such as electronics systems, adjustable speed drives or discharge lamps. In order to minimize the influence of the voltage sag, the bus-tie breakers are used to disconnect the critical loads and the in-house generator from the utility power systems by detecting the voltage magnitude when the power system's fault occurs. Thus, the voltage sag duration at the bus to which the critical loads and the in-house generators connect, is varied according to the types of the breakers and the voltage detection circuit. In case of the conventional circuit breakers with the conventional protective relay, it takes 0.2 to 0.3 sec typically to disconnect the circuits. When the thyristor type static switchgear with high-speed voltage detection circuit is used, the opening time can be shorter than one cycle of the commercial frequency. The GTO type switchgear operates faster than the thyristor type because it has a current limiting feature. Both types of high-speed switchgear are in practical use.**

In this paper, an influence of the voltage sag magnitude and duration on non-utility generator's shaft torque is investigated by simulations using the electromagnetic transients simulation program. Various types of fault are simulated, changing the number of faulted phases and the voltage phase angle at the moment of fault initiation. The following remarks were obtained from the simulation results. Electrical and mechanical shaft torques are influenced by the fault conditions. The case which gives maximum torques is not always the three phase fault which gives a maximum voltage sag. In the unbalanced fault cases, the influence of fault initiation angle cannot be neglected. The protection using the high-speed switchgear using static switch is effective for the stable operation of the dispersed generation systems and the critical loads, which are subjected to the voltage sag.

Keywords: Voltage sag, Dispersed generation, Co-generation systems, Static switchgear, EMTP

I . INTRODUCTION

It has become popular for large industrial customers to have in-house generation systems for feeding their own loads. Especially the co-generation systems have been introduced to many customers such as hotels and hospitals. The non-utility generator is often connected to the utility power systems to supplement the electric power to the loads or to have higher reliability than the isolated operations. However, when a fault occurs on the utility transmission lines due to lightning etc., the voltage at the customer's bus drops until the fault clearance. This voltage sag might affect the customer's voltage sensitive loads such as electronics systems, adjustable speed drives or discharge lamps [1]-[3]. In order to minimize the influence of the voltage sag, the bus-tie breakers are used to disconnect the critical loads and the in-house generator from the utility power systems by detecting the voltage magnitude when the power system's fault occurs. Thus, the voltage sag duration at the bus to which the critical loads and the in-house generators connect, is varied according to the types of the breakers and the voltage detection circuit. In case of the conventional circuit breakers with the conventional protective relay, it takes 0.3 sec at maximum to disconnect the circuits. When the thyristor type static switchgear with high-speed voltage detection circuit is used, the opening time can be shorter than one cycle of the commercial frequency [4]-[6]. The GTO type switchgear operates faster than the thyristor type because it has a current limiting feature [7].

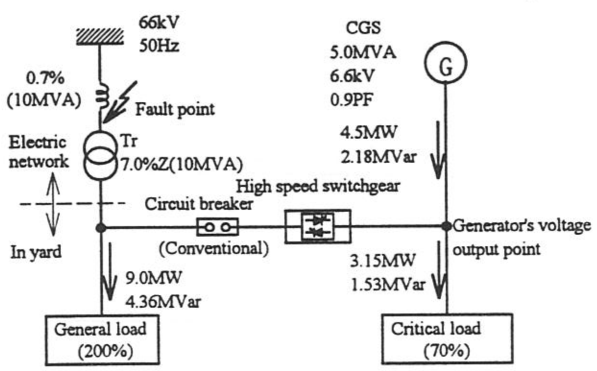
The voltage sag might also affect the in-house generator's operation, because the transient electromagnetic torque is generated at the moment of fault initiation and its clearing by the breaker and continues to oscillate. If the prime mover of the generation system is gas-turbine unit, the shear pins are used to protect the turbine units against the excessive shaft torque. During the oscillation of the electromagnetic torque, the shaft torque also oscillates according to the mechanical oscillation modes and the shear pin might be damaged by the transient shaft torque. If the shear pin is cracked, the turbine unit is separated from the generator and the customer systems are blackout. For the shaft torsional torque of utility's large generators, a lot of research have been dedicated [8]-[19]. They include the research for transient torque with fault incidence, [9],[13],[14] fault clearing,[9],[17] line reclosing, [11],[[12],[14],[16],[17] and synchronization [19]. However, for those torque of non-utility small generators, very few research results have been presented [20],[21].

In this paper, an influence of the voltage sag magnitude and duration on non-utility generator's shaft torque is investigated by simulations using the electromagnetic transients program (ATP-EMTP). Various types of fault are simulated, changing the number of faulted phases and the voltage phase angle at the moment of fault initiation. The opening time of the bus-tie breakers is varied.

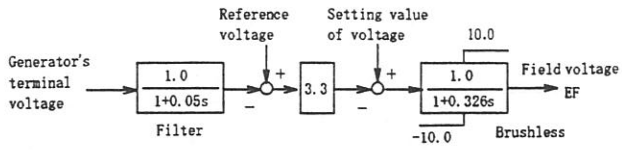
II. A SIMULATION CIRCUIT

A simulation circuit is shown in Fig.1. In simulations using ATP-EMTP, conventional circuit breaker is simulated with time controlled ordinary switch and GTO type high-speed switchgear is simulated with TACS controlled switch. A inhouse-generator is simulated with Park's detailed model and a utility system is simulated with a constant-magnitude constant-frequency voltage source and a constant source impedance. A transformer is simulated with the TRANSFORMER model in ATP-EMTP. Block diagrams of an AVR and a governor are also shown in Fig.1. They are simulated using a first order S-block and a limiter in TACS function of ATP-EMTP.

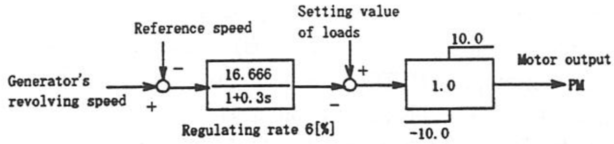
Specification of a generator is shown in Table 1. The data are typical generator's values. The q-axis constants equal to the d-axis constants, i.e. Xq=Xd, Xq"=Xd" and Tqo"=Tdo". Xq' and Tqo' are not considered. A generator shaft system is represented by a spring-mass model with 7 masses. In Table 2, moments of inertia and spring constants between each masses are shown. The data are determined based on the typical gas-turbine unit data shown in reference [22] and are modified according to the rated capacity of the generator in the simulation. Self and mutual damping are neglected, because this study is focused on peak values of mechanical shaft torque and damping data are hard to specify. From the eigenvalue calculation using the data of mechanical system, natural oscillation frequency of shaft torsional torque is about 20.2 Hz.



(a) An in-house generation system



(b) An AVR circuit



(c) A governor circuit

Fig.1 A simulation circuit.

Table 1 A specification of a generator

Item	Value
rated frequency: f_G	50 Hz
rated capacity: P_G	5.0 MVA
rated voltage: V_G	6.6 kV
number of poles	4
armature resistance: Ra	0.0064 pu
armature leakage reactance: X_L	0.0937 pu
d-axis synchronous reactance: Xd	2.027 pu
d-axis transient reactance: Xd'	0.210 pu
d-axis sub-transient reactance: Xd"	0.173 pu
d-axis open-circuit transient time constant: Tdo'	3.100 s
d-axis open-circuit sub-transient time constant: Tdo"	0.0387 s

Table 2 Mechanical constants of a generator shaft

	Moment of inertia (10^6 kgm^2)	Spring Constant (10^6 Nm/rad)
1	335.00E-6	8.728
2	12.78E-6	37.780
3	3.68E-6	15.935
4	0.70E-6	8.410
5	0.70E-6	1.804
6	89.64E-6	1.380
7	1.23E-6	

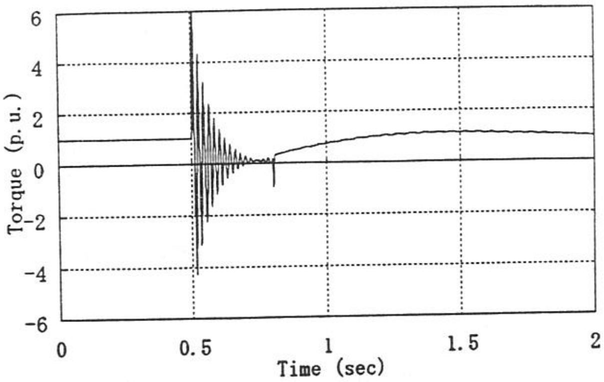
III. SIMULATION RESULTS

Simulated waveforms for a three-line-to-ground (3LG) fault are shown in Fig.2 and Fig.3. Instantaneous electrical torque of the generator and instantaneous mechanical shaft torque at the coupling between the mass 4 and the mass 5 are shown. Fault location is the primary terminal of the transformer, which is the point of common coupling. Fault is initiated at t=0.5 seconds in both cases of conventional circuit breaker (CB) and GTO type high-speed switchgear (GTO). In CB cases, the breaker is opened when the phase current crosses zero after t=0.8 seconds (0.3 seconds from the fault initiation). In GTO cases, GTO switch is opened when on of the phase-to-phase voltages is lower than 85% of the rated voltage or one of the generator phase currents is higher than 300% of the rated current of the generator. In the steady state of GTO case shown in Fig.3, oscillation in torque is observed. This is due to the transients of TACS controlled switch's closing at t=0. This could not be controlled. However, the transients are not remarkable at t=0.5 seconds.

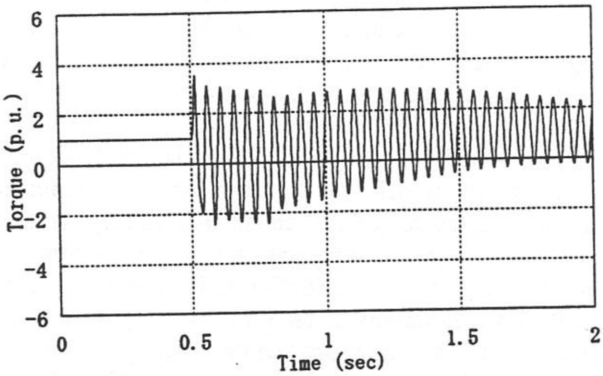
In case of CB, the voltage sag magnitude is larger than 80% and the duration is 0.3 seconds. Most critical loads will be affected by this voltage sag. For the electrical torque in Fig.2(a), the peak value is 6.0 p.u., which nearly equals to 1/(Xtr+Xd")=4.9 p.u plus steady state torque 1.0 p.u. and the frequency of oscillations due to transient DC component in currents is 50 Hz. In Fig.2(b), the peak value of shaft torque is 3.5 p.u. and the frequency of oscillation in mechanical shaft system is 20.2 Hz, which equals to the generator mechanical natural frequency.

In case of GTO, the voltage sag magnitude is smaller than 30% and the duration is shorter. Most critical loads will not be affected by this voltage sag. For the electrical torque in Fig.3(a), the peak value is 2.9 p.u and the oscillations after fault clearing is negligible. For the shaft torque, in Fig.3(b), the peak value is 1.3 p.u. and the magnitude of oscillation in mechanical shaft system is smaller compared to the CB case. Oscillation frequency is same as the CB case.

Then, to investigate the influence of the fault type, number of faulted phase is varied. Fault location is the transformer terminal and the fault resistance is nearly zero. Results for the CB cases are shown in Fig.4 to 7, for the cases of double-line-to-ground (2LG-bc) and one-line-to-ground (1LG-a), respectively. In these cases, the fault initiation phase angle at he generator terminal voltage is same as Fig.2 and Fig.3, in which the fault is initiated at the phase angle of zero degree (sine wave). Electrical torque is largest in double-line-to-ground case, which gives over 6.0 p.u. This feature is well known [23]. However, for the GTO cases, electrical torque is largest in three-line-to-ground case, which gives 3.0 p.u. This is because of the current limiting capability of GTO type switchgear. As the current peaks are limited to the same value, the larger the number of phase, the larger the peak electrical torque. For the shaft torque, three phase fault is the severest case.

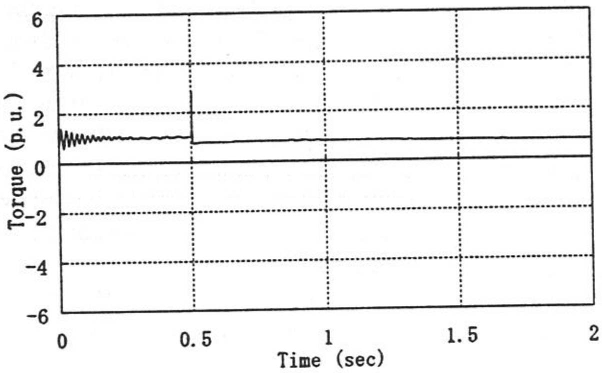


(a) Electrical torque

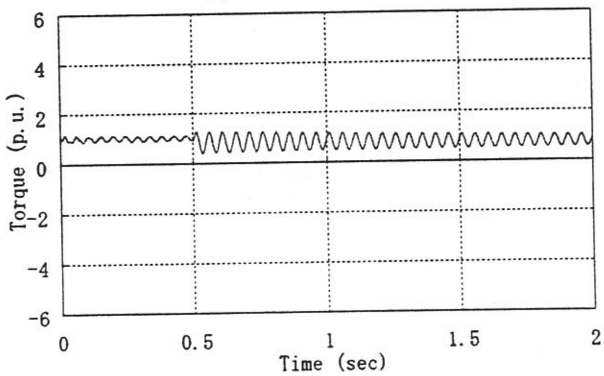


(b) Shaft torque

Fig.2 Simulation results with conventional circuit breaker (3LG)

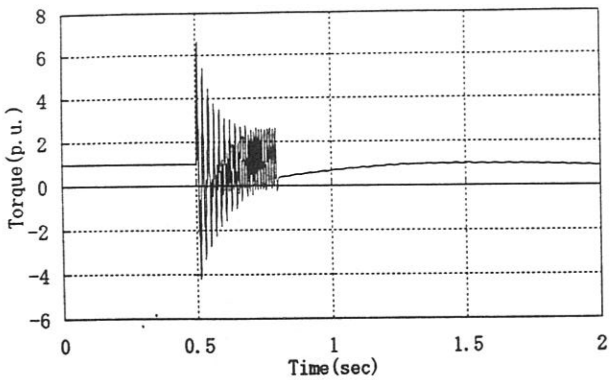


(a) Electrical torque

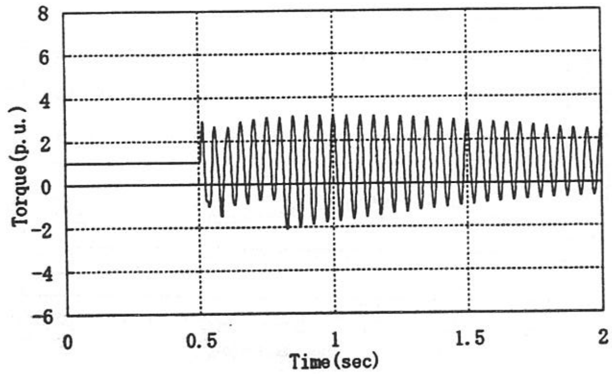


(b) Shaft torque

Fig.3 Simulation results with GTO type high speed switchgear (3LG)

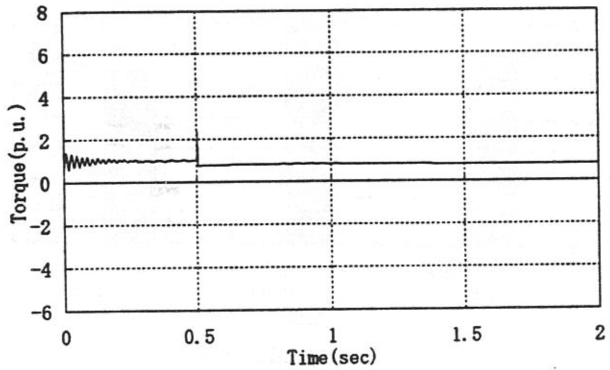


(a) Electrical torque

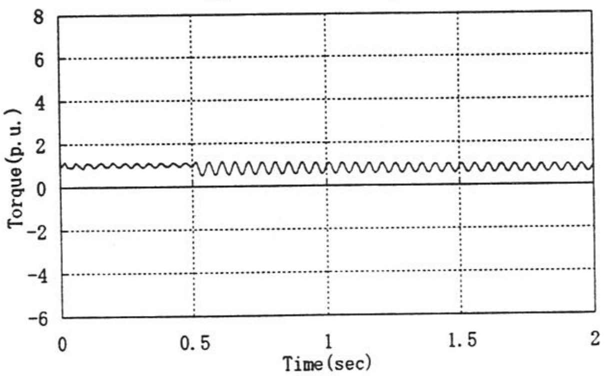


(b) Shaft torque

Fig.4 Simulation results with conventional circuit breaker (2LG-bc)

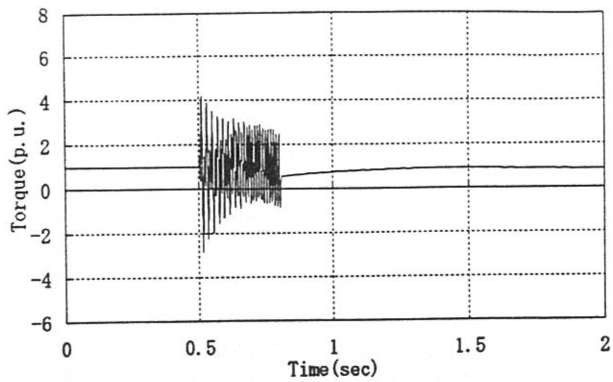


(a) Electrical torque

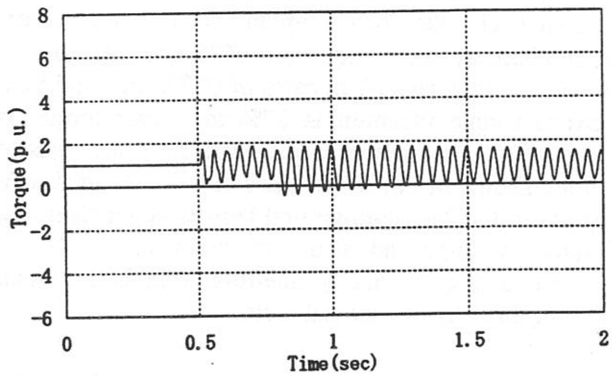


(b) Shaft torque

Fig.5 Simulation results with GTO type high speed switchgear (2LG-bc)

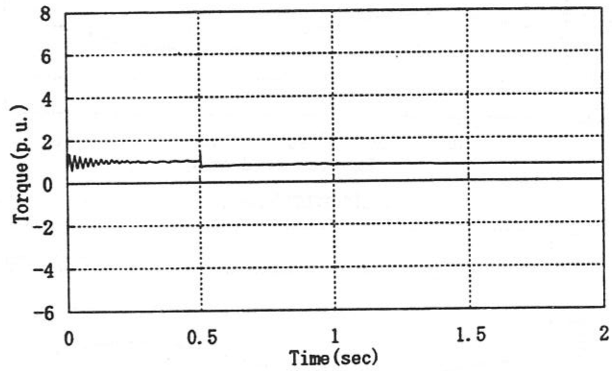


(a) Electrical torque

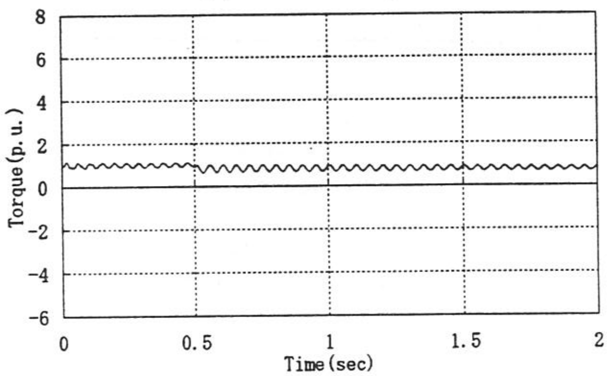


(b) Shaft torque

Fig.6 Simulation results with conventional circuit breaker (1LG-a)



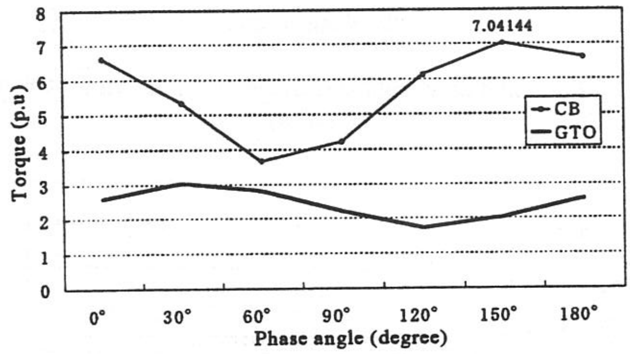
(a) Electrical torque



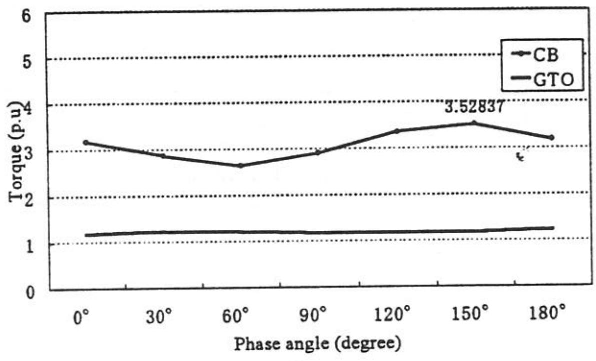
(b) Shaft torque

Fig.7 Simulation results with GTO type high speed switchgear (1LG-a)

To investigate the influence of phase angle at the moment of fault initiation, time of the fault initiation is varied from t=0.5 to 0.51 by 1.667 msec, i.e. the electrical phase angle is 0 to 180 degrees. Fault location is transformer terminal and fault resistance is nearly zero. The peak values of electrical and shaft torques are shown in Fig.8 and Fig.9. For the three phase fault, the influence of fault initiate angle can be neglected as far as the parameter value of three phases is equal to each other. Therefore, the double-line-to-ground and the single-phase-to-ground fault are applied here. In cases of CB, the electrical and mechanical torque peaks are sensitive to phase angle change. The maximum deviation in electrical and mechanical shaft torque are 30% and 14% of the mean value, respectively. In cases of GTO, the maximum electrical torque variation is 27% and shaft torque is negligible. The maximum torque peaks for three types of fault are shown in Fig.10. In cases of CB, the maximum torques for double-line-to-ground fault is larger than that of three-line-to-ground fault. In cases of GTO, the maximum torques for double-line-to-ground fault is equal to that of three-line-to-ground fault.

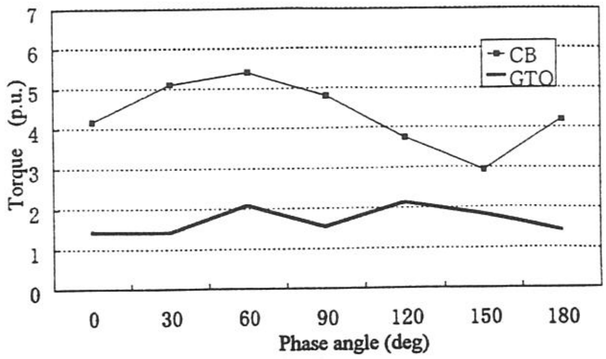


(a) Electrical torque

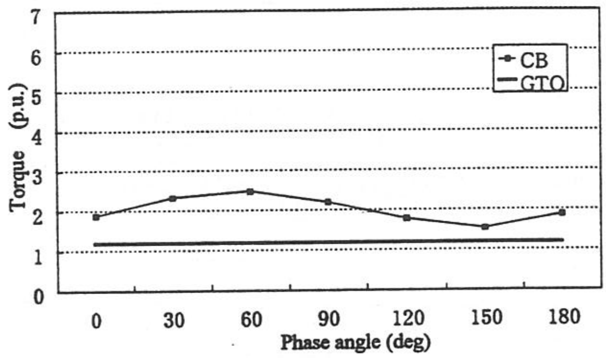


(b) Shaft torque

Fig.8 Influence of phase angle. (Double-line-to-ground fault).

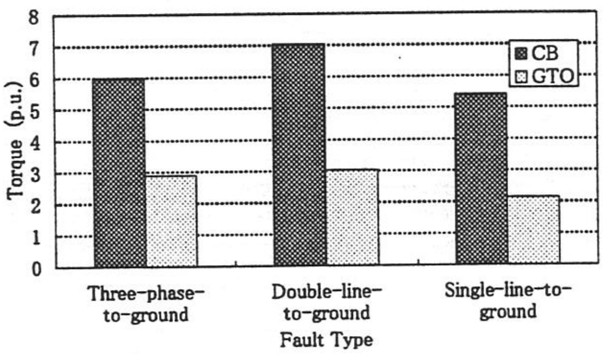


(a) Electrical torque

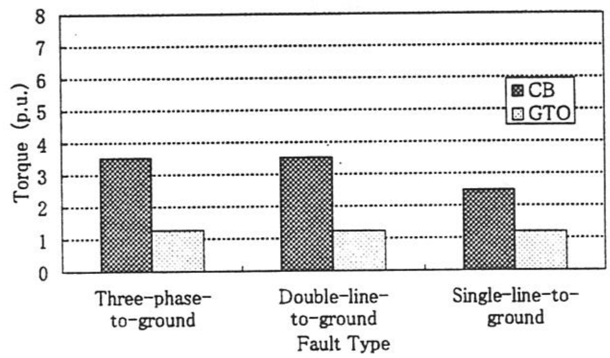


(b) Shaft torque

Fig.9 Influence of phase angle. (Single-line-to-ground fault).



(a) Electrical torque



(b) Shaft torque

Fig.10 Influence of fault type.

IV. CONCLUSIONS

An influence of the voltage sag initiation phase angle on non-utility generator's shaft torque was investigated. The following remarks were obtained from the simulation results. Electrical and mechanical shaft torques are influenced by the fault conditions. The case which gives maximum torques is not always the three phase fault which gives a maximum voltage sag. In the unbalanced fault cases, the influence of fault initiation angle cannot be neglected. The protection using the high-speed switchgear using static switch is effective for the stable operation of the dispersed generation systems and the critical loads, which are subjected to the voltage sag.

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