Analysis of Quadrilateral Out-of-Step Protection Relay Operation

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***Abstract*--Generally, electrical torque in synchronous generator is balanced with the rotor mechanical torque under steady-state condition. Thus, the synchronous generator rotor rotates at constant speed. However, under fault condition, the electrical torque output is suddenly decreased and the sum of both torques does not remain constant. If the mechanical torque is not decreased at the same time, the generator rotor would accelerate. Therefore, this accelerating generator rotates at different speeds with respect to other generators in the power system. This phenomena is called as Out-of-Step (OOS). In this paper, we presented a certain two-step type quadrilateral OOS relay setting, which is applicable in actual field, and examined the validity of its setting value with OOS simulation conditions due to delayed fault clearing in transmission line. In order to conduct the study of OOS relay characteristics, we checked the impedance locus and generator output characteristics under the various delayed fault clearing conditions. Moreover, we proposed a countermeasure for avoiding the mis-operation of OOS relay during the stable swing by modifying the setting values.**

***Keywords*: EMTP-RV, Generator Out-of-Step, Quadrilateral Out-of-Step Protection Relay.**

I. INTRODUCTION

AS the extension and increasing the complexity of power system, a power system disturbance could be considered as detrimental factors to threat the protection of power system equipment and power system stability. Therefore, it is required to protect the generator and power system immediately from the system disturbance and prepare the proper method not to spread the system fault impacts. For example, if the fault is cleared with delayed time, system stability and generator output could drastically oscillate. In severe situation, generator could rotate in different speed compared to other generators, thus, Out-of-Step (OOS) condition could occur. Generally, this OOS condition is considered one of the worst disturbance in power system, this fault should be removed from system immediately. In order to detect and protect the OOS condition, various type of OOS protection relays are implemented in power system based on distance (impedance) relay concept [1]-[4].

The detection schemes for OOS condition are dealt in various research [5]-[7], but, the analysis of OOS protection relay operation characteristics and review of OOS relay setting value are still necessary. Therefore, in this paper, in order to conduct practical study, we considered an actual 345kV nuclear power plant, transmission system and OOS relay setting values. Through sensitivity analysis of fault clearing time, we analyzed the characteristics of quadrilateral OOS protection relay operation. Moreover, we proposed modified quadrilateral OOS protection relay logic, which can prevent the mis-operation under stable power swing. All of modeling and simulation studies were conducted with ElectroMagnetic Transient Program (EMTP).

II. GENERATOR OUT-OF-STEP

A. The Definition of Generator Out-of-Step

In steady-state, the synchronous generator electrical torque output is balanced with mechanical torque input through the shaft system. During this torque input/output equivalent condition, the synchronous generator rotor rotates in constant speed, which has power frequency. Under a system fault condition, power tranfer is reduced and electrical output torque that counters the mechanical input torque is also reduced. If the mechanical input torque is not reduced during fault condition, the generator will accelerates. Thus, this system condition causes that one generator rotates at a different speed from the other generators on the system. This condition is called as a loss-of-synchronism or an OOS condition [8]-[9].

B. Generator Out-of-Step Protection

An OOS condition causes high currents and mechanical forces in the generator windings and high level of transient shaft torques. Therefore, it is desirable to immediately trip the unit because shaft torque levels build up with each subsequent slip cycle. This buildup results from continually increasing slip frequency passing through the first natural torsional frequency of the shaft system. Pole slipping events can also result in abnormally high stator core end iron fluxes that can lead to overheating and shorting at the stator core ends. Therefore, if an OOS condition occurs, the generator or system should be separated immediately using OOS protection, which has IEEE device number 78 [10].

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C. A Quadrilateral Out-of-Step Protection Relay

Fig. 1 shows a quadrilateral OOS protection relay characteristic, which has two-step blinder. The inside rectangular protection zone is called as Inner blinder and the outside zone is called as Outer blinder. Only if the generator apparent impedance passes through Outer, Inner and Outer blinder sequence with preset time delay satisfaction, the OOS protection relay trip logic detects the OOS condition and activates the trip signal [11].

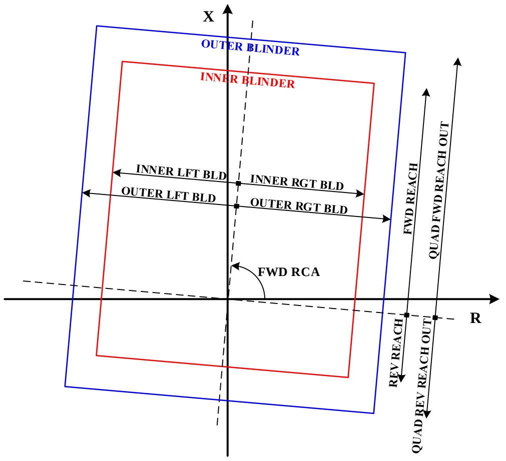

Fig. 1. A quadrilateral out-of-step relay characteristics.

III. SYSTEM MODELING

A. Study System

The quadrilateral OOS relay characteristic was implemented to a 345kV Korean nuclear power plant and transmission system as shown in Fig. 2. The detailed system parameters are stated in Table I. The study system has almost same characteristics with actual power system, since it is modeled based on power flow study in steady-state and dynamic response under contingency fault study. In this study system, we focused on the response of OOS relay for generator #1 as a representative machine. All of system components such as generator and controllers are modeled by EMTP-RV.

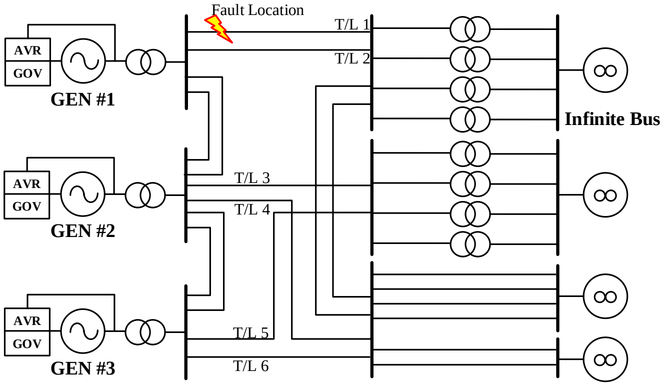

Fig. 2. A 345kV nuclear power plant and transmission system.

TABLE I
PARAMETERS FOR GENERATOR #1

Generator electrical	Rating	4-pole, 1284MVA, 3-phase, 22kV	
	Reactance (p.u.)	$R_a = 0.0020$ $X_l = 0.1590$ $X_0 = 1.8380$ $X_d = 0.2580$ $X_q = 0.1900$	$X_d^{'} = 0.0411$ $X_d^{''} = 1.7260$ $X_q^{'} = 0.6250$ $X_q^{''} = 0.1900$
	Time Constant (s)	$T_{d0}^{'} = 9.1000$ $T_{d0}^{''} = 0.0340$	$T_{q0}^{'} = 0.4050$ $T_{q0}^{''} = 0.0500$
Excitation system	ESST4B	$T_a, T_r = 0$ $K_{pr} = 4, K_{ir} = 4$ $V_{rmax} = 1$ $V_{rmin} = -0.87$ $K_{pm} = 1, K_{im} = 0$ $V_{mmax} = 1$	$V_{mmin} = -0.87$ $K_q = 0$ $K_p = 5.91, K_i = 0$ $V_{bmax} = 6.3$ $K_c = 0.17$ $X_l, \theta_p = 0$
Governor system	IEEEG1	$K, T_1, T_2=0$ $T_3=0.1,$ $U_o=0.1$ $U_c=-0.2$ $P_{max}=0.856$ $P_{min}=0.077$	$T_4=0.3, K_1=0.317$ $T_5=15, K_3=0.266$ $T_6=0.4, K_5=0.417$ $K_2, K_4, K_6, K_7, K_8,$ $T_7=0$
Transmission line data	T/L 1. 2 (ohm)	R0=3.951628 L0=68.272744	R1=0.987907 L1=17.068186
	T/L 3. 5 (ohm)	R0=5.33232 L0=95.743712	R1=1.333080 L1=23.935928
	T/L 4. 6 (ohm)	R0=7.6176 L0=131.403596	R1=1.904400 L1=32.850899

B. Out-of-Step Protection Relay Modeling

In this paper, we compared the magnitude between the impedance angle and the OOS blinder angle. Thus, if the calculated impedance angle is larger or smaller than blinder angle, the OOS relay is picked-up and ready to operate. This comparison method could be different according to left/right or upper/lower blinder. Fig 3 shows the OOS relay model, which has a two-step quadrilateral characteristic using EMTP-RV. This OOS relay model can be divided as voltage and current measurement part, impedance calculation part and OOS detection part.

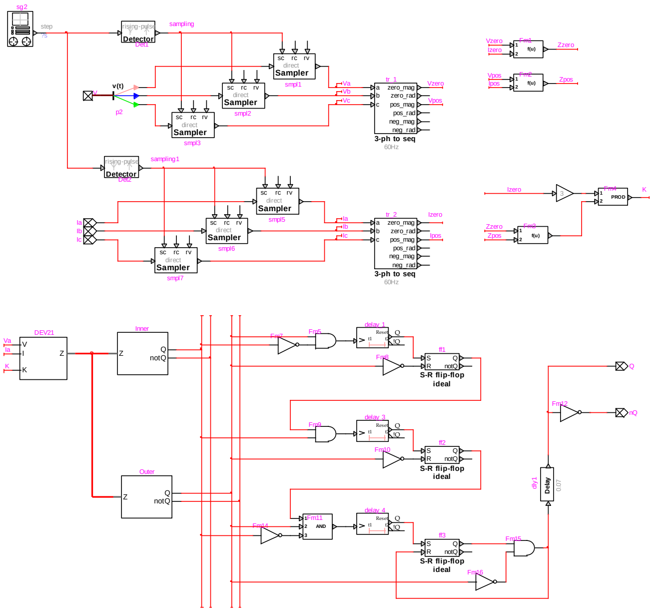

Fig. 3. A quadrilateral out-of-step relay modeling.

IV. ANALYSIS OF QUADRILATERAL OUT-OF-STEP PROTECTION RELAY OPERATION

A. Simulation Conditions

In order to analyze the quadrilateral OOS relay characteristics, simulation scenarios were assumed as Fig. 4. A three phase fault was assumed in 10% location of T/L 1 in Fig. 2, which is adjacent to generator #1. Then, we considered delayed fault clearing to make OOS condition for generator #1. In other words, we conducted sensitivity analysis for OOS relay operation characteristics according to three phase fault clearing time. In simulation scenarios, Case 1 can be considered normal fault clearing condition. Case 2 and Case 3 are delayed fault clearing, but they do not cause the system unstable, since the fault is cleared within Critical Clearing Time (CCT). Case 4 was assumed as the fault is removed right after CCT. Thus, it could make the system unstable and OOS condition of generator. The CCT was derived by system simulation.

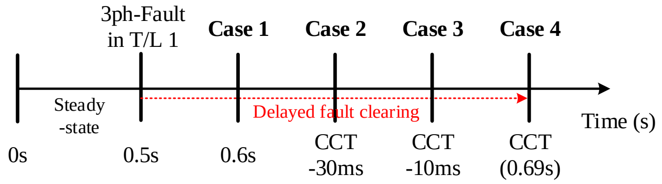

Fig. 4. Simulation scenarios.

Table II shows the quadrilateral OOS relay setting values of generator #1 in 345kV Korean nuclear power plant. The quadrilateral OOS relay has two-step characteristic, which has Inner and Outer blinders. These setting values are visualized as R-X diagram in simulation results in the next section.

TABLE II
A QUADRILATERAL OUT-OF-STEP RELAY SETTING VALUE

SHAPE	Quad	OUTER LFT BLD	0.4236 p.u.
MODE	Two Step	INNER RGT BLD	0.2971 p.u.
FWD REACH	0.5229 p.u.	INNER LFT BLD	0.2971 p.u.
QUAD FWD OUT	0.6493 p.u.	DELAY 1 Pick-up	0.070 s
FWD RCA	89°	DELAY 1 RESET	0.070 s
REV REACH	0.0695 p.u.	DELAY 3 Pick-up	0.008 s
QUAD REV OUT	0.1960 p.u.	DELAY 4 Pick-up	0.005 s
OUTER RGT BLD	0.4236 p.u.	SEAL IN DELAY	0.070 s

B. Simulation Results

Fig. 5 shows the quadrilateral OOS protection relay protection zone and impedance locus for each simulation scenarios in R-X diagram. In steady-state, the impedance loci stay in fixed point. However, the impedance loci move to OOS protection area. These impedance loci are different according to fault clearing time.

In Case 1, the fault is cleared at normal fault clearing time, the impedance locus shows the stable swing. Thus, this condition does not satisfy the trip requirements of the quadrilateral OOS protection relay. In Case 2, the fault is removed at delayed fault clearing time (CCT-30ms, 0.66s). Because of delayed fault clearing, the impedance locus enters in Outer blinder of OOS protection relay. It means the generator power output swings more severely. However, system stability is maintained, because the fault is cleared within CCT. Thus, this condition also does not satisfy the requirements of the quadrilateral OOS protection relay.

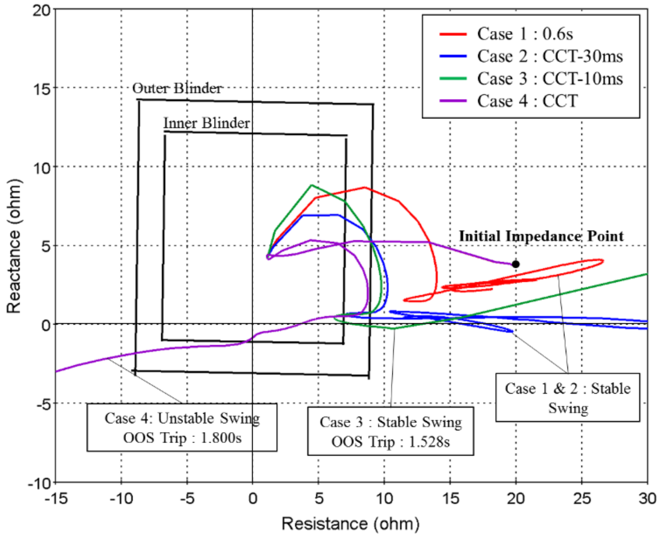

Fig. 5. Analysis of quadrilateral out-of-step protection relay operation.

In Case 3, the fault is removed at delayed fault clearing time (CCT-10ms, 0.68s). Because of delayed fault clearing, the impedance locus enters into Outer and Inner blinder of OOS protective relay. In this case, although the system stability is maintained as stable swing, the trip requirements of the quadrilateral OOS relay is satisfied. In other words, although the impedance locus does not passes through the electrical center, the quadrilateral OOS relay could establish the trip signal. Therefore, undesired generator trip could occur. In Case 4, the fault is cleared after CCT (0.69s), the system stability could not be maintained as unstable swing. Thus, the impedance swing characteristic satisfies the trip requirements of the OOS relay. In this case, the quadrilateral OOS protection relay detects the OOS condition correctly.

C. Simulation Results for Modified Quadrilateral Out-of-Step Protection Relay

As through previous quadrilateral OOS protection relay analysis, we can conclude that the OOS relay could make mis-operation in specific stable swing condition. This undesired OOS protection relay operation could be caused by the limitation of the quadrilateral OOS relay operation logic. Thus, we modified the relay operation logic as Fig. 6 not to operate in stable swing condition. We inserted one more trip requirements, which detects the resistance polarity of the impedance locus. This logic continues to check the resistance polarity. If the resistance polarity stays in positive area in impedance diagram, it means the system stability is maintained with stable swing. Therefore, in this stable swing condition, the quadrilateral OOS protection relay operation is blocked.

Through simulation, we proved the effectiveness of the modified quadrilateral OOS protection relay characteristics as

Fig. 7. In addition, we checked that the proposed method is still effective for other power system configurations in Korea. We only considered the Case 3, since this condition makes the undesired trip.

In conventional quadrilateral OOS relay, although the system stability is maintained as stable swing, the impedance locus characteristic satisfies the trip requirements. Therefore, the generator is tripped unnecessarily. However, in modified quadrilateral OOS relay, the resistance polarity detection logic blocks the relay operation. Unless the impedance locus passes through the inner left blinder, the quadrilateral OOS relay trip signal does not established. Thus, it guarantees the continuity of generator operation in stable swing condition. In other words, the modified quadrilateral OOS protection relay does not operate in stable swing condition.

The modification of present setting values of the left and right blinder of the quadrilateral OOS protection relay also could prevent the undesired generator trip. The reduced reach values of the left/right blinder could guarantee more accurate and robust operation of the quadrilateral OOS protection relay.

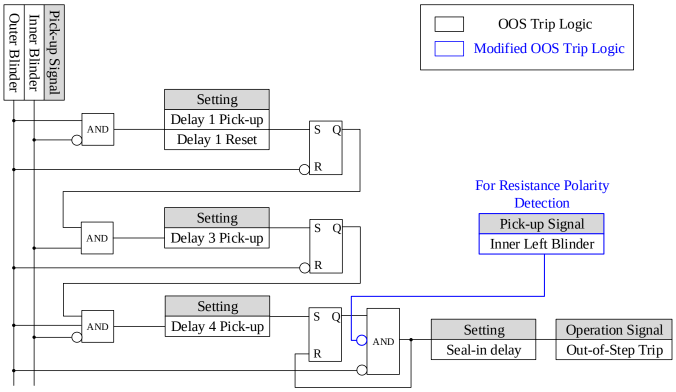

Fig. 6. A modified quadrilateral out-of-step relay logic.

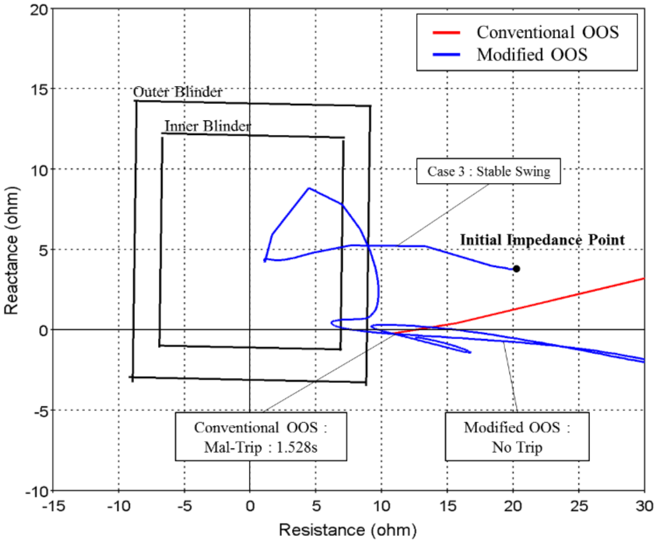

Fig. 7. Analysis of modified quadrilateral out-of-step protection relay operation.

V. CONCLUSIONS

In this paper, we modeled a 345kV nuclear power plant and transmission system with quadrilateral OOS protection relay. After that, we analyzed the characteristics of the OOS relay according to various delayed fault clearing time. During this simulation analysis, we found the possibility of mis-operation of OOS relay under stable swing condition. Therefore, we modified the quadrilateral OOS protection relay logic not to trip the generator unnecessarily under stable swing condition. This could contribute to the continuity of generator operation and robust and accurate operation of the OOS relay.

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