A Coordination Review of AVR Limiter and Protective Function in Excitation System for Reliable Power System Operation in NPP

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Abstract: Because of inadequate setting values of Automatic Voltage Regulator (AVR) limiter and protective functions, it is possible to happen the unintentional generator trip, which affects to the reliable power system operation. Therefore, it is important to coordinate the setting value of AVR limiter and protective functions in excitation system properly. Even, there could be redundant protective functions in generator protection system. In this paper, we focused on generator under-excitation region to review the performance and coordination of the Under-Excitation Limiter (UEL), Under-Excitation Protection (UEP) and Loss-of-Field (LOF) relay protection, which can affect to generator operation and system reliability. All of the review were conducted by computer simulations with Electro-Magnetic Transient Program (EMTP). After that we concluded the importance of protective coordination of AVR limiter and redundant protective functions. In addition, we discussed the regulatory recommendation for the verification of the protective coordination.
Keyword: Automatic Voltage Regulator, Excitation System, Loss-of-Field Relay Protection, Protective Coordination, Under-Excitation Limiter, Under-Excitation Protection.

1 Introduction

North American wide area black out occurred on August 14, 2003. Especially generator protection system including excitation system control issues were reported one of main reasons for the disaster [1]. Since then, the importance of protective coordination with generator protection system, excitation system limiter and protective functions has been increasing.

In general, excitation system has various functions such as automatic/manual voltage regulation and generator operation limit functions from over-excitation, under-excitation and V/Hz limiters. Therefore, the limiter function in excitation system is one of considerations of protective coordination. For example, in case of protective coordination for generator under-excitation operation region, it is necessary to consider Loss-Of-Field (LOF) relay in generator protection system, Under-Excitation Limiter (UEL), Under-Excitation Protection (UEP), Stead-State Stability Limit (SSSL) and Generator Capability Curve (GCC) at the same time [2-5].

Therefore, in this paper, we focused on generator under-excitation region to review how the performance of the UEL, UEP and LOF relay can affect to Nuclear Power Plant (NPP) generator operation and its power system reliability. And that we concluded the importance of protective coordination of AVR limiter and redundant protective functions. In addition, we discussed the regulatory recommendation for the verification of the protective coordination.

2 Excitation system

2.1 Automatic Voltage Regulator (AVR)

Generally, the major functions of Automatic Voltage Regulator (AVR) could be summarized as two aspects. The first is that it maintains generator terminal voltage and enhances power system performance and reliability. The second is the limiter functions, performed by over-excitation, under-excitation and V/Hz limiters. These functions have no effects on excitation system output during normal conditions. However, in severe operating condition, the limiters act to modify excitation system output to compensate the generator operation.

2.2 Under-Excitation Limiter (UEL)

The Under-Excitation Limiter (UEL) performs the boost excitation and sustains the reactive power of generator to prevent out-of-step, when excitation level is too low. If the generator is in severe under-excited condition, the UEL output overrides the AVR output signal to increase the field voltage and current. Fig. 1 shows the type UEL 2, which is commonly applied in practice. By setting each segments in terms of the active and reactive power, the type UEL 2 characteristic is determined.

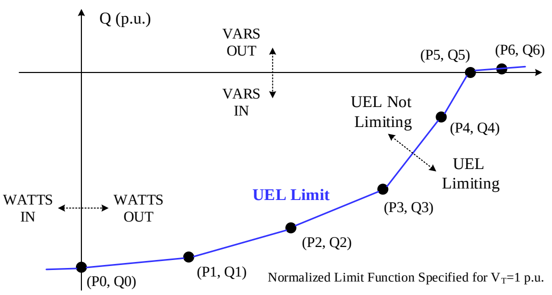


Fig. 1 IEEE type Under-Excitation Limiter 2.

2.3 Under-Excitation Protection (UEP)

If the UEL fails to limit the operation of the generator in severe under-excited condition, the protective function, which is Under-Excitation Protection (UEP) same as the Loss-of-Field (LOF) relay, is activated to prevent thermal damage of the generator. It provides a generator trip or alarm signal based on the impedance characteristics of Zone 1 and Zone 2 as Fig. 2. X_d means generator synchronous reactance and $X_d^{'}$ stands for the transient reactance. This UEP can be applied to both the generator protection system and excitation system redundantly [6].

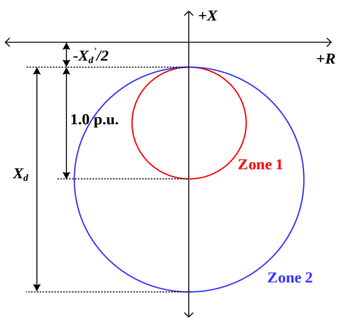


Fig. 2 Characteristics of the UEP (LOF relay).

3 Coordination review of UEL and UEP in excitation system

3.1 Study system modeling

In order to review the coordination of UEL and UEP, we considered a 345 kV Korean nuclear power plant and transmission system as Fig. 3. The study system has almost the same characteristics as the actual power system, since it is modeled based on the study of power flow in steady-state and the dynamic response under contingency. In addition, the AVR and UEL control blocks are considered as Fig. 4. In Fig. 4, if UEL gain is sufficient, its output takes over the summing control of the AVR (ESST4B) to boost the excitation in order to move the generator operation back toward the UEL limit [7]. All of systems are modeled using EMTP-RV and unit #1 is considered as a representative generator and the detailed electrical parameters for unit #1 is omitted in this paper.

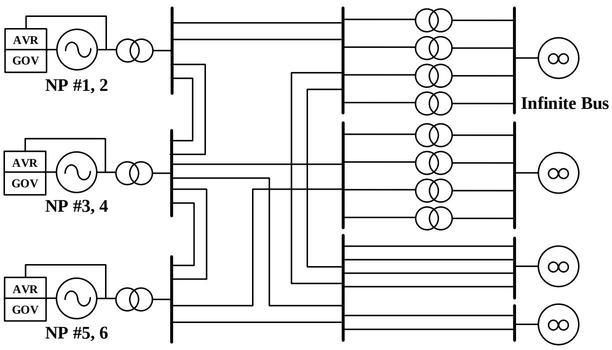


Fig. 3 A 345 kV Korean nuclear power plant and transmission system.

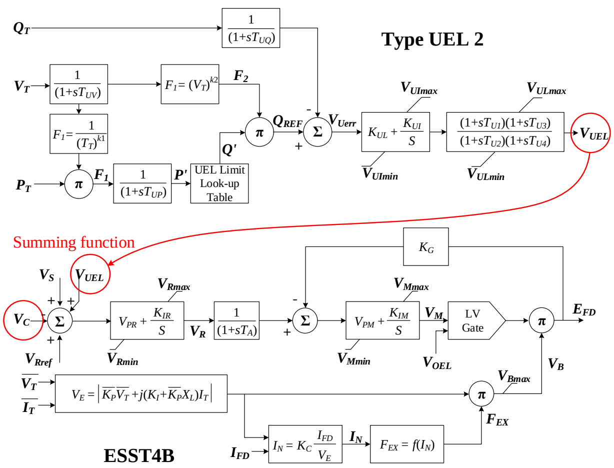


Fig. 4 AVR control block model (ESST4B) and UEL control block model (Type UEL2).

3.2 Simulation conditions for UEL and UEP performance

At first, in this section, we explain the performance of UEL and UEP based on various simulation scenarios as Table 1. In order to analyze the performance of UEL and UEP, we assumed the setting values as Table 2, which is the normally adopted setting philosophy of UEL and UEP.

Table 1 Simulation scenarios

LOF condition	Case #	Descriptions
E_{FD} 30% (Field voltage sag)	Case 1-1	Only UEP
	Case 1-2	UEP with UEL
E_{FD} 25% (Field voltage sag)	Case 2-1	Only UEP
	Case 2-2	UEP with UEL

Table 2 UEL and UEP setting values (example)

UEL (Active, Reactive Power)	0MW, -423.72Mvar 385.2MW, -423.72Mvar 770.4MW, -398.04Mvar 1155.6MW, -295.32Mvar 1540.8MW, 603.48Mvar	
UEP (Negative Offset Mho, secondary ohm)	Zone 1	Zone 2
	Diameter : 16.39Ω Offset : 3.5Ω Time Delay : 0s	Diameter : 29.41Ω Offset :3.5Ω Time Delay : 0.5s

Case 1-1 and 1-2 show the performance of UEL and UEP under generator under-excitation conditions, E_{FD} 30% (partial loss-of-field), which means the field winding voltage sag, comparing to normal field winding voltage. Similarly, Case 2-1 and 2-2 show the performance of UEL and UEP under generator under-excitation conditions, E_{FD} 25%. Based on these simulation cases, we can analyze the effectiveness of the UEL and UEP when the generator is under-excitation condition.

3.3 Simulation results for UEL and UEP performance

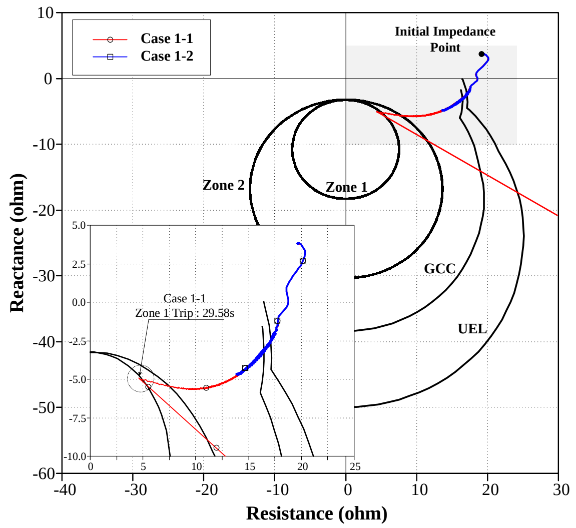
3.3.1 Simulation results for Case 1-1 and Case 1-2

In Fig. 5, the simulation results of Case 1-1 and Case 1-2 are shown with the generator apparent impedance locus and field voltage profile. In Fig. 5 (a), the generator apparent impedance point of Case 1-1 directly passes through the GCC curve, and enters into the UEP zone in excitation system. Thus, the LOF relay commands the Zone 1 trip signal at 29.58s.

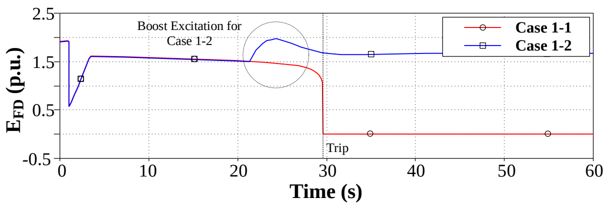
In Cases 1-2, the generator can operate within the UEL and GCC curve through the boost excitation by the UEL control. As shown in Fig. 5 (b), owing to the boost excitation by the UEL control, E_{FD} is increased drastically after the activation of UEL. Therefore, when the UEL control is applied with AVR, the generator under-excitation condition could overcome. Thus, we can conclude that the UEL should be equipped and activated in the excitation system in order to avoid unnecessary generator trip as Case 1-1.

3.3.2 Simulation results for Case 2-1 and Case 2-2

In Cases 2-1 and 2-2, the generator apparent impedance point passes through the UEL and GCC curve, and enters into the UEP zone in excitation system as shown in Fig. 6 (a). Finally, the UEP commands the trip signal at 10.83s and 20.29s, respectively. In Cases 2-2, although the UEL control performs the boost excitation as shown in Fig. 6 (b), the generator under-excitation condition could not overcome and the UEP operates in the end. Thus, depending on LOF condition severity, the detection time of the UEP could be delayed due to the UEL control.

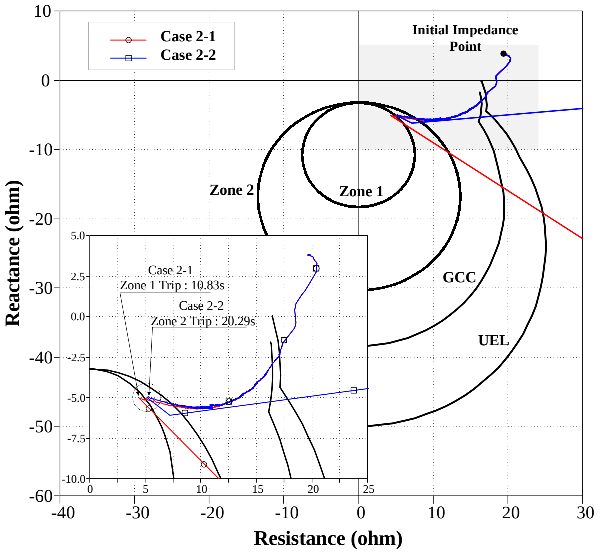


(a) Generator apparent impedance locus

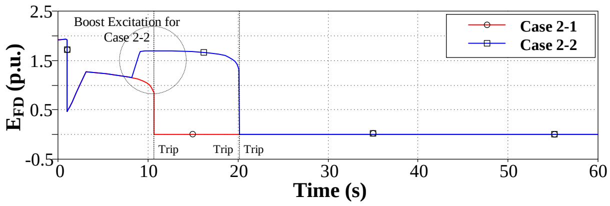


(b) Field Voltage, E_{FD} 30%

Fig. 5 Simulation results for Case 1-1 and 1-2.



(a) Generator apparent impedance locus



(b) Field Voltage, E_{FD} 25%

Fig. 6 Simulation results for Case 2-1 and 2-2.

3.4 Coordination review of UEL and UEP in excitation system

On the left hand side of Fig. 7, it shows the UEP setting diagram of NPP unit #1 in R-X diagram. This is same as with the UEP (Zone 1 and Zone 2) in Fig. 5 and Fig. 6. The right hand side of Fig. 7 shows the UEP (LOF relay) setting diagram, which is followed by IEEE recommendation setting method. As shown, both setting diagrams are almost same. Thus, 345kV NPP unit #1's UEP in excitation system is set appropriately with IEEE recommendation method. The setting value is determined based on the 345kV NP unit #1's generator electrical parameters, such as synchronous and transient reactance.

We can describe the coordination recommendation for generator under-excitation protection using UEL and UEP in excitation system as below.

1) The UEL should carry out the priority control action to avoid the generator operation, which sustains or exceeds the operation of stator end-iron limit. Thus the UEL curve should envelope the GCC curve in R-X diagram.
2) The GCC curve should be verified and supervised by operator. This curve could be obtained from the manufacturer.
3) The UEP (LOF relay) should be enveloped by the GCC. This is because that the UEP is not to limit the generator's flexible operation near the under-excitation limit area and not to cause the unnecessary trip of generator.

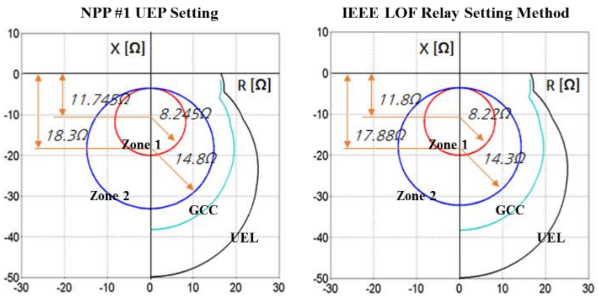


Fig. 7 UEP setting diagram for NPP #1 and LOF relay diagram setting according to IEEE recommendations.

4 Coordination review of UEP in excitation system and LOF relay in generator protection system in NPP

4.1 Coordination review of the redundant protection functions for generator under-excitation

As mentioned before, a protection function in excitation system and generator protection system could have redundant protective functions such as loss-of-field, V/Hz, overvoltage and etc. Thus, it is worthwhile to review how these redundant protective functions are coordinated each other. On the left hand side of Fig. 8, it shows the UEP setting diagram of NPP unit #1 in R-X diagram as explained section 3.4. The right hand side of Fig. 8 shows the 345kV NPP unit #1's LOF relay setting diagram. Both redundant under-excitation protective functions are almost same each other based on generator's electrical parameters.

Based on above redundant protection functions' setting value, we simulated the LOF condition of the 345kV NPP unit #1 in order to verify the protective coordination suitability. The simulations were conducted for 10s and the LOF condition was applied in 1s by eliminating field winding voltage.

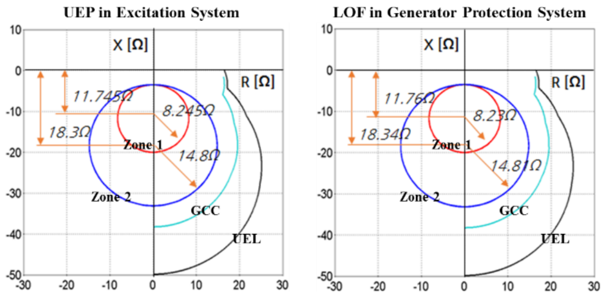


Fig. 8 Setting values for redundant under-excitation protective functions in excitation system and generator LOF protection system.

4.2 Coordination verification of the redundant protection functions with simulation

As mentioned previous coordination of UEP in excitation system and generator LOF relay in NPP unit #1, the simulation results are shown in Fig. 9. Since the redundant under-excitation protective functions are similar with each other, the trip signals are established simultaneously. In other words, when the LOF condition occurs in NPP unit #1, the UEP and LOF relay detect the LOF condition and generate the trip signal in Zone 1 at almost same time.

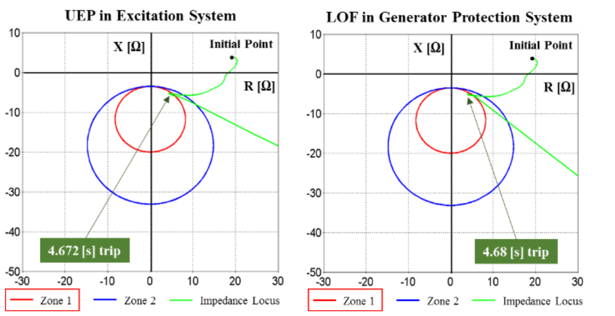


Fig. 9 Simulation results for redundant under-excitation protective functions in excitation system and generator LOF protection system.

Thus, we can checked that the under-excitation protective coordination factors, such as UEL, UEP and LOF relay of 345kV NPP unit #1, are well-established with almost same setting value based on IEEE setting recommendation.

Generally, it is required to minimize the detrimental effects due to mal-function of protective functions. Thus, the reliable operation of power system of NPP could be achieved from a proper coordination of redundant protective functions.

When a generator trip function is applied redundantly in excitation system and generator protection system, it is possible to coordinate the redundant functions as below methods.

1) Set the redundant trip functions in excitation system and generator protection system as same value. This method could provide duplex trip functions for generator, thus, the system protection reliability could be enhanced.
2) Change the generator trip function in excitation system as an alarm function with more sensitive setting than generator protection system, but less sensitive than UEL. Only generator protection system has the trip function, which is followed IEEE recommendation setting method to protect the generator. Through this method, it is possible to ensure the margin of UEL control and clarify the main performer of the generator circuit breaker trip.

5 Discussions

According to reference [8], it shall satisfy the requirements for installation and testing the protective functions (relay). In nuclear power plant power system, class-1E protective relay is implemented to protect the electrical components in safety system and safety related system. In addition, non class-1E protective relay is also applied to protect the other electrical component in non-safety system.

The protective function in excitation system and generator protection system are considered as non class-1E, since they do not carry out the safety functions or safety related auxiliary functions in NPP. This kind of non class-1E protective relay should be designed based on proper regulatory code, such as KEPIC EEF-1000 (IEEE C37.90) or IEC 60255, and performs a role for enhancing the availability and reliability of electrical components.

Generally, the protective relay (especially generator protection relay) minimizes the system impacts from the system fault to protect the remained sound power system. Thus, it is required that the protective functions in excitation system and generator protection system shall have high reliability and accuracy. In order to meet these requirements, we propose the regulatory recommendations as follow:

1) Check and report that the limiter and protective functions setting values in excitation system are well-coordinated followed by industrial recommendation.
2) Based on periodical test for the above functions, it should verify the original characteristics and performance and report the all of the test procedure.
3) Test procedure and devices are equipped and supervised to verify the availability of control, limit and protective functions in excitation system and protective relay in generator protection system for reliable power system operation.

The NPP power system operator should follow the above mentioned regulatory recommendations for appropriate coordination of redundant protective functions. Therefore, it is possible to achieve the reliable operation and protection for NPP power system.

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