476 Journal of Electrical Engineering & Technology Vol. 4, No. 4, pp. 476~484, 2009

Application of Multi-step Undervoltage Load Shedding Schemes to the KEPCO System

Jeonghoon Shin†, Suchul Nam*, Jaegul Lee*, Youngdo Choy*, Taekyun Kim* and Hwachang Song**

Abstract – This paper deals with improvements to the special protection schemes (SPS) which have been applied to the low probability and high impact contingencies in the Korea Electric Power Corporation (KEPCO) system since 2004. Among them, the SPS for voltage instability in the Seoul metropolitan area is considered in this paper, and is a form of event-based undervoltage load shedding with a single-step scheme. Simulation results based upon a recent event that occurred on 765kV lines show that the current setting values of the SPS have to be revised and enhanced. In addition, by applying response-based multi-step undervoltage load shedding (UVLS) schemes to severe contingencies in the system, more effective results than those of the existing single-step SPS can be obtained. Centralized and distributed UVLS schemes are considered in the simulation. ULTC-based load recovery models and over excitation limiters (OXL) for the KEPCO system are also included in the long-term voltage instability studies.

Keywords: ULTC-based load model, Over eXcitation Limiter model, Special Protection Scheme, Under Voltage Load Shedding, Long-term voltage instability, Centralized and distributed UVLS

1. Introduction

As a last resort to avoid voltage collapse, undervoltage load shedding (UVLS) is one of the special protection schemes available. It should, therefore, be applied very carefully in situations where voltage collapse might occur in order to prevent a blackout.

In the KEPCO system, the SPS has been applied to a set of interconnected transmission lines between Seoul metropolitan area and the non-metropolitan area since 2004. It was designed to ensure the secure operation of the power system in Korea and to increase interface flow limits. The KEPCO system is peculiar in that a large majority of the load is situated around the Seoul metropolitan area. Generators with relatively low generation costs are mostly located in the southern coastal part of Korea (about 80%), while loads are heavily concentrated in the Seoul metropolitan area (about 42%) located in the northern part of the country. It is for this reason that a large amount of active power flows originate in the south and flow northwards.

For the purpose of transferring the power, two parallel 765kV transmission lines and four 345kv parallel lines are used as interface transmission lines (see Fig. 1). The SPS has been applied to increase the limit of the interface lines in case of outages in the 765kV lines. An outage of one of the two parallel 765kV transmission lines and a violation of the threshold voltage on a pilot bus with duration of 200 milliseconds triggers the SPS to shed approximately 1,000MW loads, designated in advance using steady-state analysis.

However, an unexpected event in the 765kV transmission lines recently occurred, providing the impetus to improve the existing SPS as the setting value of the supervising voltage to be operated is relatively high and the delay time of the under voltage relay is too short. This paper shows the simulation results for this event and the necessity to improve the existing SPS in order to prevent the system from experiencing a rapid voltage collapse.

In addition, by applying response-based multi-step UVLS schemes to the severe contingencies, it is shown that the shedding load amount can be significantly decreased over that of the current single-step SPS. The threshold voltages and shedding load amount in each step are simply used as the examples introduced in this paper [1]. In addition, a centralized and a distributed UVLS scheme are also considered in the simulation. ULTC based

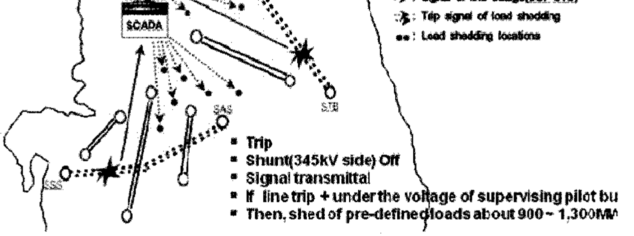

Fig. 1. Special Protection Scheme in the KEPCO system

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Received : July 27, 2009; Accepted : September 14, 2009

load recovery models and over excitation limiters (OXL) for the KEPCO system are included in the long-term voltage instability studies.

2. Review of current sps in the system

2.1 Current single-step SPS

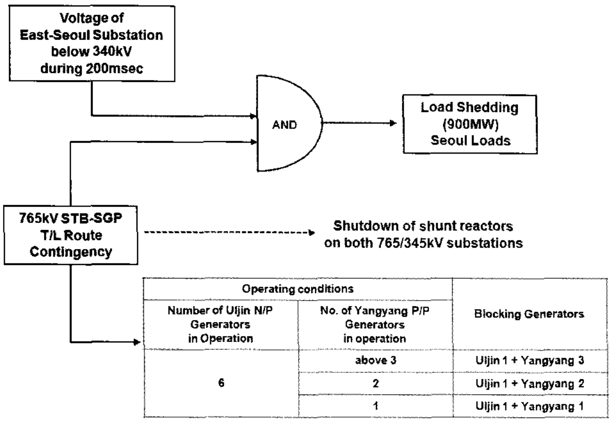
The current SPS for voltage instability applied to the KEPCO system has been designed to operate during extreme contingencies including the loss of one of two 765kV double circuit lines in the load pocket area (Seoul).

The operational steps for this SPS are demonstrated as shown below.

If the loss of one of two 765kV lines occurrs, line trips are first detected by the operation of transmission line protective relays. This signal is then transmitted to the SCADA system in a regional control center of the KEPCO system.

On the other hand, there are two 345kV pilot buses available for supervisory purposes. When one bus voltages is lower than 340kV (0.985p.u.) during a 200 millisecond period, the under voltage relay is operated to send the signal to the same SCADA system. If these two conditions are satisfied, the predefined loads, which are the same locations as those for UFLS (Under Frequency Load Shedding), are shed with a single-step to prevent voltage collapse of the system (see Fig. 1). The amount of the shedding load is about 900MW and 1,300MW respectively.

Fig. 2 demonstrates the schematic diagram of the current SPS in the system. In this figure, blockings of the related generators are for maintaining the transient stability of the system.



Operating conditions		Blocking Generators
Number of Uljin N/P Generators in Operation	No. of Yangyang P/P Generators in operation	
6	above 3	Uljin 1 + Yangyang 3
	2	Uljin 1 + Yangyang 2
	1	Uljin 1 + Yangyang 1

Fig. 2. Current SPS scheme (for STB-SGP outage)

2.2 Simulation results for the recent event

Recently, an unexpected line tripping event occurred on the 765kV transmission lines due to unstable DC source voltage of the protective relays in the STB S/S. Four circuit breakers on both 765kV transmission lines were opened at this time although not by critical faults (see Fig. 3).

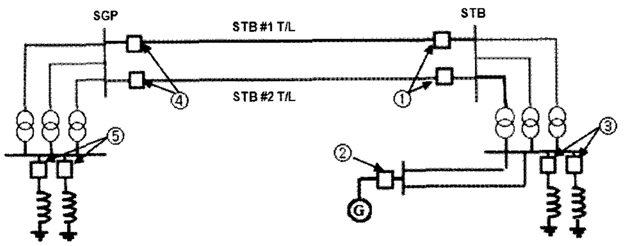


Fig. 3. System diagram for 765kV/345kV substations

At the time, fortunately, no predefined loads of 900MW were shed because the duration time below 340kV on the supervising pilot bus (East-Seoul) was not over 200 milliseconds. Fig. 4 shows the simulation result of voltage on the bus when the event occurred. Initially, the CBs at the STB bus were opened (step 1 in Fig. 3) and one nuclear generator was out (step 2) to maintain the transient stability of the system. After 900 milliseconds, the CBs for the shunt reactors on the 345kV bus (step 3) are opened. Because the voltage on the pilot bus at this point is 342kV, slightly over 340kV, the SPS cannot be operated. When the CB opened at the SGP bus (step 4 in Fig. 3), the voltage dropped to 336kV, which is below 340kV. But the duration time below 340kV was not more than 200 milliseconds, and load shedding does not occur in this case. However, if the system is heavily loaded (all six nuclear generators are in operation), the SPS can be operated to shed the predefined loads even though it is not the fault case (see Fig. 5). When line outages result from a fault occur and the CBs are opened at the same time, the voltage of the pilot bus goes down far below 340kV over the 750 millisecond period (see Fig. 6), and the SPS is expected to operate properly. Through the simulation results seen below, we can say that setting the values of the current SPS should be considered to change. The voltage magnitude on the pilot bus for reference, 340kV, is too high and the delay time of the under voltage relay, 200 milliseconds, is too short. The P-V curves we analyzed on the East-Seoul bus for several

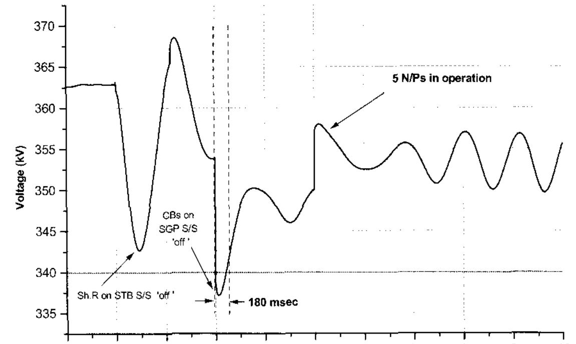


Fig. 4. Voltage of East-Seoul pilot bus for unexpected line trips (5 Nuclear Generators in operation)

system conditions (not shown in the paper) suggest that the collapse voltage to be evaluated is below 326 kV.

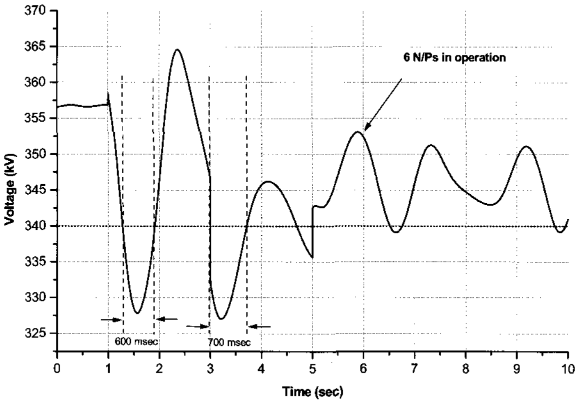


Fig. 5. Voltage of East-Seoul pilot bus for unexpected line trips (6 Nuclear Generators in operation)

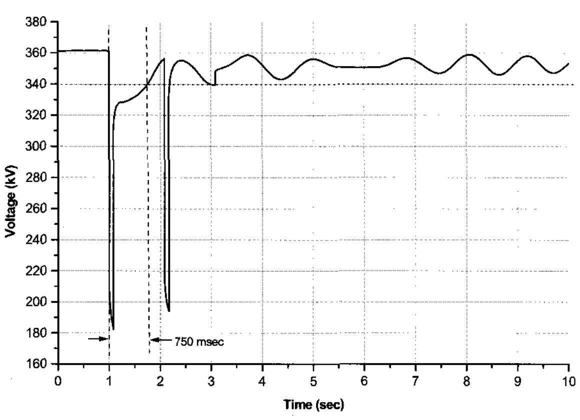


Fig. 6. Voltage of East-Seoul pilot bus for line outages (5 Nuclear Generators in operation)

3. Applications of multi-step uvls schemes to current single-step sps

3.1 System models to be considered in the simulation

In order to apply the multi-step undervoltage load shedding scheme to the current SPS in the system, long-term voltage instability studies on the time domain are necessary. System models with long-term dynamics, such as the OXL (Over eXcitation Limiter) of generators, load recovery models, switched shunt compensation, etc., should be considered in detail for accurate simulation [2, 3]. In this paper, the basic OXL models proposed by Van Cutsem [4, 5] and ULTC-based load models recommended by IEEE [8] are simply used in the simulation because exact dynamic models can only be derived from extensive generator tests in the field. Fig. 7 represents the ULTC-based load recovery model which is included in the simulations. The model and data used in the simulation are represented in Fig. 8.

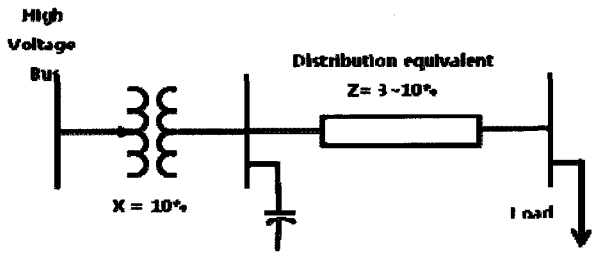
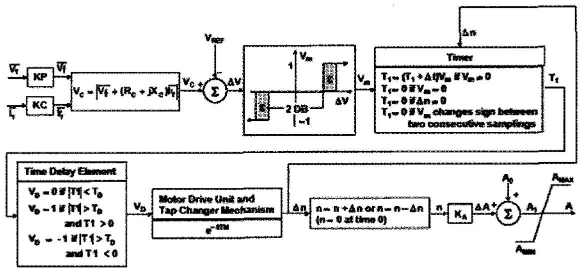


Fig. 7. ULTC-based load model recommended by IEEE [8]



```
ULTC
 1360 99001   1 990010    1.00000
  0
  0.00000  0.00000  0.01000  0.00000  1.00000  1.00000
100.00000  3.00000  0.50000  0.01250  1.20000  0.80000
EDATA
```

Fig. 8. ULTC-based load model and data used in TSAT simulation

The OXL is to protect the exciter in each generator. Exciters can normally raise exciter voltage up to the ceiling point, a value of about 200% of their current ratings, to maintain a constant terminal voltage for transient stability after the faults. However, since the current cannot be maintained continuously at this level, the OXL reduces the level to 120% of the nominal value within the designated time. If OXL models are not used in the simulation, all generators in the system can produce exciter currents up to the ceiling points. Then, the amount of reactive power generators can produce is higher than the real values. Therefore, the models should be considered to get the correct results in long-term simulations for voltage instability studies.

In the OXL model given in Fig. 9, the most important parameter is the maximum value of the field current of the generator. Because it should be derived from field tests of the generator and excitation system, the approximate value calculated by the equation below (1), and represented in Fig. 10, is used in the simulation. Eq. 1 and Fig. 10 can be derived from EPRI's VSTAB report [9].

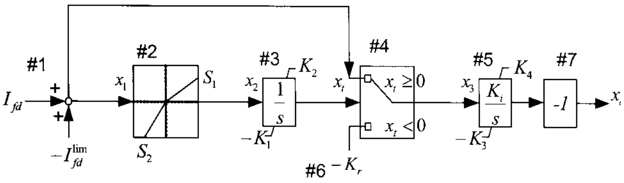


Fig. 9. Over eXcitation Limiter model (OXL) used in the simulation

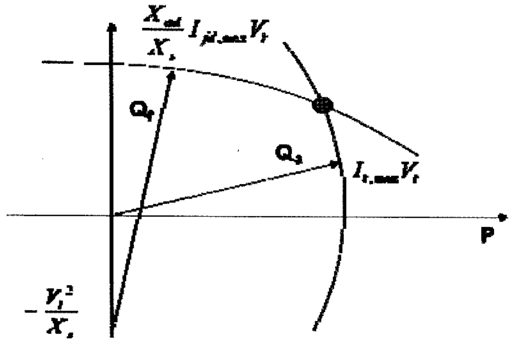


Fig. 10. Determination of the approximate value of $I_{fd,\max}$

$$I_{fd,\max} = \frac{X_s}{V_t X_{ad}} \left| P_{\max} + j\left(Q_{\max} + \frac{V_t^2}{X_s} \right) \right| \quad (1)$$

Where, $X_s = X_q$, $X_{ad} = X_d - X_l$

For the UVLS model, 'LVSHBL' bus load shedding with a 3 step model in PSS/E, PTI was used in the simulation. All system data in the KEPCO system was changed to have a transformer with a ULTC between 154kV bus and a 22.9kV load. The OXL model was also considered as a user-defined model in TSAT (Transient Stability Assessment Tool, by PowerTech Inc., Canada), which is given below. In the user-defined model shown below, the numbers indicate the number of control blocks represented in Fig. 9.

```
21921,'OELUDM',1 /DEVICE IDENTIFICATION
0 /REMOTE BUS
0 0 0 /REMOTE BRANCH
1,'BLK1','SUM' /CONTROL BLOCK 1
2,'BLK2','NLF',-10,-20,-5,-10,-1,-2,0,0. 1,1,10,10 /CONTROL BLOCK 2
3,'BLK3','IN',1.0,10.0,-10.0,0.0 /CONTROL BLOCK 3
4,'BLK4','LSW',0.0,0.00,0.00 /CONTROL BLOCK 4
5,'BLK5','IN', 1.00, 0.10,-0.10,0.0 /CONTROL BLOCK 5
6,'BLK6','SUM' /CONTROL BLOCK 6
7,'BLK7','GN',-1.0,0.0,0.0 /CONTROL BLOCK 7
1,2, 2,3, 1,4, 6,4, 3,-4, 4,5, 5,7 /BLOCK INTERCONNECTION
1,'IFD'1.0,1,'CONT',  -2.452,6,'CONT',0.0  /BLOCK INPUT
7 /BLOCK OUTPUT
```

3.2 Validation of the ULTC-based load model used in the simulation

Figs. 11, 12 and 13 represent the load recovery characteristics using the ULTC-based load model in the long-term simulation. No UVLS schemes are applied to validate the load recovery models used in the simulation after one of the 765kV double-circuit lines is out (SGP-STB in Fig. 3). After around 100 seconds, the system

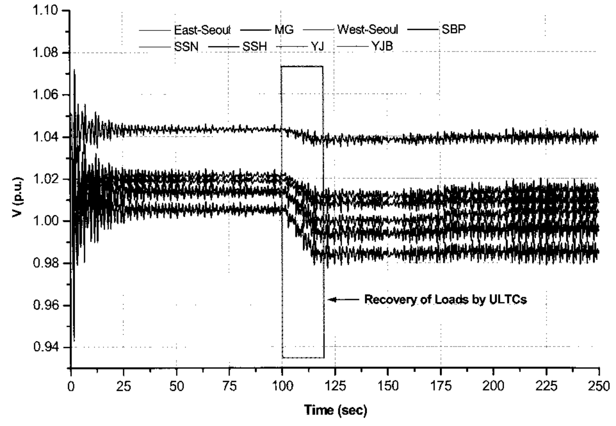


Fig. 11. Load recovery characteristic by ULTC-based models (345kv bus voltages)

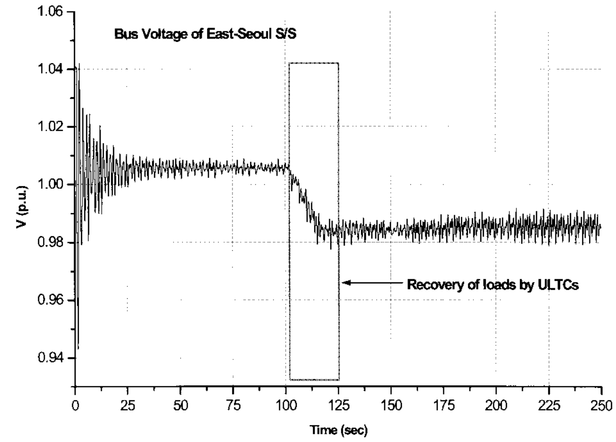


Fig. 12. Load recovery characteristic by ULTC-based models (Bus voltage of the pilot bus (East-Seoul))

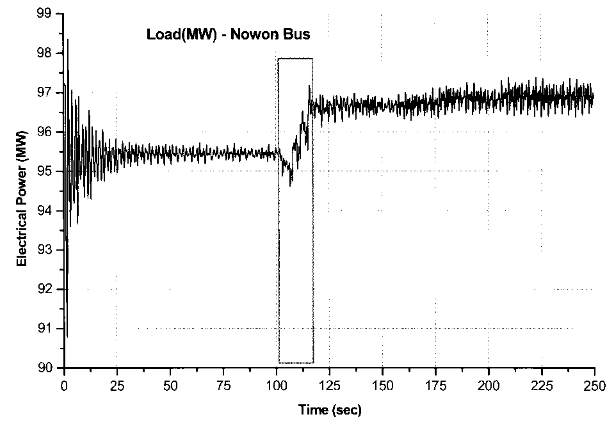


Fig. 13. Load recovery characteristic by ULTC-based load models (The amount of MW load on the load bus (Nowon))

voltages (including the East-Seoul bus) go down to a different operating condition with loads recovered (Figs. 11 and 12) by the ULTC operations.

Fig. 13 indicates the amount of MW load recovered at the Nowon bus, on which the load recovery model is applied. As can be seen, the initial MW load of the Nowon bus is 97.2MW, the MW of the load is changed to approximately 95MW at 100 seconds, and is finally recovered to the initial amount of load, 97.2MW.

3.3 Comparison of simulation results between current SPS and multi-step UVLS schemes

a. Current single-step SPS

For the purposes of comparison, a single-step SPS is first simulated in this section. The models introduced in the previous section were needed for long-term voltage instability studies, and are used in the simulation. A severe contingency of SGP-STB 765kV lines (see Fig. 3) is applied. Then, reactors on each bus and the generators are disconnected from the system after half a cycle. Predefined load amounts at designated locations are simply shed when two conditions are met (represented in Fig. 2). After applying the contingency, the voltage of the supervising bus is dropped below 340kV (0.985p.u.) during a 700msec. period as can be seen in Fig. 14. The current single-step SPS will be properly operated to shed approximately 900MW. Table 1 shows the locations and the amount of loads to be shed.

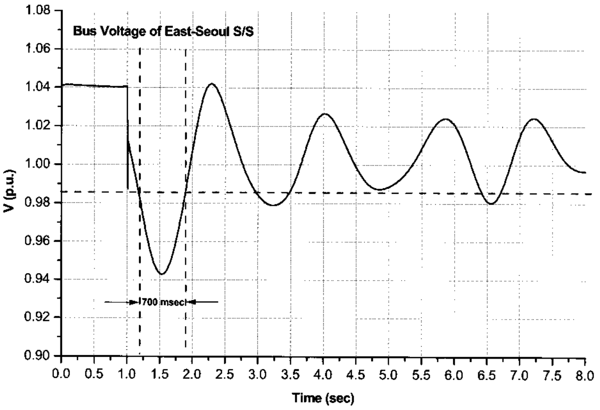


Fig. 14. Bus voltage of East-Seoul S/S for SGP-STB line contingency.

b. Multi-step UVLS schemes – A distributed UVLS scheme

For the same critical contingency as is used in the current SPS in the system, a form of distributed UVLS with multi-step schemes is applied in the simulation (see Fig. 15).

Compared to the current SPS, there are no supervising pilot buses in the system. The individual voltages of the buses to shed loads are monitored for operation of the UVLS.

After a 765kV double line contingency has occurred, if the voltages of the buses are lower than 4% below the lowest normal voltage with a delay of over 3.5 seconds, then 20% loads are shed at each load bus, which are selected in advance (the same locations used in the current SPS).

The lowest normal voltages of the load buses over several years and the reference voltages of those buses for triggering the distributed UVLS scheme are represented in Table 2. The delay times for the UVLS are the same as in paper [1].

Table 1. The locations and amount of shedding load for the current single-step SPS.

Bus No.	Pload(MW)	Pshed(MW)
1525	97.2	88.6
1775	71.9	27.3
1565	96.7	34.7
1745	142.5	27.1
1520	148.6	30.8
1530	152.7	30.5
1545	66.8	22.8
1580	58.5	20.3
1590	114.9	76.2
1595	94.8	32.7
1630	87.4	35.8
1635	87.8	60.5
1655	121.2	27.1
1680	132.0	24.7
1695	106.0	18.5
1765	94	30.7
1770	90.2	55.9
1785	129.6	60.2
1790	139.2	55.6
1845	69	17
1670	102.6	31.8
Total	2202.8	808.8

- 20% of area load shed at voltage 4% below the lowest normal voltage with a 3.5 second time delay
- 20% of area load shed at voltage 4% below the lowest normal voltage with a 5 second time delay
- 20% of area load shed at voltage 4% below the lowest normal voltage with an 8 second time delay

Table 2. The lowest normal voltages of load buses and the reference voltages for triggering the distributed UVLS scheme

Bus No.	The lowest normal voltages of buses (p.u.)	4% below the lowest normal voltages of buses (p.u.) = reference voltages
1525	1.01716	0.976474
1775	1.02448	0.983501
1565	1.01369	0.973142
1745	1.02547	0.984451
1520	1.01871	0.977962
1530	1.01795	0.977232
1545	1.02041	0.979594
1580	1.02656	0.985498
1590	1.01603	0.975389
1595	1.01336	0.972826
1630	1.01659	0.975926
1635	1.02532	0.984307
1655	1.02650	0.985440
1680	1.02579	0.984758
1695	1.02541	0.984394
1765	1.02427	0.983299
1770	1.02095	0.980112
1785	1.02613	0.985085
1790	1.02077	0.979939
1845	1.03288	0.991565
1670	1.02666	0.985594

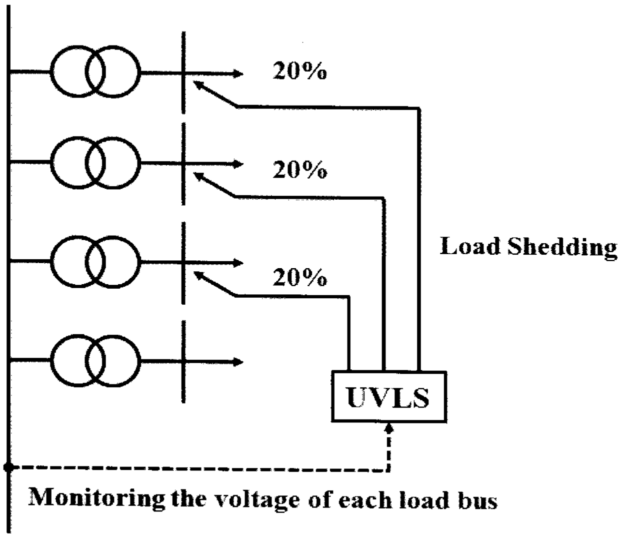


Fig. 15. Concept of the distributed UVLS scheme applied in the simulation

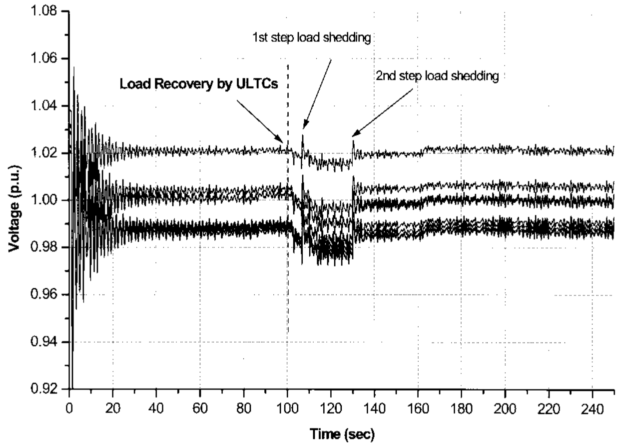


Fig. 16. Voltages of load shedding buses

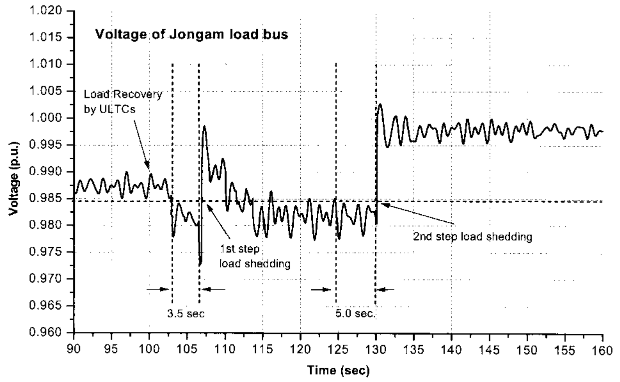


Fig. 17. Voltage of Jongam load bus (1765) to be monitored for shedding loads (zoomed in)

Table 3. The amount of shedding load and number of steps applied for the distributed UVLS scheme

Bus No.	Pload (MW)	steps applied	Pshed(MW)
1595	94.8	0	0
1565	96.7	0	0
1590	114.9	0	0
1545	66.8	0	0
1630	87.4	0	0
1765	94	2	33.7
1525	97.2	0	0
1530	152.7	0	0
1520	148.6	0	0
1580	58.5	0	0
1770	90.2	2	37.9
1845	69	0	0
1790	139.2	1	22.3
1670	102.6	2	18.5
1785	129.6	2	41.5
1635	87.8	2	40.4
1695	106.0	2	20.1
1680	132.0	2	27.7
1655	121.2	2	24.2
1745	142.5	2	17.1
1775	71.9	0	0
Total	2202.8	-	283.4

Fig. 16. shows the voltages of the load shedding buses during the SGP-STB line outage. The magnitudes of voltages are comparatively lower than those of the current

SPS. The first or second step is applied to shed the loads for recovering the voltages of each bus. The voltage of one of the load buses, 1765, is shown in Fig. 17. The second shedding step is applied on this bus. Not all load buses are operated to shed the loads because the voltages of the buses are raised by the load shedding on the nearest bus (see Table 3).

c. Multi-step UVLS schemes – A centralized UVLS scheme

In this paragraph, 'centralized UVLS' means the information needed to operate the UVLS gathered into the one central unit and then sends the signal to shed the predefined loads.

A very similar approach for shedding loads for the current SPS in the KEPCO system is taken, other than for the multi-step shedding scheme. Fig. 18 represents the centralized UVLS scheme applied in the simulation.

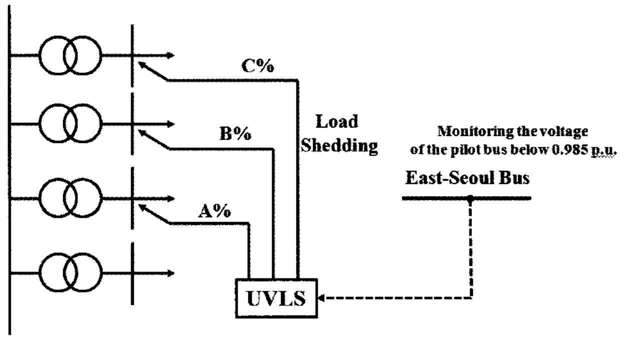


Fig. 18. Concept of the centralized UVLS scheme applied in the simulation.

The scheme applied for the simulation is as follow:

- 1st step of the UFLS loads shed at below 340kV (0.985p.u.) on the pilot buses with a 3.5 second time delay
- 2nd step of the UFLS loads shed at below 340kV on the pilot buses with a 5 second time delay
- 3rd step of the UFLS loads shed at below 340kV on the pilot buses with an 8 second time delay

Figs. 19 and 20 show the bus voltages of the pilot bus (East-Seoul) and the load buses with the loss of the SGP-STB lines, respectively.

If the voltage is lower than 0.985p.u. with a time delay over 3.5 seconds after the 765kV line trips, then the 1st step of UFLS (Under Frequency Load Shedding) loads are shed. No further load shedding after the 1st step occurs in this case because the pilot bus voltage is raised to over 0.985p.u. Table 4 summarizes the amount of shedding loads and the steps on each load bus.

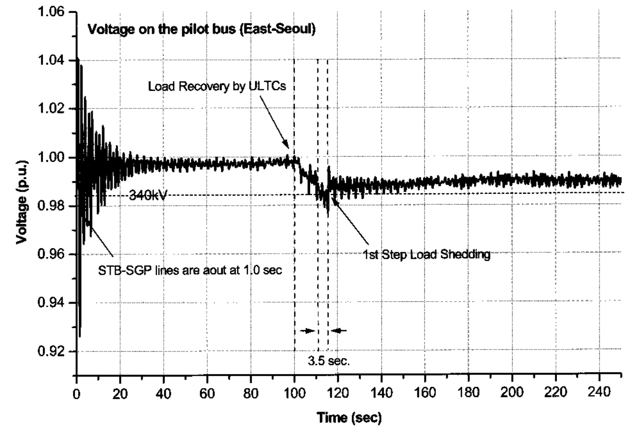


Fig. 19. Voltage of the pilot bus (East-Seoul) to be monitored for shedding loads

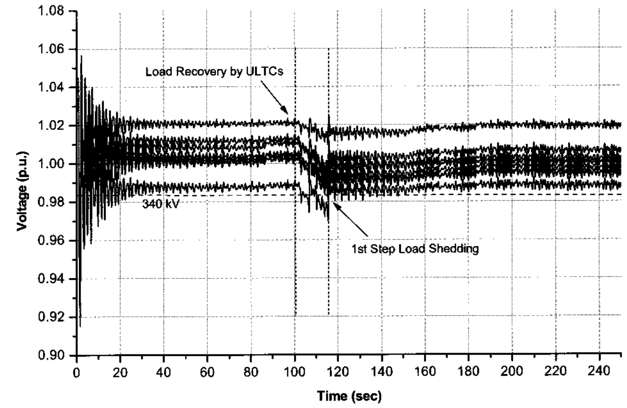


Fig. 20. Voltages of the load buses after shedding loads

Table 4. The amount of shedding load and number of steps applied for the centralized UVLS scheme

Bus No.	Pload(MW)	steps applied	Pshed(MW)
1595	94.8	1	6.7
1565	96.7	1	17.4
1590	114.9	1	26.3
1545	66.8	1	9.4
1630	87.4	1	10.5
1765	94	1	16.9
1525	97.2	1	28.2
1530	152.7	1	7.7
1520	148.6	1	7.4
1580	58.5	1	10.5
1770	90.2	1	19.8
1845	69	1	9
1790	139.2	1	22.4
1670	102.6	1	9.2
1785	129.6	1	20.7
1635	87.8	1	20
1695	106.0	1	10.6
1680	132.0	1	14.4
1655	121.2	1	12.1
1745	142.5	1	8.5
1775	71.9	1	6.6
Total	2202.8	-	294.3

4. Conclusion

This study has shown that the current single-step SPS operated in the KEPCO system to prevent voltage instability should be revised and improved. By analyzing unexpected events such as has recently occurred in the KEPCO transmission system, it has been revealed that the setting values of the current SPS, the reference voltage of the pilot bus and the delay-time of the UVR (Under Voltage Relay) should be changed to below 326kV and over a second, respectively (for the delay-time of the UVR, it has recently changed to 500msec instead of 200msec).

In addition, as alternatives to the current single-step SPS, multi-step UVLS schemes, one distributed and one centralized, were applied to the KEPCO system followed by the introduction of system models needed for long-term voltage instability studies.

As can be seen in this paper, the application of multi-step UVLS schemes, both distributed and centralized, can significantly reduce the amount of shedding load compared to that for the current single-step SPS.

The amount of shedding load for the current single-step SPS is approximately 900MW. However, those for multi-step UVLS schemes were 283MW and 293MW, respectively. Only 30% of the amount of shedding loads for the current single-step SPS can make the system stable against a critical contingency in the system.

However, more extensive and rigorous case studies under various system conditions are needed to determine the setting values of the UVLS, such as the amount of shedding load and the delay-times per step, etc.

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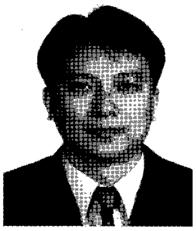

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