Utilizing Under Voltage Load Shedding Strategy to Prevent Delayed Voltage Recovery Problem in Korean Power System

Yun-Hwan Lee*, Seung-Chan Oh**, Hwan-Ik Lee**, Sang-Geon Park*** and Byong-Jun Lee†

Abstract – The presence of induction motor loads in a power system may cause the phenomenon of delayed voltage recovery after the occurrence of a severe fault. A high proportion of induction motor loads in the power system can be a significant influence on the voltage stability of the system. This problem referred to as FIDVR(Fault Induced Delayed Voltage Recovery) is commonly caused by stall of small HVAC unit(Heating, Ventilation, and Air Conditioner) after transmission or distribution system failure. This delayed voltage recovery arises from the dynamic characteristics associated with the kinetic energy of the induction motor load. This paper proposes the UVLS (Under Voltage Load Shedding) control strategy for dealing with FIDVR. UVLS based schemes prevent voltage instability by shedding the load and can help avoid major economic losses due to wide-ranging cascading outages. This paper review recent topic about under voltage load shedding and compare decentralized load shedding scheme with conventional load shedding scheme. The load shedding strategy is applied to an actual system in order to verify the proposed FIDVR mitigation solution. Simulations demonstrate the effectiveness of the proposed method in resolving the problem of delayed voltage recovery in the Korean Power System.

Keywords: Delayed voltage recovery, Motor stall, Load shedding, Voltage instability

1. Introduction

With economic growth, increasing incomes, and a variety of consumer oriented electrical gadgets, power consumption levels are rising at rates unseen before. While the increase in industrial load demand is quite low, the proportion of residential load in the overall load has increased significantly. When the number of induction motors installed in a system increases beyond a certain limit, there can be serious repercussions on the voltage stability of the power system. Having a significant proportion of the total load from induction motor loads is one of the most crucial impact factors on the stability of a power transmission and distribution system. The mechanism for FIDVR (Fault Induced Delayed Voltage Recovery) is that once an HVAC (Heating, Ventilation, and Air Conditioner) unit trips and stalls after the occurrence of a fault, the voltage remains at significantly reduced level due to the motors draw excessive reactive power from the grid. This is followed by shunt capacitors switching off in response to reduce this overvoltage, which brings the system voltage to below the pre-fault level. This type of

system fault has been observed to occur in residential areas in North America where small induction motor loads such as domestic air conditioners have been installed [1-9]. Owing to the increased occurrence of FIDVR, large and complex power grids are being subject to increasing disturbances, while power networks are being continuously exposed to elevated levels of risk and vulnerability. Failure to provide adequate controls to these systems against such faults could result in severe industrial and economic damages, as well as partial or area-wide power outages.

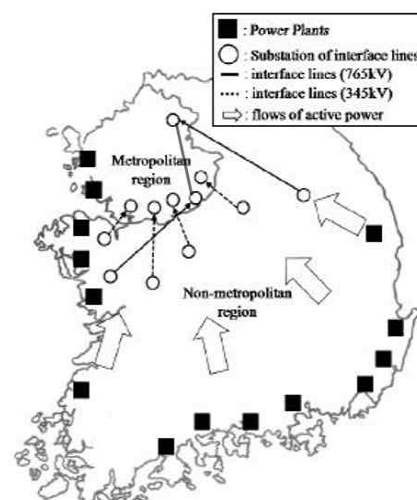Fig. 1 shows the Korean power system. From a geo-

Fig. 1. Characteristic of Korean power system

graphical point of view, it demonstrates the characteristics of imbalance in power demand with the load demand being concentrated in the metropolitan areas. It is quite expensive to run generators in the metropolitan areas. So, it is economically profitable to have loads in metropolitan areas be supplied by generators located in the coastal regions at lower cost. The primary causes of voltage instability and voltage collapse in the Korean power system arise from having concentrated loads, long-distance transmission lines, and continual load increases.

For this reason, two parallel 765 kV transmission lines and four 345 kV parallel lines are used as interface transmission lines for transferring power. Interface transmission lines can suffer from large scale disturbances that cause voltage instability or voltage collapse to occur. In order to solve the problems related to voltage instability, which can affect other elements of the power system, the ULVS (Under Voltage Load Shedding) control method can be implemented. Employing a method such as this can mitigate the consequences of load shedding in the most economical way possible. In the current UVLS scheme is not considered to be an FIDVR phenomenon. However, the actual load configuration, the proportion of the induction motor load, increased. For induction motors, the load characteristics corresponding to the voltage are singular because of the special operating range and stall. FIDVR occurs due to the phenomenon of induction motor stalls. The conventional composite load model does not capture the phenomenon of slow voltage recovery. The ZIP plus induction motor model can instead be used to simulate the phenomenon of voltage delay recovery.

In this study, we apply the UVLS strategy to provide a solution to FIDVR on the Korean power system considering an induction motor load. FIDVR is caused by the stalling of small induction motor loads during transmission level contingencies. A UVLS scheme can be an effective method to mitigate the risk of FIDVR and tripping of the motors to prevent voltage drop and delayed voltage recovery. And, this paper review recent topic about under voltage load shedding and compare with decentralized load shedding scheme with centralized(conventional) load shedding scheme. The load shedding algorithm is applied to an actual system in order to verify the proposed FIDVR mitigation solution. Simulations demonstrate the effectiveness of the proposed method in resolving the problem of delayed voltage recovery in the Korean power system.

2. Description of Fault Induced Delayed Voltage Recovery

One of the main objectives in the operation of power systems operation is to maintain voltage stability. It is desirable to maintain an acceptable voltage at each bus after being subjected to a disturbance. In recent times,

the short-term voltage stability issue FIDVR has gained increased attention. This phenomenon has been observed following faults in the transmission or distribution system and, in some cases, has led to fast voltage collapse. The NERC (North American Electric Reliability Corporation) Transmission Issues Subcommittee has characterized FIDVR in the following manner[10]. After the transmission or distribution fault is cleared, the system voltage remains at a significantly low level for several seconds or longer.

2.1 Induction motor stall phenomenon

FIDVR root caused induction motor stall state described. During an FIDVR event, the voltage recovers to the nominal level in a timeframe over tens of seconds instead of in the tens of cycles after a fault is cleared (the faults are usually cleared in 3 to 5 cycles at the transmission level). Sustained low voltages can cause power quality issues and raise concerns of voltage system collapse. Meanwhile, a significant reduction in the voltage stability margin may lead to a similar chain of events. Therefore, it is critical that FIDVR events be modeled and prevented [10].

After the contingency occurs in the system, when a voltage is consistently low levels drop inability supply reactive power, the motor load is stalled. This dip in voltage causes small motor compressor loads to stall and the voltage on the distribution circuits drops even lower. The stalled HVAC units prevent the voltage from recovering to nominal level. When the thermal overload protection inside the HVAC units trips, the voltage gradually recovers but overshoots the nominal voltage because the capacitor banks used to raise depressed voltages remain connected to the circuit after they are no longer needed. The over-voltage causes the capacitor bank to then trip out. With the capacitors tripped out and the air conditioner load returning to normal, the voltage then drops below the nominal voltage.

2.2 ZIP and induction motor load modeling
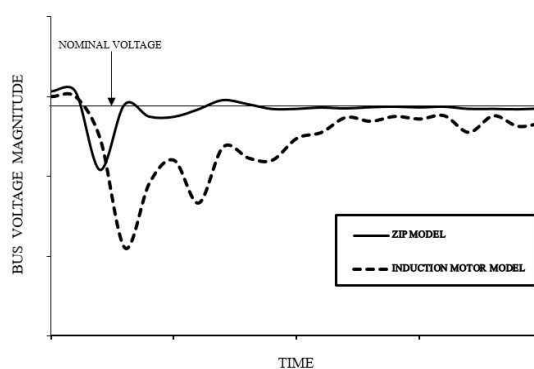
To ensure the voltage stability, voltage characteristic of

Fig. 2. Voltage variation for ZIP and induction motor model

the loads is especially important. There are many models to represent the voltage characteristics of the load. In this paper, utilize load model which is combined by ZIP load model and induction motor model [11].

Load models which are commonly used in static analysis is ZIP model and exponential model. ZIP model is a model consisting constant impedance load, the constant current load, the constant power load. Equations of the ZIP model are as follows.

$$P_{ZIP} = P_0 \left[a_P \left(\frac{V}{V_0} \right)^2 + b_P \left(\frac{V}{V_0} \right)^1 + c_P \right] \qquad (1)$$

$$Q_{ZIP} = Q_0 \left[a_P \left(\frac{V}{V_0} \right)^2 + b_P \left(\frac{V}{V_0} \right)^1 + c_P \right] \qquad (2)$$

P0, Q0 are real and reactive load power in steady state, magnitude of the load when the voltage 1.0 p.u.. Value of the expression a, b, c represents the proportion of constant impedance, current, power load. Typically, these values are always positive, and the assumption is always 1.

And dynamic model of induction motor load based on the voltage behind the transient reactance Vd`, Vq` and the slip parameter s. Equations of the induction motor model are as follows.

$$\frac{dV_d^{'}}{dt} = -\frac{1}{T_r} \left[V_d^{'} - (X_s - X_s^{'}) i_q \right] + s \omega_0 V_q^{'} \qquad (3)$$

$$\frac{dV_q^{'}}{dt} = -\frac{1}{T_r} \left[V_q^{'} + (X_s - X_s^{'}) i_d \right] - s \omega_0 V_d^{'} \qquad (4)$$

$$\frac{ds}{dt} = \frac{1}{2H_r} \left[V_d^{'} i_d + V_q^{'} i_q - T_L \right] \qquad (5)$$

Id and Iq are the stator currents, ω0 is the synchronous speed, H is the inertial constant, Tr is the time constant, and TL is the load torque. The parameters Xs, Xs` represent the synchronous reactance and transient resistance, respectively.

The load impedance Zload is the combined impedance of the induction motors and other loads. Induction motor impedance is simplified as follows [12].

$$Z_{load} = \frac{R}{Slip} + jX \qquad (6)$$

When in steady-state, the value of the motor slip approaches the value of 0, which denotes synchronous speed. On the other hand, the value of motor slip approaches 1 in the locked rotor current condition. When the load voltage decreases and the slip increases towards a stall-state, it is not possible for the power system voltage recovery to cause the phenomenon of motor stall.

2.3 FIDVR mitigation solution

The control solutions employed to mitigate the phenomenon of FIDVR can be classified as supply-side solutions and demand-side solutions. The most popular supply-side solution applied by utilities is the implementation of FACTS devices such as SVC and STATCON to increase reactive power support. However, these devices have high installation costs, making them uneconomic in most situations. SVC and STATCOM can be employed in FIDVR affected regions to reduce the effects of FIDVR by taking into account the specific characteristics of the power system in the region and the proportion of motor load. Demand-side solutions that use protection systems to rapidly disconnect motors under low voltage conditions can also be an effective and economic solution to tackle FIDVR. These include the implementation of protective relaying and control equipment to achieve faster fault clearing times for credible delayed fault clearing scenarios, new faster breakers and/or independent pole operated breakers tied into a UVLS scheme. In order to alleviate the FIDVR phenomenon, several methods have been described. There is a method to utilize the recovery characteristics of the voltage changes depending on the accident removal time. How to easily reset the operation time of the relay shall be considered a problem associated with the issues of protection coordination and improvement of equipment performance [12].

3. UVLS Scheme in Korean Power System

With the UVLS scheme currently in operation, outages in one of the two parallel 765 kV transmission lines is considered a significant contingency that has the potential to cause a cascading blackout. SPS(Special Protection Scheme) has been applied to a set of interconnected transmission lines since 2004. If the magnitude of power flowing through the interface transmission lines exceeds a certain level, it can lead to the occurrence of voltage collapse when there is an outage in the interface flow transmission lines. Therefore, power system operators observe the magnitude of the interface flow as a constraint used to prevent voltage instability. For efficient power system operations, four PMUs (Phasor Measurement Unit) were installed in the Korean power system by the K-WAMS (Wide Area Monitoring System) project in the year 2009. The K-WAMS obtains synchronized real-time data on the active power, reactive power, voltage, and frequency from each PMU. Various indices are used to perform monitoring of parameters and data related to wide area voltage stability and small-signal stability. The K-WAMS has been developed to ensure reliability of system operation, prevent system wide blackouts and be used as a foundation technology for future power system control schemes. Along with K-WAMS; since 2010, a WAMAC
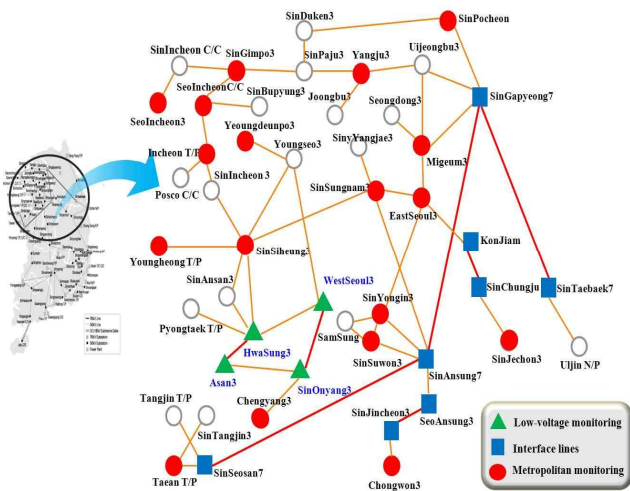
Fig. 3. PMU Installations

(Wide Area Monitoring And Control) system has been developed and made available to better cope with large disturbances that have the potential to cause voltage collapse. This is a concept that combines WACS (Wide Area Control System) with K-WAMS. To advance the reliability and availability of WAMAC, a total of 40 PMU units have been installed.

Currently, research is ongoing into multi-step load shedding and reduction of load shedding capacity using real-time information from the PMUs. The SCADA/EMS (Supervisory Control and Data Acquisition/Energy Management System) systems already installed were not able to take the role of a monitoring system efficiently, because they cannot respond to contingencies in real-time. In terms of the PMU application, there are two types of directions of power system operation that the PMU can be applied. As described above, the installation of a PMU is necessary for efficient and reliable system operation. As the number of PMUs in a power system becomes larger, it is possible to improve the effectiveness of monitoring, but owing to considerations of economic efficiency, it is not possible to increase the number of PMUs beyond a certain limit [13, 14].

As seen in Fig. 3, a total of 40 PMUs are installed on the 30 buses in the Korean power system. The PMUs are installed on both sides of six interface transmission lines and buses that have been selected for optimization from among the 345 kV buses in metropolitan areas. The transmission lines and buses were selected by the ILP (Integer Linear Programming) method. The locations were selected for PMU installation for the purposes of low voltage monitoring and bus voltage monitoring.

3.1 Centralized UVLS scheme

The WAMACs are currently being designed and operated on the basis of centralized management schemes. The process uses a method consisting of two-step load shedding
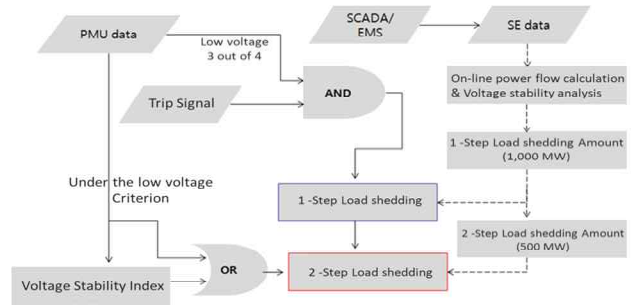

Fig. 4. Centralized scheme procedure

with an aim to reduce the quantum of load shedding required. The data obtained from the PMUs is used to calculate voltage stability margin and to build SE(State Estimation) data.

The existing SPS applied to the Korean power system has been designed to operate during severe contingencies including a scenario involving an outage in one route of a 765-kV double circuit line in the load concentrated area. When a contingency occurs, the transmission line is tripped out within five cycles. The SPS is operated at each end of the transmission line by a protective relay. The contingency signal detected by the protective relay is transmitted to a SCADA system. The monitoring for low voltage bandwidth violations is sensitive to the voltage maintained on the 345-kV pilot buses. If one of the two pilot bus voltages is lower than 340 kV (0.9885 p.u.) during a 200-ms timeframe, a signal is transferred to the SCADA system by the under-voltage relays. The SCADA system receives a signal and performs a predetermined load shedding in order to avoid voltage collapse. The locations where load is to be shed are determined by simulation result and selected among the locations for UFLS (Under Frequency Load Shedding). The current load shedding schemes have been designed to operate in two steps, and the amount of load shedding is about 1500 MW and it is shed whole amount at a time. Fig. 4 shows the process used in implementing the centralized scheme.

3.2 Decentralized UVLS scheme

The decentralized UVLS scheme uses the individual load bus data, such as the PMU device measurements obtained by the real-time monitoring system. In addition, the active power margin, a key component in determining the optimal quantum of load shedding, is calculated in real time. Instruments, such as the PMU, record the values of voltage and current delivered to the load in real time, and calculate the amount of load estimated by the system from the equivalent circuit. To avoid voltage collapse, the real-time monitoring system should build a real-time voltage stability index, which can serve as the basis in dealing effectively with system instability. The decentralized scheme can control the load at the substation using the measured data. A real-time voltage stability margin can be
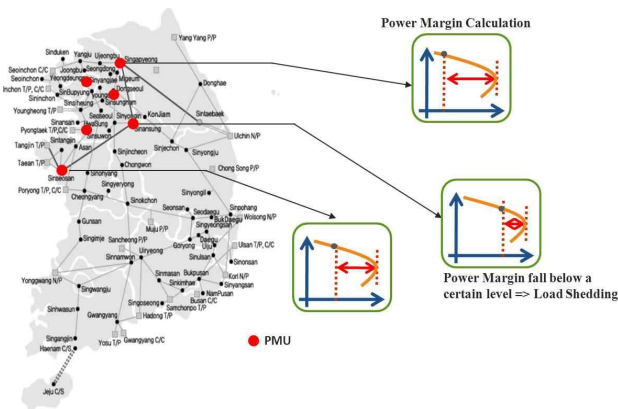
Fig. 5. Decentralized scheme procedure

Fig. 6. Not considering induction motor load without FIDVR

Fig. 7. Considering induction motor load with FIDVR

provided for load shedding by the local operators of the bus system. Furthermore, load shedding can be performed to avoid voltage collapse, and coordination with other substations is continuously done to monitor and maintain wide-area voltage stability. This application will develop new hierarchical control architecture to perform voltage instability load shedding using the VIP(Voltage Instability Predictor) concept. VIP uses the values of locally measured voltage and current to estimate the proximity to voltage instability. The Voltage protection scheme will be developed based on the VIP concept to replace the conventional UVLS scheme at designated locations. Moreover, PMUs will also use the VIP concept to calculate the proximity to voltage instability at different geographical locations and inform operators when these devices detect a local voltage instability condition. This will enable operators to monitor the system for voltage stability enhancement [13, 14].

Fig. 5 demonstrates the concept utilized in the decentralized scheme. The values of voltage and equivalent impedance for each load bus are estimated, such as the quantum of maximum power transfer and the P and Q values from each load bus, to determine the values for active power and reactive power margin of each load. If these values fall below a certain level, then load shedding is implemented. If a sufficient number of PMUs is installed on the buses as needed, each bus can calculate indices that reflect the situation in the adjacent area in real-time. This information can be used to take measures for maintaining regional power system stability.

4. Case Studies

The FIDVR phenomenon is caused by induction motor loads such as small HVAC units. We have investigated scenarios on the assumption that the concentration of induction motor loads in the overall household electricity consumption of South Korea is high. In fact, we assume that such induction motor loads occupy a proportion in the range of 50%~60% (by using the data from Korean Power System) and difference applying a high percentage of load
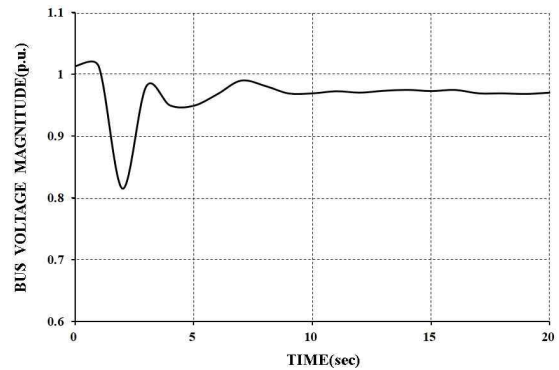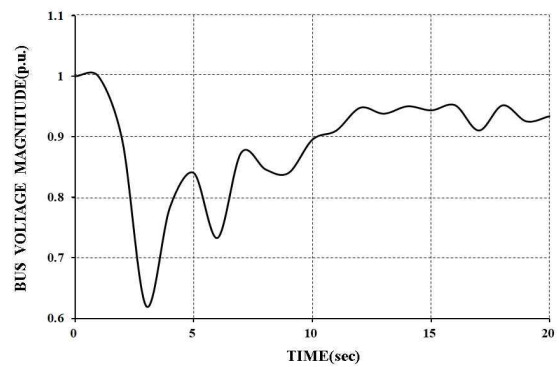
of the induction motor to the central region it is to be examined.

In this study, the objectives of simulation is consideration of an induction motor load with FIDVR. And, application of the load-shedding algorithm to an actual system in order to verify the proposed FIDVR mitigation strategy. Simulations shows the effectiveness of the proposed method in decreasing the Delayed Voltage Recovery. Simulations of the most extreme line fault events, including the loss of one of the double-circuits, were performed. Dynamic simulations were executed using data from the Korean power system.

4.1 Considering induction motor load with FIDVR

The Korean power system currently does not consider the induction motor loads and, consequently, does not take the FIDVR phenomenon into modeling and simulation efforts. Fig. 6 shows the scenario where induction motor loads are not considered and the FIDVR phenomenon is not observed.

In Fig. 7, we consider the scenario where induction motor loads are considered and the FIDVR phenomenon is observed. Given the scenario that the voltage is not restored to a stable voltage level for a few seconds after the contingency, this case of voltage variation represents delayed recovery. In general, considering the stall area of
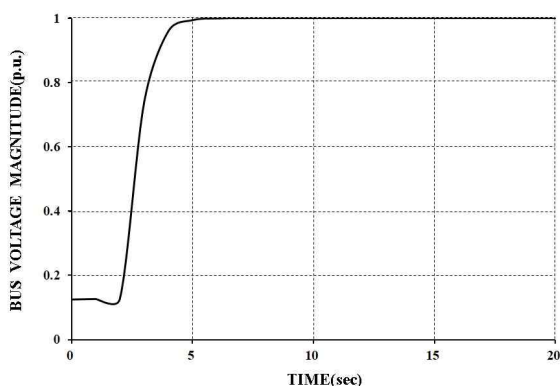
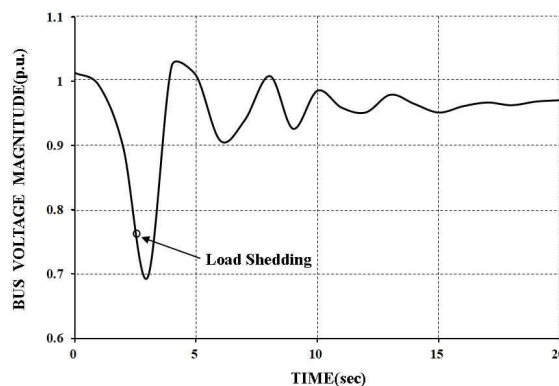**Fig. 8.** Induction motor slip (locked-rotor current)

Fig. 9. After load shedding (Centralized)

Fig. 10. After load shedding (Decentralized)

the induction motor, the voltage drops below 70% of the rated voltage at 0.5-0.7 p.u.. When considering the load of the induction motor after the contingency, the stability of the system is determined by observing the voltage waveform of the short-term variation. If the system is unstable, the appropriate control process is executed.

In Fig. 8, shows the variation of induction motor slip against time. If the load is applied to the motor, the rotational speed so that the speed is reduced and shifted to the synchronous speed. The current drawn by a stalled induction motor is termed locked rotor current and is linear with the voltage. The instant the voltage drops below 0.7 p.u., the locked rotor current is represented. When both the load and slip increase, but the rotational speed reduces, the current flowing through the motor increases. In the state of making rotations outside, the rotation speed of the motor is the speed of the synchronous speed or, in some cases, slip becomes negative. When the induction motor stalls, it is under the condition of locked rotor current that the motor consumes five to six times the induction motor current and demands a dramatically increased reactive power.

4.2 Applied under voltage load shedding scheme for FIDVR mitigation strategy

The purpose of under voltage load shedding is to inhibit voltage collapse by mitigating the FIDVR phenomenon. UVLS basically detects low voltage and prevents power outages in advance. To effectively eliminate the instability in the grid, the system should establish a preset voltage to prevent unnecessary load shedding. A very low voltage set point can prevent the occurrence of serious disturbances in the grid. The UVLS scheme determined the locally, based on the local measured quantities, communication link is

Table 1. Review procedure UVLS scheme

Step	Time (s)	Details
1	2.0000	Transmission line fault
		Disconnect Sh-Reactor
2	2.0833	Clearing of a line fault
3	2.1500	Disconnect generator
4	2.5000	Load Shedding
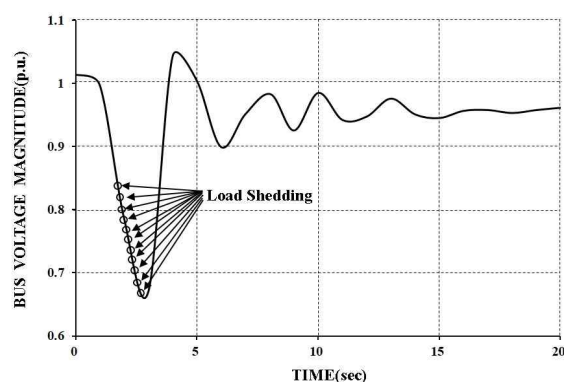
Table 2. Centralized load shedding — Delay time and amount

Bus No.	Delay Time (s)	Amount(MW)
1	2.5	64.148
2	2.5	60.445
3	2.5	50.487
4	2.5	143.909
5	2.5	150.038
6	2.5	171.671
7	2.5	167.504
8	2.5	110.132
9	2.5	49.952
10	2.5	10.854
11	2.5	267.145
12	2.5	93.485
13	2.5	417.118
Total		1,756.888

required for implementation UVLS scheme.

The following shows the assumed voltage instability case and reviews the appropriate implementation of the procedures.

In this study, the UVLS scheme was applied to demonstrate the effect of a voltage collapse case during a severe contingency. The simulation result reviewed the load shedding observation after the voltage recovery and initial voltage recovery after the clearing of a fault to less than 90% of the pre-contingency voltage. Figs. 9 and 10 show the results from the implementation of centralized

and decentralized schemes for FIDVR mitigation.

The centralized scheme determines the measured voltage and other information in many locations using the central controller or a single controller to determine the stability of the system, employing multiple information systems to do so. In the centralized scheme, load shedding is done 0.5 s after the occurrence of the contingency. In this case, all the buses implemented load shedding at the same time, with the whole amount being shed. The quantum of load shedding was about 1,756 MW. The voltage of the monitoring bus was 1.0134 p.u., which dramatically dropped after the contingency. However, after the implementation of the load shedding, the voltage was restored to 0.9854 p.u..

In the decentralized scheme, once the values fall below a certain level, load shedding is implemented. The decentralized scheme operates using data from the local PMUs. By utilizing real time monitoring systems, it will be able to reduce the amount of load shedding.

Subsequently, the PMU is considered to control the loads on the Korean power system so that the system can respond quickly during emergency events that occur in the grid. In addition, it can calculate the exact amount of load to be shed.In this case, load shedding is implemented if the load bus power margin falls below a certain level. The quantum of load shedding amounts to about 1,600 MW. After the implementation of the load shedding, the voltage was restored to 0.9843 p.u..

After load shedding is executed in both the centralized and decentralized schemes, the monitoring bus had the similar voltage. But the actual quantum of load shedding in the centralized and decentralized schemes was different. In the decentralized scheme, the shedding will decrease the amount by about 156 MW.

Fig. 11 shows the variation of the slip of the induction motor with time. The slip and speed of the induction motor are stabilized after the contingency. The FIDVR phenomenon is alleviated after shedding the load, showing that the system is stabilized quickly. By utilizing the UVLS scheme, it is confirmed that the FIDVR phenomenon is mitigated in practice.

Table 3. Decentralized load shedding — delay time and amount

Bus No.	Delay time (s)	Amount(MW)
9	2.573	49.952
7	2.699	167.504
5	2.732	150.038
2	2.756	60.445
11	2.798	267.145
10	2.916	10.854
6	2.956	171.671
4	3.083	143.909
3	3.112	50.487
8	3.259	110.132
13	3.354	417.118
Total		1,599.255
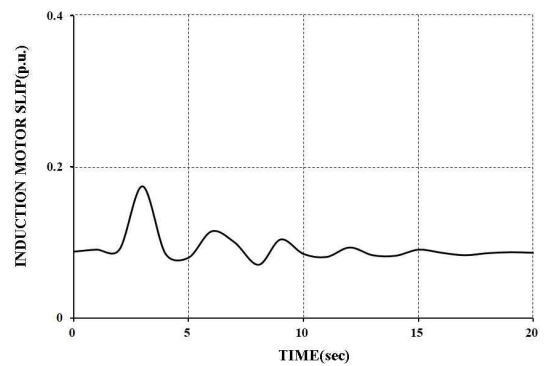
(a) Centralized scheme
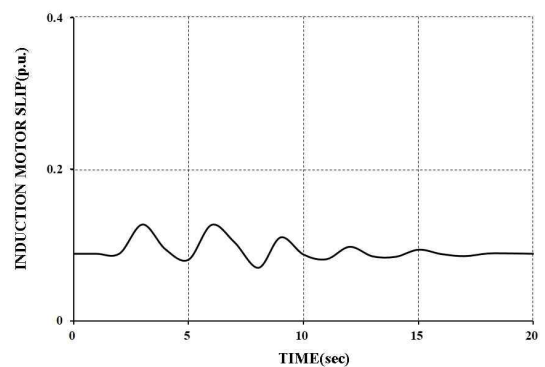
(b) Decentralized scheme

Fig. 11. Induction motor slip (steady-state motor current condition)

5. Conclusion

In this study, the centralized and decentralized UVLS schemes were applied against severe contingencies to mitigate FIDVR. When voltage instability occurred, under voltage load shedding was implemented. The decentralized UVLS scheme was implemented using real time local data obtained by the PMU. When voltage instability occurred, load shedding was determined from the individual substation, and the amount of the active power margin was determined through observation. It is also demonstrated that with severe faults, implementation of UVLS has mitigated the delayed voltage recovery. The centralized scheme and decentralized scheme algorithm are applied to an actual system in order to verify the proposed FIDVR mitigating scheme. Simulations show the effectiveness of the proposed method in alleviating delayed voltage recovery.

References

[1]   Zhang Yue1, a, Li Xiaoming, "Dynamic Voltage/Var Sensitivity Approach for Improving Fault-induced Voltage Delayed Recovery Problems," *International Power, Electronics and Materials Engineering Conference*, 2015.

[2] Xiu-xing Yin, Yong-gang Lin, Wei Li, Ya-jing Gu, Peng-fei Lei, Hong-wei Liu, "Sliding Mode Voltage Control Strategy For Capturing Maximum Wind Energy Based on Fuzzy Logic Control," *International Journal of Electrical Power & Energy Systems*, vol. 70, pp. 45-51, 2015.

[3] Xiu-xing Yin, Yong-gang Lin, Wei Li, Ya-jing Gu, Hong-wei Liu, Peng-fei Lei, "A Novel Fuzzy Integral Sliding Mode Current Control Strategy For Maximizing Wind Power Extraction and Eliminating Voltage Harmonics," *Energy*, vol. 85, pp. 677-686, 2015.

[4] Xiu-Xing Yin, Yong-Gang Lin, Wei Li, Hong-Wei Liu, Ya-Jing Gu, "Fuzzy-logic Sliding-Mode Control Strategy for Extracting Maximum Wind Power," *IEEE Transactions on Energy Conversion*, vol. 30, no. 4, pp. 1267-1278, 2015.

[5] Xiu-xing Yin, Yong-gang Lin, Wei Li, "Predictive Pitch Control of An Electro-Hydraulic Digital Pitch System for Wind Turbines Based on The Extreme Learning Machine," *Transactions of the Institute of Measurement and Control*, vol. 38, pp. 1392-1400, 2016.

[6] Michael W. Fisher, Ian A. Hiskens, "Phase Boundary Computation for Fault Induced Delayed Voltage Recovery," *2015 IEEE 54th Annual CDC*, 2015.

[7] Richard J. Bravo, Robert Yinger, Patricia Arons S. "Fault Induced Delayed Voltage Recovery (FIDVR) indicators," *IEEE PES T&D Conference*, 2014.

[8] Krishnanjan Gubba Ravikumar, Scott Manson, "Analysis of Fault-Induced Delayed Voltage Recovery Using EMTP Simulations," *IEEE PES Transmission and Distribution Conference and Exposition*, 2016.

[9] Mingming Du, MinXiao Han, Zhihui Cao; Chu, F., Ei-Kady, M., "Utilizing STATCON to Resolve Delayed Voltage Recovery Problem in SEC-WR," *Power and Energy Engineering Conference, APPEEC 2009. Asia-Pacific*, 2009.

[10] NERC Technical Reference Group. Fault-induced delayed voltage recovery(FIDVR). Technical report, NERC, 2009.

[11] Y. Lee, B. Park, S. Oh, B. Lee, J. Shin, T. Kim, "Implementation of Under Voltage Load Shedding for Fault Induced Delayed Voltage Recovery Phenomenon Alleviation," *Journal of Electrical Engineering and Technology*, vol. 9, no. 2, pp. 406-414, 2014.

[12] Prabha Kundur, "Power System Stability and Control," 1994

[13] "Under Voltage Load Shedding Protection," Working Group C-13, System Protection Subcomittee IEEE PES Power System Relaying Committee Draft 4.1. 2003.

[14] Jeonghoon Shin, Suchul Nam, Jaegul Lee, Youngdo Choy, Taekyun Kim, Hwachang Song, "Application of Multi-step Undervoltage Load Shedding Schemes to the KEPCO System," *Journal of Electrical Engineering & Technology*, vol. 4, no. 4, pp. 476-484, 2009.

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