Real Time Wide Area Voltage Stability Index in the Korean Metropolitan Area

Sangwook Han†, Byongjun Lee*, Sangtae Kim and Younghwan Moon*****

Abstract – Through the development of phasor measurement units (PMU), various aspects of power system dynamic behavior could be monitored and diagnosed. Monitoring dynamic voltage stability has become one of the achievements we can obtain from PMUs. It is very important to select the most appropriate method for the Korea Electric Power Corporation (KEPCO) system since there are many voltage stability indices. In this paper, we propose an advanced WAVI (Wide Area Voltage Stability) that is well suited for the purposes of monitoring the dynamic voltage stability of KEPCO's PMU installation plan. The salient features of the proposed index are: i) it uses only PMU measurements without coupling with EMS data; ii) it is computationally unburdened and can be applied to real-time situations. The proposed index is applied to the KEPCO test system and the results show that it successfully predicts voltage instability through comparative studies.

Keywords: Wide Area Voltage stability Index, Synchro-Phase, Phasor Measurement Unit

1. Introduction

The recent development of phasor measurement units (PMU) makes dynamic network supervision possible. The traditional method of monitoring a power system, SCADA/EMS, cannot provide synchronized data. Although they have the same time tags, it is not in fact the same time as the clocks in the equipment differ slightly, and it is too difficult to monitor the power system due to the technological limitations of the SCADA/EMS systems. However, the information obtained from a PMU is synchronized by a global positioning system (GPS), and all data has the same time tags and will indicate the same time, allowing for the creation of dynamic snapshots of the situation across a wide area of a power system. Accurate, time-tagged phasor data can be transmitted almost in real time to a control center for monitoring and analysis purposes, providing the possibility for a wide range of stability monitoring and control applications.

There are many known applications for wide area voltage stability monitoring with PMUs. Most are evaluated theoretically, although some are in practical use. Voltage Instability Prediction (VIP) [1] is the best-known algorithm for monitoring voltage stability and uses only one local measurement to predict voltage collapse by observing the Z-index. In order to calculate the thevenin impedance of a system, a parameter estimation method such as a least square solution is used as there are 4 unknown values and just 2 equations. Consequently, it can have a time delay unsuitable for real-time applications. In addition, the result is not reliable if the PMU is not installed on a radial bus. Corridor Monitoring [2] is also a well-known method, and measures both ends of the transmission corridors before making the voltage stability index. The main advantage of this algorithm is that it doesn't require parameter estimation, and so it does not have the time delay. However, there is a disadvantage in that a large number of PMUs are necessary to obtain robust results. There are other methods of voltage stability such as the Real-Time Indicator of Local Voltage Instability, Voltage degradation monitoring, and so on [3-5]. Every method has its advantages and disadvantages as mentioned above.

It is very important to select the method most appropriate to the Korean system from many voltage stability indices. In this paper, an advanced algorithm, WAVI (Wide Area Voltage stability Index) suitable for monitoring the voltage stability of the KEPCO system, is introduced which uses only voltage and current phasor data obtained from PMUs without coupling with EMS data. It is computationally unburdened so that it can be applied to real-time situations, and is remodeled in a part of the calculating parameter from the developed voltage stability index, such as VIP and Corridor Monitoring. Since the algorithm is founded taking into consideration KEPCO's plan to install the PMUs on major buses in Korea, it is very appropriate to detect voltage instability in the KEPCO system.

WAVI is performed using an actual system in Korea, and The 2007 Korean peak system (1500-buses) is applied to the WAVI analysis. The case study selected shows that it can predict a voltage collapse in Korea.

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2. Wide Area Voltage Stability Index

2.1 Detecting voltage instability

The WAVI algorithm shows whether a power system is stable or not, and uses a similar method to VIP's Z-index. Fig.1 shows the concept of the VIP in a Thevenin equivalent system. |Zapp| divided by |Zth| is Z-index.

From this circuit theory, maximal power transfer occurs when |Zapp| equals |Zth|. The apparent impedance |Zapp| is the ratio between the voltage and current phasors measured at the bus. When loading is normal, the |Zapp| is much greater than the |Zth|. In other words, the Z-index is approximately zero. When the system suffers voltage instability, the difference between the two impedances approaches zero, and the Z-index is increased by about 1.0.

WAVI uses the same method. Consequently, WAVI is a real number, 0.0~1.0, and if the index indicates a number over 1.0, the system will be unstable theoretically. Similarly, an index under 1.0 indicates the system is stable.

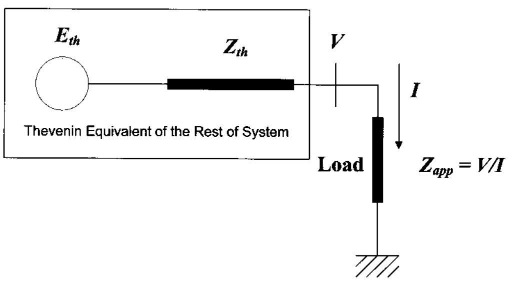


Fig. 1. Local bus and system Thevenin equivalent

2.2 Foundation of WAVI method

The WAVI method is similar to that introduced in reference [2]-[3], with only minor differences. Fig. 2 shows the concept of the WAVI method, which needs at least two PMUs since it uses data obtained from both the metropolitan and the non-metropolitan areas.

We constructed a virtual bus in the metropolitan area, and its voltage is the average of all buses in the metropolitan area where the PMU is installed. We also constructed a virtual bus in the non-metropolitan area. The current flowing from each bus will be the sum of the flow of lines linking the two areas. We then construct the T-equivalent model

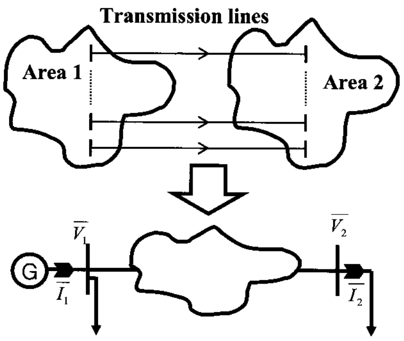


Fig. 2. A wide area system and an equivalent circuit.

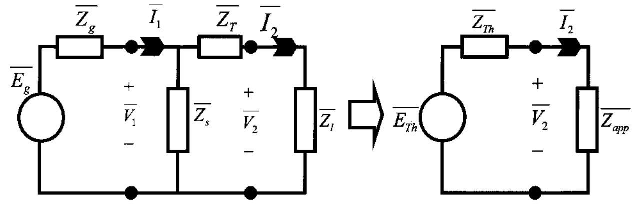


Fig. 3. Reduction to a thevenin equivalent

shown in Fig. 3, and the KCL and KVL help compose the equations. Zs and Zt are the shunt and series impedance of transmission lines of the T-equivalent form, respectively.

It is necessary to calculate the Zg impedance of the generators and transformers in the generation area, although this can be calculated continuously once Zg has been attained. We used the VIP method in order to derive the first Zg, and performed the VIP method using the virtual bus in the non-metropolitan area. We also obtained the first Zg from the VIP's result, Eth.

$$\overline{Z_l} = \frac{\overline{v_2}}{\overline{i_2}} \tag{1}$$

$$\overline{Z_s} = \frac{\overline{v_1}}{\overline{i_1} - \overline{i_2}} \tag{2}$$

$$\overline{Z_T} = \frac{\overline{v_1} - \overline{v_2}}{\overline{i_2}} \tag{3}$$

$$\overline{Z_{Th}} = \overline{Z_T} + \frac{1}{\frac{1}{\overline{Z_g}} + \frac{1}{\overline{Z_s}}} \tag{4}$$

$$\overline{Z_{app}} = \overline{Z_l} \tag{5}$$

$$\overline{E_{Th}} = \overline{v_2}\,\frac{\overline{Z_{Th}} + \overline{Z_{app}}}{\overline{Z_{app}}} \tag{6}$$

$$WAVI = \frac{\overline{Z_{Th}}}{\overline{Z_{app}}} \begin{cases} < 1 : stable \\ \geq 1 : unstable \end{cases} \tag{7}$$

2.3 WAVI Using Only 1 Area's Data

Since a PMU is the most up to date equipment and is rather expensive, only a few PMUs have been installed in the KEPCO system as yet. Also, the installation process is not easy, thereby limiting the number of PMUs set up in real systems. Thus, it is very important that the number of PMUs be reduced as much as possible and that the voltage stability using them is monitored.

It is possible to calculate the WAVI in one area using a PMU which provides voltage and current phase data. If it offers the currents of all lines connected with bus installed PMUs and we know the line impedance, the voltage and current phase data of the end of the line can be obtained [5]-[8]. Therefore, when we applied the WAVI method to the KEPCO system, we monitored just one side of the lines. Assuming that line impedances are known, we need only half the number of PMUs. Eqs. (8) and (9) help calculate the voltage and current phase data of the end of the line.

$$V_2 = V_1 - \left(\left(\frac{S}{V_1} \right)^* - j\frac{B}{2}V_1 \right) \times Z \quad (8)$$

$$I_2 = \left(\frac{V_2 - V_1}{Z} + j\frac{B}{2}V_2 \right) \quad (9)$$

V_1 : voltage of bus #1
I_1 : current of bus #1
V_2 : voltage of bus #2
I_2 : current of bus #2
S : power transferred bus#1 to bus#2
Z : R+jX, impedance of line
B : charging susceptance of line

The results of comparing this advanced method and the original WAVI method is exactly the same in the same contingency scenario. The voltage of the end of the line could not be calculated if two circuits are open, since the current would be zero, but this is not a critical problem because the original WAVI is also affected by the line currents. Their difference is only 1.0E^-7 so it is expected that it also detects voltage instability situations well. The cost of installing PMUs will decrease and PMUs could be installed in another important bus.

3. Applying WAVI to KEPCO System

3.1 Corridor Monitoring

KEPCO system has very special characteristics. Most loads are massed in the metropolitan area located in the northern part of South Korea. And most generations are crowed in the non-metropolitan area located in the southern part of South Korea. So, the power flows from south to north. There are six lines which are the most important lines in KEPCO system. They supply most of the power needed in metropolitan area. Therefore, observing the both sides of those six lines, 12 PMUS, is the best solution for the monitoring voltage stability in KEPCO. The impedance of those lines is known value, so 6 PMUs are required.

Thus, in this paper, it is assumed that the 6 PMUs are installed on every receiving end of 6 major transmission lines. Fig.4 shows the KEPCO system and the major transmission lines. Voltages and currents are measured in phase form, and voltages and currents of sending ends are calculated from equation (8)~(9). It is supposed that impedances of the lines are obtained from power flow data and fixed while time domain simulation is doing. The virtual bus#1 and #2 are made by binding the buses in the non-metropolitan area and the metropolitan area respectively. The initial Zg is 0.001679899-j0.000126401, which is obtained from VIP method [1]. For the time domain simulation, '2007 KEPCO peak power flow data is used. Table 1 shows the contingency scenario. This is not practical scenario, but is good example to observe WAVI.

Fig.5 is the voltage magnitude of Hwasung bus. According to occurring contingencies, voltage magnitude decreases. At about t=88s, simulation is terminated because of voltage collapse.

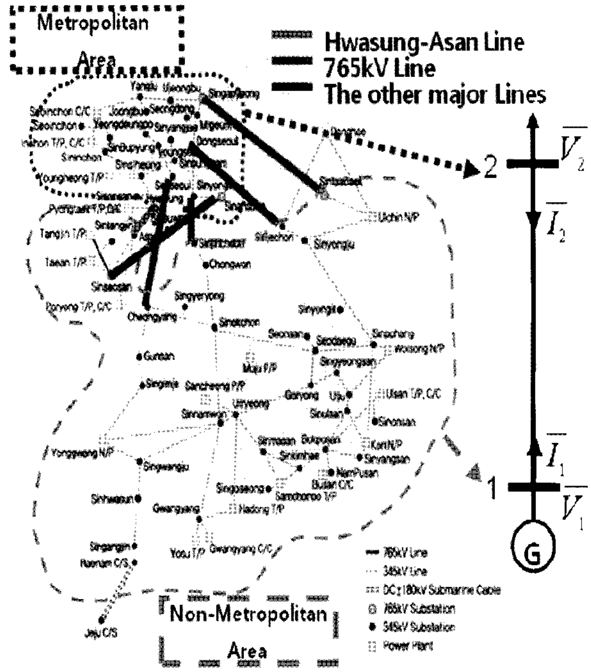


Fig. 4. KEPCO system and the network of virtual buses

Table 1. Contingency Scenario

At time	From	To	CKT
10 sec	Singapyeong	Sintaebaek	1
20 sec	Sinansung	Sinseosan	1
30 sec	Hwasung	Asan	1
40 sec	Gonjiam	Sinjaecheon	1&2
50 sec	Chungwon	Sinokcheon	1&2

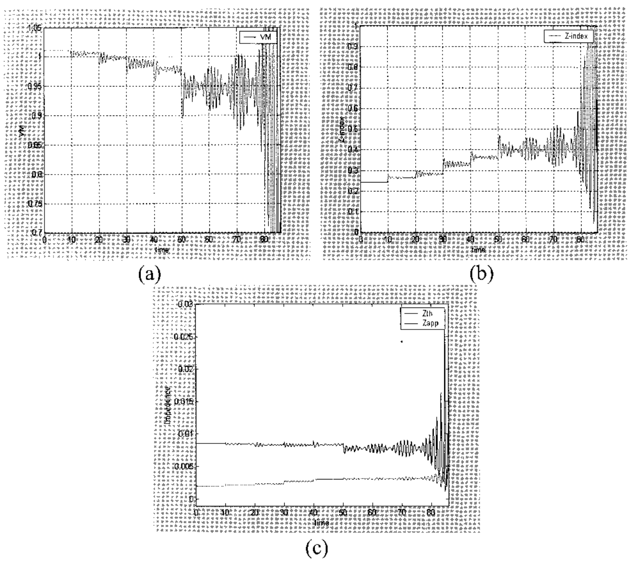


Fig. 5. (a)Voltage magnitude of Metropolitan Area (b) WAVI (c) Zth and Zapp on a contingency scenario.

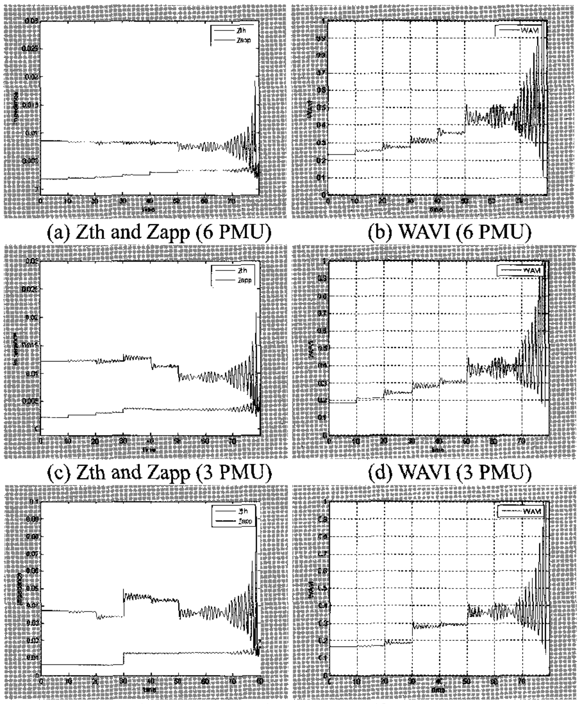
According to occurring contingencies, the voltage magnitude of the Metropolitan area decreases. At about t=88s, simulation is terminated because voltage collapse is occurring. Fig. 5(b) shows that WAVI increases as the lines are tripping and finally indicates 1.0 at about t=82s. Fig 5.(c) is the detail of WAVI (WAVI=Zth/Zapp). Zth goes up and Zapp goes down, indicating the system is going to become unstable. They then meet together at about t=82s, suggesting that WAVI equals 1.0 and the system is ultimately unstable. It is sufficient that WAVI is the index of voltage instability since it reacts to any contingencies and catches the voltage instability well.

3.2 Influence of the number of PMUs

PMU is expensive equipment and so its installation may be restricted. The optimum number of PMUs offering the best performance is 6, although this figure may be unrealistic due to available funds, environmental conditions, etc. Therefore, a compromise between accuracy and economy will be proposed, and the accuracy of the algorithm decreases when the number of PMUs decreases. Three set up scenarios are assumed and compared:

1. 6 PMUs (All 6 lines)
2. 3 PMUs (Hwasung-Asan line + 765kV lines)
3. 1 PMUs (Hwasung-Asan line)

Traditionally, voltage stability problems occur often in the Hwasung-Asan transmission line in the KEPCO system. Consequently, a PMU is installed on this line in scenario #3. There are two 765kV based lines in the KEPCO system, which flow a very large amount of power. Thus, the two PMUs are added on those lines in scenario #2. Six PMUs are set up on every six lines in scenario #1.



(a) Zth and Zapp (6 PMU) (b) WAVI (6 PMU)
(c) Zth and Zapp (3 PMU) (d) WAVI (3 PMU)
(e) Zth and Zapp (1 PMU) (f) WAVI (1 PMU)

Fig. 6. Zth, Zapp and WAVI depending on the number of installed PMUs.

Zth, Zapp and WAVI depending on the number of installed PMUs are described in Fig. 6. The WAVI shown in Figs. 6(b), (d) and (f) indicate 1 at the end of the simulation, so we can say that every WAVI can predict the voltage collapse well. However, it did not reflect the contingency scenario at 20s and 40s as shown in Fig.6(f), where It is not increasing. The Zapp should be decreasing according to a contingency, but it increases at 30s. Therefore, monitoring the voltage stability with only 1 PMU is not robust. Although the result of 3 installed PMUs is less accurate than the result of 6 installed PMUs, it is sufficiently available for detecting the voltage instability. As a result, installing 3 PMUs is a compromise between accuracy and economy if the number of PMUs is restrictive.

4. WAVI and PV MARGIN

To verify the WAVI, PV analysis is used as the PV-margin is well known as an off-line voltage stability index. If the PV-margin is small, the possibility that the system will suffer a voltage instability will increase. WAVI is also a voltage stability index, and if it approaches 1.0, the system will be unstable.

In order to compare the PV-margin and WAVI, practical contingency scenarios are used composed of 2-circuit line contingencies. Table 2 shows the contingency cases.

Table 2. Contingency Cases

#Case	From	To	CKT
1	Hwasung	Asan	1&2
2	Seoseoul	Cheongyang	1&2
3	Sinyongin	Sinjincheon	1&2
4	Kwangju	Sinjecheon	1&2

When performing the PV analysis, a transfer scenario consisting of the loads in the metropolitan area and generations in the non-metropolitan area are increasing. Fig. 7 shows the graph of PV curves, and margin is the amount of power at the maximum point minus the first-operating point. Base-case has the most PV margin, of course, and case #1 has the least PV margin. The Hwasung-Asan case (#1) must be the most severe case.

The WAVI is computed using the same contingency scenario. Total simulation time is 100 seconds and every contingency occurs at t=20s. Fig. 8 shows the WAVI of each case, which are all stable cases. Consequently, it does not meet 1.0. The WAVI seen in case #1 has the most value, and the WAVI also shows that the Hwasung-Asan case is the most unstable.

The PV-margin and WAVI actually offer different values, but it is clear that they can catch the severe contingency case. The PV-margin is already a well known index, and since the WAVI result is similar to the PV-margins', WAVI is also a good index to judge voltage stability.

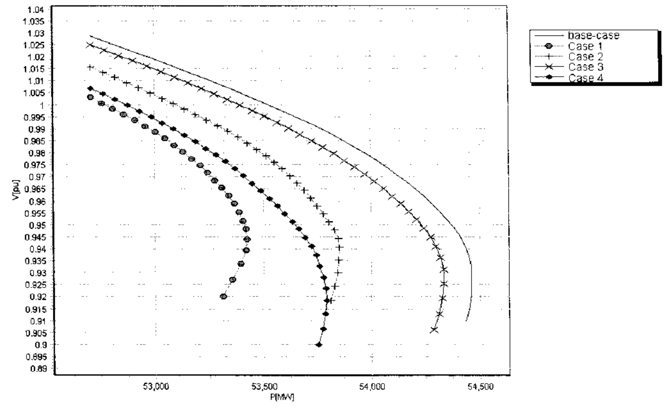


Fig. 7. PV curves with several contingencies.

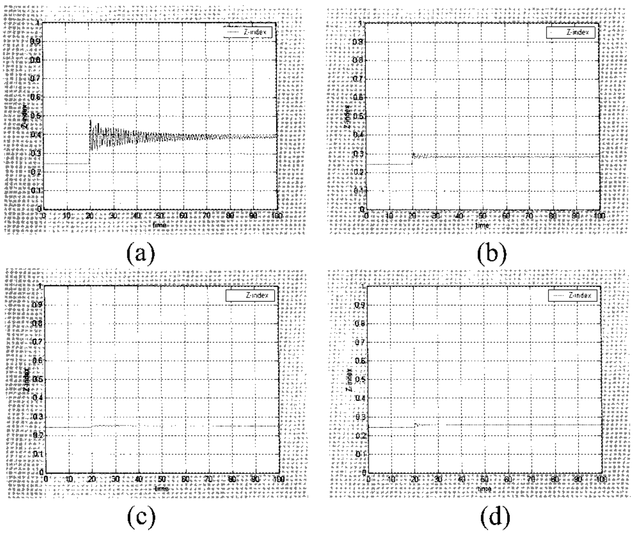


Fig. 8. WAVI (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4.

5. Conclusion

In this paper, we proposed a WAVI index suitable for the KEPCO system. As WAVI uses only PMU measurements without coupling with EMS data, it is computationally fast so can be applied to real-time situations.

WAVI uses similar methods to VIP's Zindex, and shows the value between 0.0~1.0 whether the system is stable or not. The WAVI equation is so simple it can be justified using just KCL and KVL. However, it is an issue when calculating the Zg, when we used the VIP method in order to derive the first Zg. We performed the VIP method using the virtual bus in the non-metropolitan area and obtained the first Zg.

Applying WAVI to the KEPCO system, we saw that WAVI could detect the voltage instability through the comparative study using the conventional PV margins. Consequently, a compromise between accuracy and economy are proposed. The optimal number of PMUs is 3. Although the result of 3 installed PMUs is less accurate than the results for 6 installed PMUs, it is sufficient to detect voltage instability.

It is still an issue deciding upon a location for the PMUs and to select the optimal algorithm monitoring voltage stability. KEPCO plans to eventually install 3 PMUs for voltage stability, a number that may be adjusted if the resources become available. The algorithm is also adjusted, and related research will be continue.

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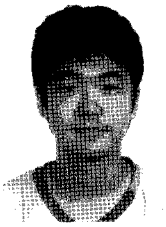

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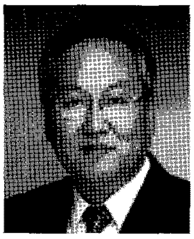

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