Development of a User-Friendly Application for Voltage Sag Analysis

Chang-Hyun Park*, Gilsoo Jang†, Chul-Hwan Kim and Jae-Chul Kim*****

Abstract - This paper presents a windows application for voltage sag analysis and effective data visualization. The developed Voltage Sag Analysis Tool (VSAT) was designed by using the Object-Oriented Programming (OOP) concept and C++ programming language. The VSAT provides basic functions for voltage sag analysis such as power flow analysis, short circuit analysis and stochastic analysis. In particular, the VSAT provides effective data visualization through computer graphics and animation. Analysis results are expressed realistically and intuitively on geographical display. The Graphic User Interface (GUI) of VSAT was designed specifically for voltage sag analysis. In this paper, the development and implementation of VSAT is presented. In order to demonstrate the capabilities of VSAT, it is used to analyze the Jeju Island power system in South Korea.

Keywords: Object-Oriented Programming (OOP), power quality, power system, visualization, voltage sags

1. Introduction

Voltage sag is one of the most important power quality problems affecting many industrial customers using sensitive equipments. Sensitive equipments at the customer site are damaged by momentary voltage sag due to remote faults in the utility system, and such damages can affect the entire process at the customer site. With rising production of sensitive equipments, production and financial losses due to sag are also increasing. Utilities have been faced with growing complaints about the supplied power quality due to voltage sags. Sensitive equipments can be impacted by faults in the remote transmission system as well as their own and adjacent circuits. Fig. 1 shows an example of the sag events that caused sensitive equipment failures for one customer [1].

An effective analysis tool that considers voltage sags both in transmission and distribution systems is needed. Basically, a sag analysis tool must provide functions, such as power flow analysis, short circuit analysis, and stochastic analysis. In power system analysis applications, effective visualization is as important as analytical ability. The developed Voltage Sag Analysis Tool (VSAT) has effective visualization schemes for analysis results as well as the above mentioned analytical functions. The VSAT displays analysis results on a geographical map for realistic and intuitive understanding. It provides visualization by windows Graphics Device Interface (GDI) and animation. The effective visualization can help power system engineers to understand analysis results and the state of a system. The VSAT utilizes the Information Technology Industry Council (ITIC) curves of sensitive equipments to determine areas of vulnerability.

The remaining sections of this paper are as follows. In Section 2, the background of the voltage sag problem is described and in Section 3, the structure and visualization schemes of VSAT are discussed. In Section 4, the Jeju Island power system in South Korea is analyzed by using VSAT. Finally, conclusions are made in Section 5.

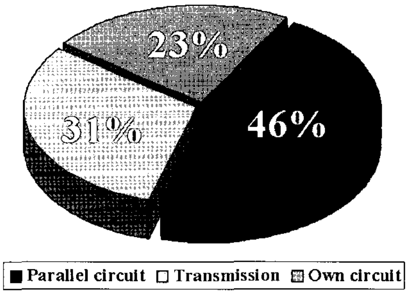

Fig. 1 An example of fault locations that caused misoperation of sensitive equipment

2. Voltage Sag Problem

2.1 Voltage Sag Characteristics and Area of Vulnerability

Voltage sag is a short-duration reduction in the root-

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mean-square (rms) voltage. In general, sag magnitudes range from 0.1 to 0.9 p.u. and durations from 0.5 cycles to 1 min. [1-4]. The important characteristics of voltage sags are magnitude and duration. The magnitude depends on fault type, pre-fault voltage, transformer connection, and fault impedance. The sag magnitude is rms voltage during a fault and is expressed in percent or per-unit. Generally, the magnitude is calculated by short circuit analysis.

The sag duration is determined by characteristics of system protection devices such as over current relays, circuit breakers and fuses. The clearing time for some commonly used protection devices and possible numbers of retries for automatic reclosing are listed in Table 1 [4]. The sag duration is calculated by adding the fault clearing time and the intentional time delay considering protection coordination.

Table 1 Typical fault clearing times

Type of fault-clearing device	Clearing time in cycle		
	Typical minimum	Typical time delay	Number of retries
Expulsion fuse	0.5	0.5 to 60	None
Current-limiting fuse	0.25 or less	0.25 to 6	None
Electronic recloser	3	1 to 30	0 to 4
Oil circuit breaker	5	1 to 60	0 to 4
SF6 or vacuum breaker	3 to 5	1 to 60	0 to 4

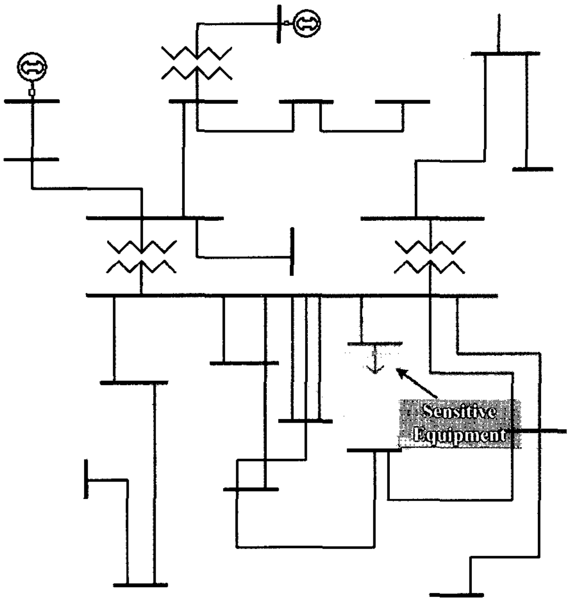


Fig. 2 Illustration of an area of vulnerability

Voltage sags also involve a phase angle shift during the fault. Some types of equipment are sensitive to phase angle jump as well as sag magnitude. The phase angle jump is defined as the abrupt changes of the phase angle between fault and pre-fault voltages.

Determining the area of vulnerability for sensitive load is significant for estimation of the expected number of voltage sags (i.e. sag frequency) from the utility system. The area of vulnerability is similar to the exposed area and "electrical neighborhood" addressed in [5, 6]. The concept of an area of vulnerability is useful to evaluate the likelihood of sensitive equipment being subjected to a voltage lower than its sensitivity threshold (i.e. voltage threshold) to voltage sags.

The voltage threshold is defined as the minimum voltage magnitude that a piece of equipment can withstand without misoperation or failure [1]. In general, an area of vulnerability containing the fault locations, which lead to sag voltage below the voltage threshold of sensitive equipment, is determined by short circuit analysis for many different points of lines and buses [2, 6]. Fig. 2 displays an example of the vulnerability area diagram for sensitive load at end-user facilities. It indicates that if the faults occur in the dark area, the sensitive equipment is damaged by voltage sags.

2.2 Power Acceptability Curve

Each device has singular sensitivity to voltage sag. For the estimation of sag impacts on each device, the sensitivity limit of the device should be determined. The ITIC and Computer Business Equipment Manufacturers Association (CBEMA) curves are useful for understanding equipment sensitivity limit for voltage sag. This limit is widely used to determine the acceptable magnitude and sag duration levels of sensitive equipment [7, 8]. The ITIC curve is the most recent version of the older CBEMA curve. Whether sensitive equipment will be impacted by sag can be determined by comparing the ITIC curve with the given voltage magnitude and duration. In this paper, the ITIC curves are used to establish the vulnerability and to verify the sag sensitivity limits of the equipments. Fig. 3 is an example of an ITIC curve for sensitive equipment. Fig. 3 tells us that if the voltage is under 0.5 p.u. for 100ms, this equipment will be impacted by sag.

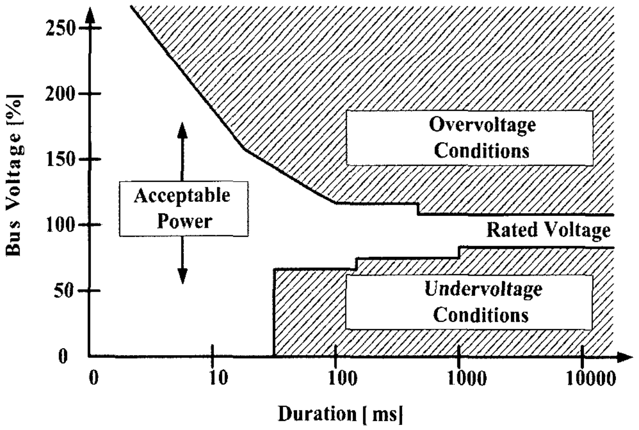


Fig. 3 An example of typical ITIC curve

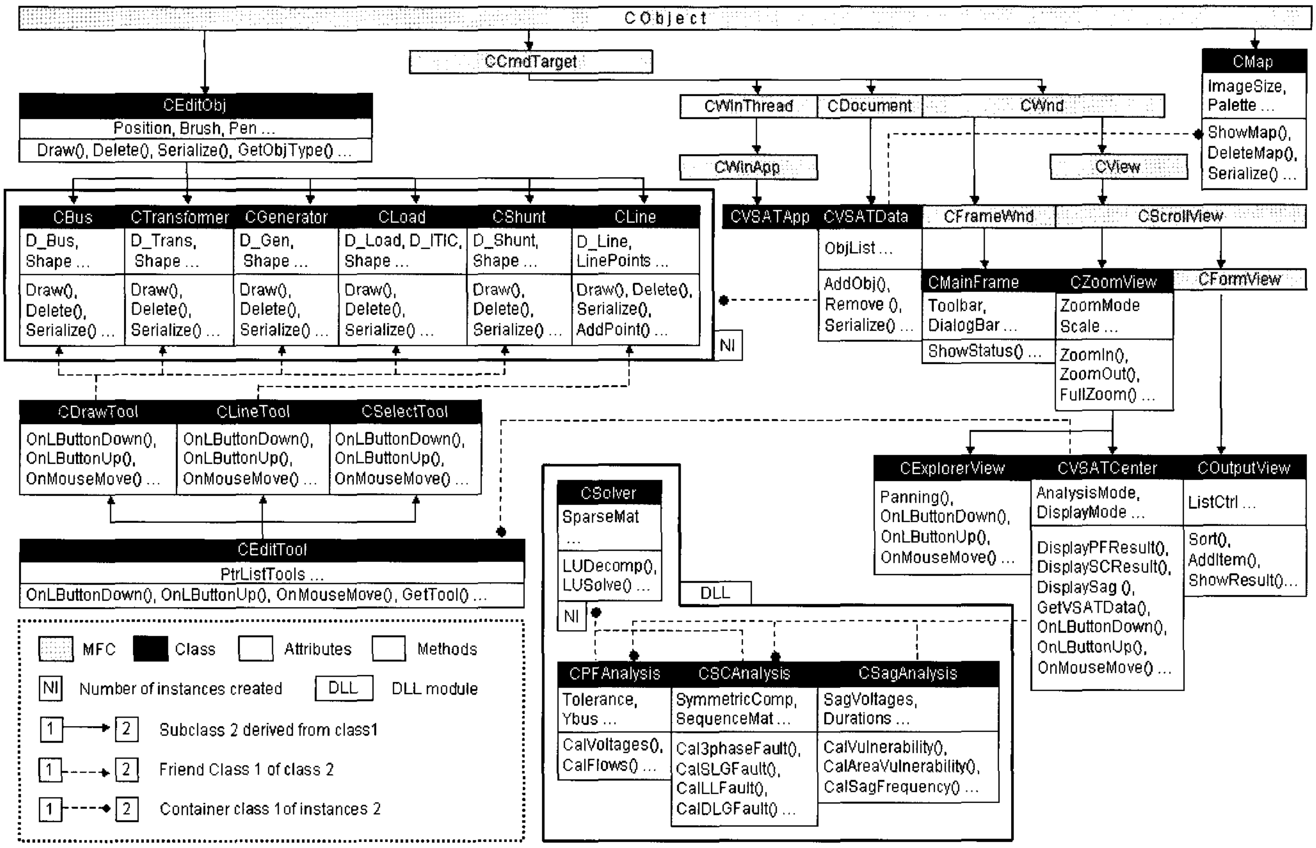


Fig. 4. Simplified class diagram of VSAT

3. Voltage Sag Analysis Tool

3.1 Object-Oriented Design and Graphical User Interface (GUI)

The developed VSAT is designed according to the OOP concept using C++ language. OOP has been accepted as a viable alternative to traditional procedural programming such as FORTRAN and C language. An OOP language like C++ has distinctive features such as class definition, operator overloading, encapsulation and inheritance [9-12]. To provide convenient GUI, the VSAT was developed using windows Application Programming Interface (API) and Microsoft Fundamental Classes (MFC) [13, 14] and compiled by using Microsoft Visual Studio Net. The MFC is a large library of C++ classes for development of windows based applications.

Each element of a power system was designed as a class for effective network editing and analysis as shown in Fig. 4. All analytical functions were also designed as classes and built into a Dynamic Linked Library (DLL). The class is the core of OOP and consists of attributes and methods. Fig. 4 displays the base attributes and methods of each class and simplified class hierarchy diagram of VSAT. All classes of network elements are derived from the base class *CEditObj*.

The *CEditObj* class has base attributes such as *Position*, *Brush* and *Pen* for elements drawing. It also has base methods such as *Draw()*, *Delete()*, and *Serialize()* functions. The *Serialize()* function is responsible for writing the class data members and reading them back from a file. Typically, a class supporting serialization is derived from the *CObject* class. Subclasses derived from *CEditObj* have their own additional attributes and methods for drawing and analysis. For example, the bus class *CBus* has a *D_Bus* structure and *Shape* as attributes and some virtual functions of *CEditObj*. The *D_Bus* structure comprises bus data such as bus number, name, type, and complex voltage, which are used for analysis. The *Shape* determines the drawing shape of buses such as vertical or horizontal bar, circle, and ellipse. The *CEditTool* class and its subclasses provide methods of various mouse events for editing a network using a mouse. The *CVSATData* class has functions for containing and managing all input data and map data for analysis and visualization. For easy insertion and deletion of network elements, we used a double linked list as the data structure for element instances [15, 16]. The *CVSATCenter* class provides process control and visualization methods.

The main window of VSAT is composed of the menu, toolbar, dialog bar, status bar, output window and explore window, as shown in Fig. 5.

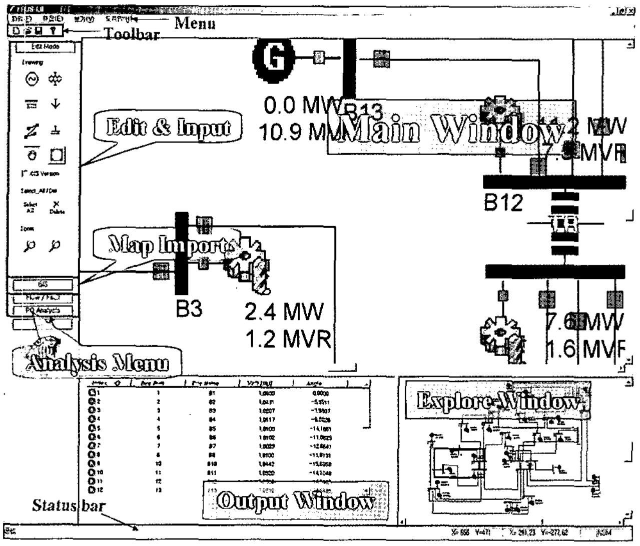


Fig. 5 Main window of VSAT

The developed VSAT is equipped with an easy interface for system edit. Users can edit a network freely using a mouse. The VSAT has two modes, the general mode and the map mode. In the general mode, buses are expressed as bar type like a typical single line diagram. In the map mode, buses can be expressed as an ellipse or various different shapes on a map. Other elements also have suitable shapes, as indicated in Fig. 6. In the map mode, a network is built up on a map in accordance with the actual locations of network elements, as can be seen in Fig. 6. The VSAT provides easy interface to import an image map file which is in BMP or JPEG format. The geographical map and system data are saved as one file by using the *Serialize()* function of MFC.

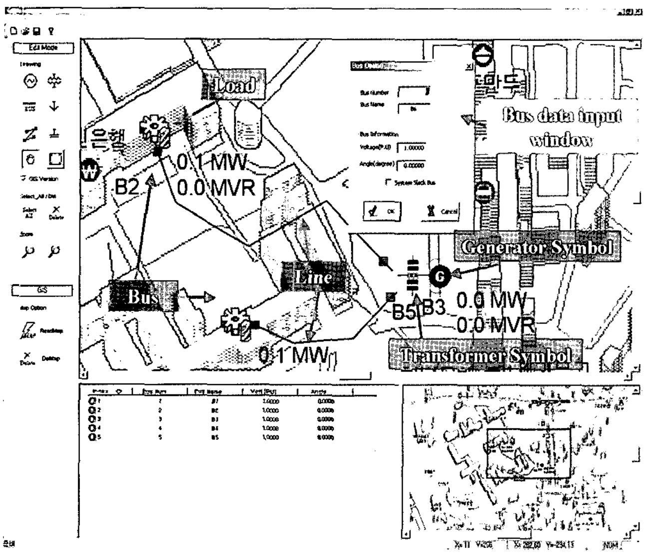


Fig. 6 Symbols of power system elements and network edit on a map

3.2 Structure of VSAT

The developed VSAT is composed of four main modules as shown in Fig. 7.

1) Data input and edit module: the VSAT provides a convenient interface for data input and network edit. Users can edit a network freely using a mouse inputting system data, map data, reliability data, and load sensitivity through various input windows. The VSAT uses the ITIC curves as the load sensitivity data. In order to calculate the sag frequency, the reliability data such as failure rate of power system elements is required. The failure rate is expressed in faults per km per year.

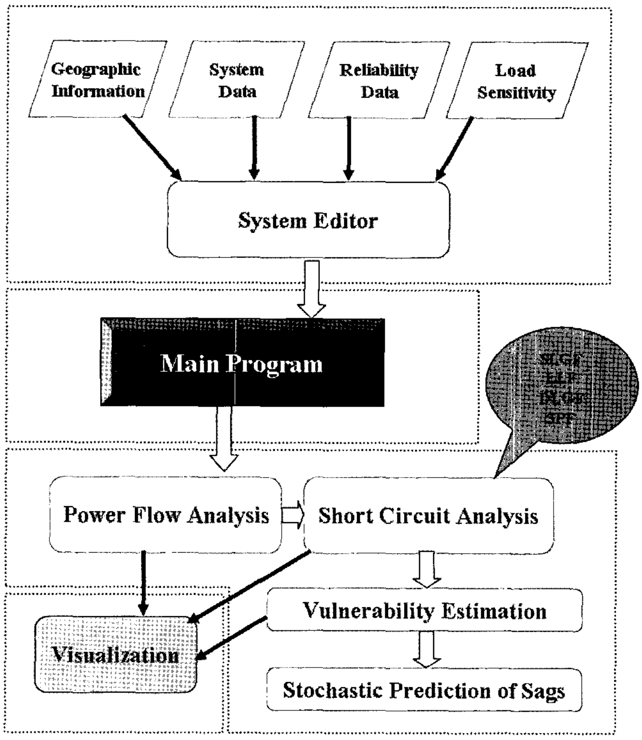


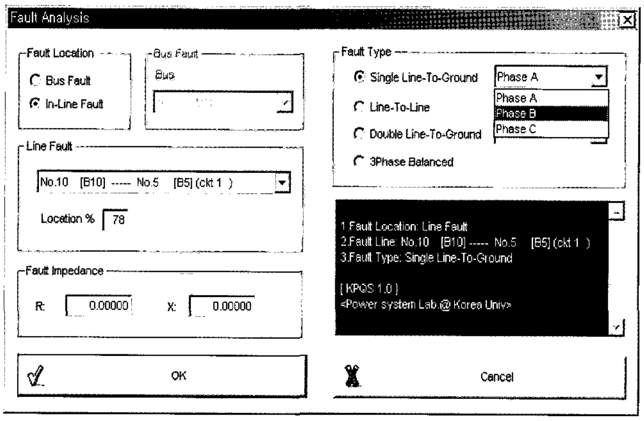
Fig. 7 Structure and process flow of VSAT

2) Main program: this module provides convenient GUI and the mainframe of the VSAT. It has functions to connect other modules and to compile input data for analysis.

3) Analysis module: this module has analytical functions such as power flow analysis, short circuit analysis, determination of the area of vulnerability for sensitive loads, and estimation of the sag frequency. In order to know pre-fault voltages, power flow analysis is required. Here, the short circuit analysis module can calculate fault currents as well as all bus voltages for single line-to-ground

(SLGF), line-to-line (LLF), double line-to-ground (DLGF) and three-phase (3PF) faults. Fault options are inputted by using the dialog box as displayed in Fig. 8.

Whether sensitive loads will be impacted by simulated faults can be determined by comparing the fault analysis results with the sensitivity thresholds. The vulnerability analysis module of VSAT can identify the sensitive loads, which are damaged by voltage sag due to simulated faults. Additionally, for stochastic prediction, the VSAT can determine the area of vulnerability for sensitive loads. Generally, the sag frequency is calculated by multiplying the failure rate of system elements included in the area of vulnerability by total exposure length in km.


Fault Analysis

Fault Location
○ Bus Fault
● In-Line Fault

Bus Fault
Bus

Line Fault
No.10 [B10] ----- No.5 [B5] (ckt 1)
Location % 78

Fault Impedance
R: 0.00000 X: 0.00000

Fault Type
● Single Line-To-Ground Phase A
○ Line-To-Line
○ Double Line-To-Ground
○ 3Phase Balanced

Phase A
Phase B
Phase C

1.Fault Location: Line Fault
2.Fault Line: No.10 [B10] ----- No.5 [B5] (ckt 1)
3.Fault Type: Single Line-To-Ground

[KPQS 1.0]
<Power system Lab.@ Korea Univ>

Fig. 8 Dialog box for fault options input

4) Visualization module: this module provides visualization of power flow, short circuit and vulnerability results on a geographical map by using windows GDI and animation.

3.3 Visualization Schemes

The effective visualization of analysis results can help power system engineers and operators to understand the state of a system. Expressing analysis results easily and exactly for quick understanding is the most important point of data visualization. Visualization schemes for each analysis are as follows.

1) Power flow analysis: bus voltages are expressed by changes of color according to voltage level as shown in Fig. 9. The voltage distribution in a system can be easily understood from the color of the buses. Numerical results such as voltage magnitudes, phase angles and power flows are indicated in the output window and pop-up window. Power flows are expressed by arrows moving along in lines to portray flows realistically. The size and color of the arrow indicates the degree of power flow and MVA loading respectively.

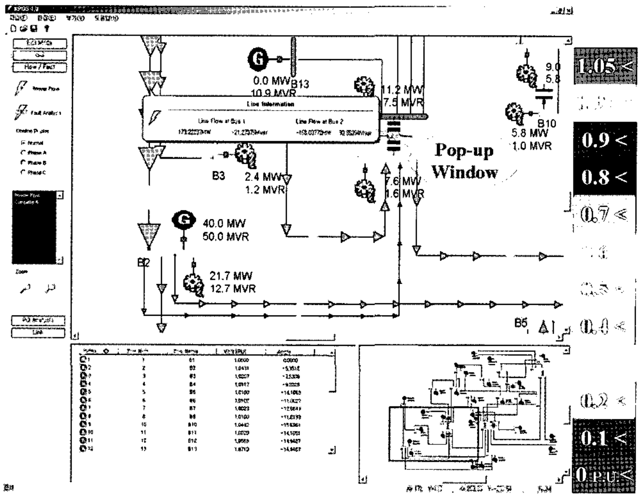


Fig. 9 Power flow analysis results visualization: general mode

2) Short circuit analysis: fault voltages are expressed by bus color changes according to the voltage level as presented in Fig. 10. Different colors according to the sag level are helpful to recognize the result intuitively. Each of the phase fault voltages are expressed separately by clicking a radio button on the dialog bar. Numerical results such as fault voltages, phase angle jumps and fault currents are shown in the output window. Users can also see these numerical results through pop-up windows after clicking on each network element.

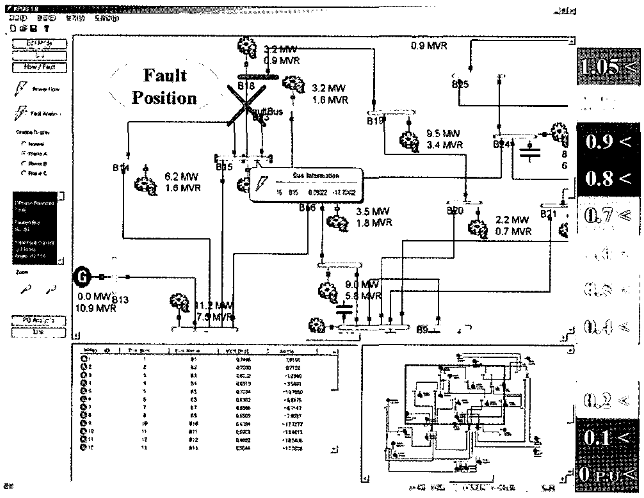


Fig. 10 Short circuit analysis results visualization: general mode

3) Vulnerability analysis: the vulnerability to voltage sag at the sensitive load site is determined by comparing the fault analysis results with the load

sensitivity data. If the fault voltage is less than the sensitivity threshold, the sensitive load will be damaged by the voltage sags. Damaged load buses are expressed by a twinkling bus symbol displaying fault analysis results. Fault voltage levels and sensitive loads that are impacted by faults can be obtained simultaneously. The area of vulnerability for sensitive loads is expressed by a red color as shown in Fig. 11. Visualizing the area of vulnerability on a geographical map is helpful to recognize the actual size and shape of the area. The effective visualization schemes are useful for easy and quick understanding of voltage sag analysis results.

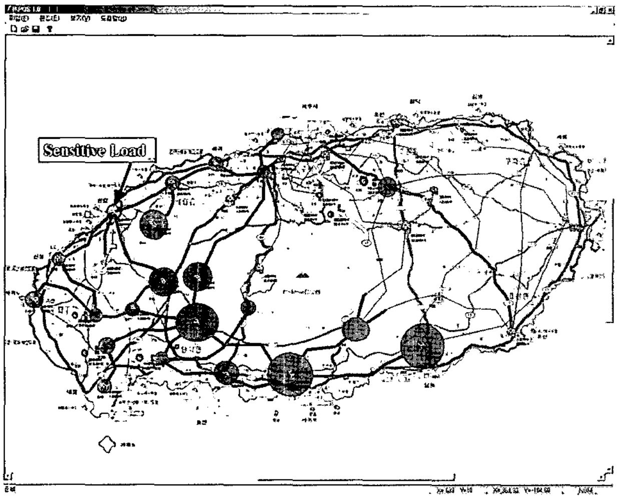


Fig. 11 Area of vulnerability visualization: map mode

4. Simulations

The system studied in this paper is the modified version of the Jeju Island power system in South Korea as shown in Fig. 12. Fifty buses and 25 sensitive loads are comprised in this system. After importing the map of Jeju Island, the system was implemented onto the map using the editor. Fig. 12 indicates the power flow analysis results. We can find that the bus voltage levels and power flows in the network easily from color of buses and moving arrows.

Using the VSAT, two cases of faults in the Jeju system were simulated, and sensitive loads impacted by simulated faults were identified. Additionally, an area of vulnerability due to the balanced three-phase faults for bus 29 was determined. Fault impedances were assumed to be zero in all cases. Criterions of each case study are shown in Table 2.

Table 2. Criterions of simulation cases

Case	Fault Type	Fault Location	
1	Balanced 3-Phase	Bus fault	Bus 5
2	Single line-to-ground	Line fault	50% point between Bus 29 and 31

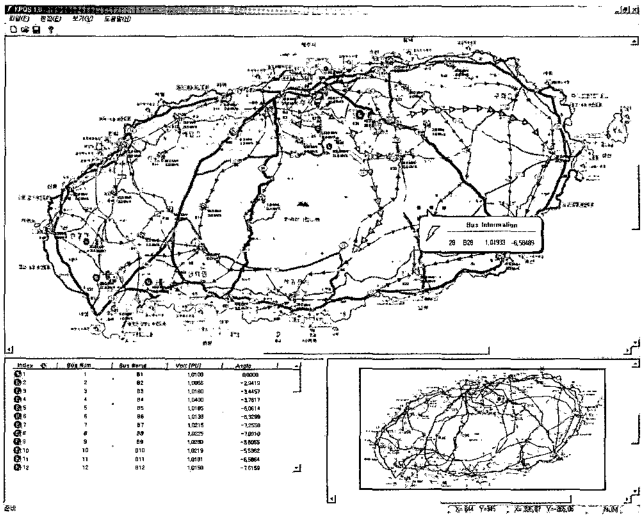


Fig. 12 The modified Jeju Island power system for simulation

1) Evaluation of vulnerability due to balanced three-phase fault

A balanced three-phase fault at bus 5 was simulated, and the result is presented in Fig. 13. The bus color represents the degree of the fault voltages. We can find that the fault voltages of buses range from 0 to 0.6 p.u. from Fig. 13. Sensitive loads, which are impacted by sag, are expressed by twinkling bus symbols showing fault analysis results. In this case, the result indicated that 20 sensitive loads are impacted by sag. The levels of fault voltage and sensitive loads impacted by faults can be identified simultaneously.

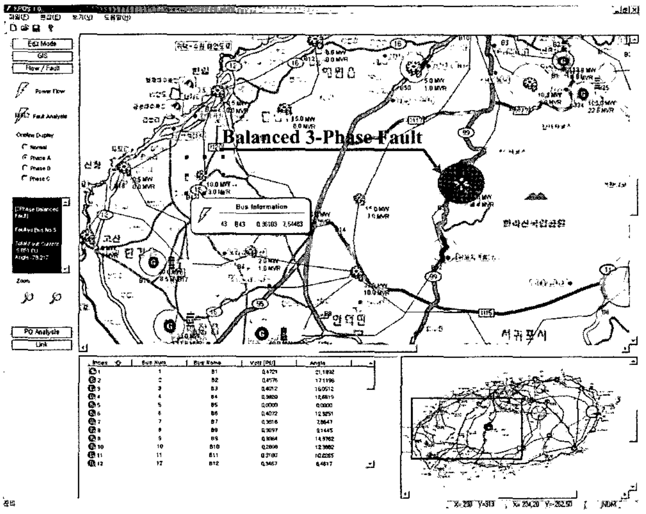


Fig. 13 Results visualization of the balanced 3-phase fault at bus 5

2) Evaluation of vulnerability due to single line-to-ground fault

An SLGF at the halfway point in a line between bus 29 and bus 31 was simulated, and the result is shown in Fig. 14. The fault phase was assumed to be phase A. Fig. 14

shows the levels of fault voltage and sensitive loads impacted by fault. We can find that the fault voltages of buses range from 0.1 to 0.7 p.u. easily from the color of the buses. In this case, the result indicated that 17 sensitive loads were impacted by sag.

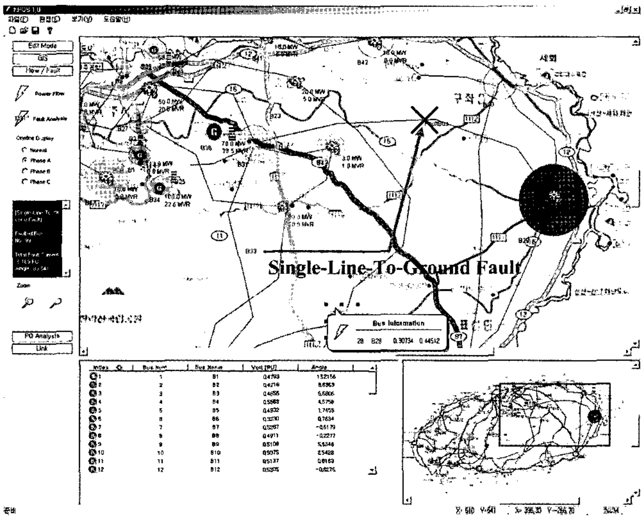
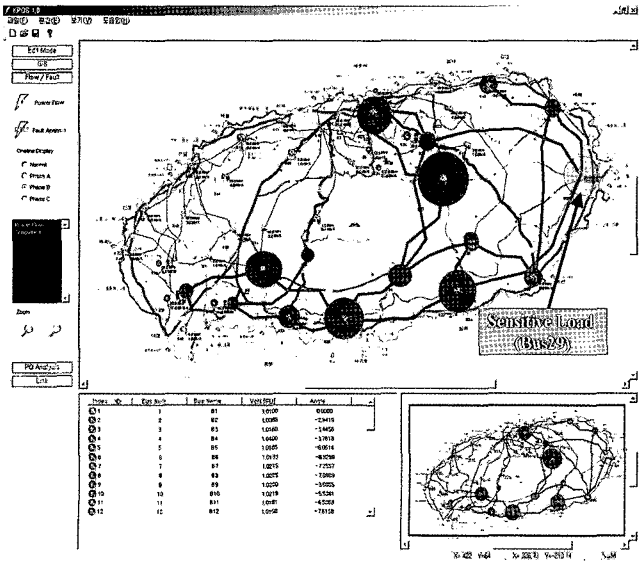


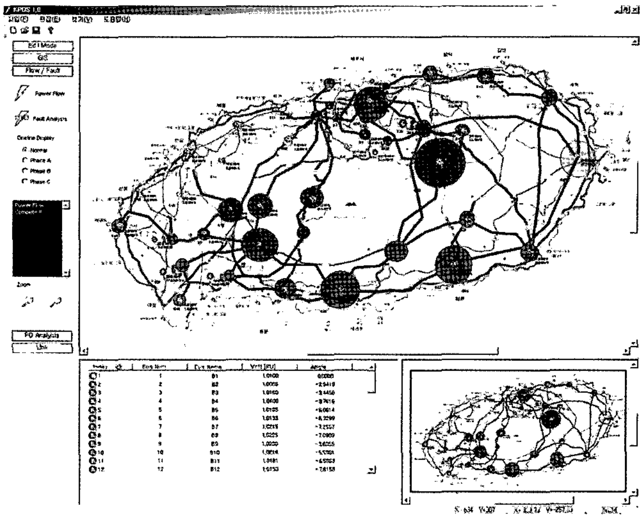
Fig. 14 Results visualization of the SLGF at the halfway point in a line between bus 29 and bus 31

3) Determination of an area of vulnerability due to faults

An area of vulnerability due to the balanced three-phase faults for bus 29 was determined. Fig. 15 (a) and (b) show the area of vulnerability for bus 29 with the voltage thresholds of 0.3 p.u. and 0.55 p.u. respectively. If the three-phase faults occur in the red area, sensitive loads at bus 29 will be damaged by voltage sags. As expected, the area of vulnerability determined using the voltage threshold of 0.55 p.u. is larger than the area using the threshold of 0.3 p.u.



(a)



(b)

Fig. 15 (a) Area of vulnerability due to the balanced 3-phase faults for bus 29 with 0.3 p.u. voltage threshold (b) Area of vulnerability for bus 29 with 0.55 p.u. voltage threshold

5. Conclusion

This paper presented a user-friendly windows application for the voltage sag analysis. The effective visualization of analysis results is as important as analytical abilities. The developed VSAT has effective visualization functions for intuitive understanding as well as voltage sag analysis functions such as power flow analysis, short circuit analysis and stochastic analysis. Analysis results are visualized realistically and intuitively on a geographical map. The VSAT provided various convenient GUIs for system edit and voltage sag analysis. In order to determine the areas of vulnerability for sensitive loads, the ITIC curves are used as sensitivity thresholds to voltage sags. The simulation of the Jeju power system clearly indicated that the developed visualization functions are helpful to understand analysis results. The proposed VSAT can be used for optimal power system design considering voltage sags mitigation.

Acknowledgements

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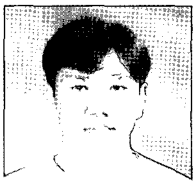

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