

A METHOD TO DETERMINE THE RELATIVE LOCATION OF VOLTAGE SAG SOURCE FOR POWER QUALITY DIAGNOSIS

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Abstract: Event source locating is very important to improve the power quality level. And it is a helpful way to find the location of the power quality event source to determine the direction of event at each monitor. This paper presents a method to determine the relative location of the source of voltage sag. For this, the relative location of the source is defined first. Then, the main causes of voltage sag are classified and their characteristics are discussed, respectively. From these investigations, the rules to determine the relative location of event source for each cause are proposed and the overall algorithm to identify the relative location and the kind of event source is organized. Finally, the proposed method is applied to the IEEE 13bus test system and it is verified that the method can be helpful to pinpoint the accurate location of the event source. *Copyright © 2005 IFAC*

Keywords: diagnosis, events, fault location, monitoring, power systems, quality

1. INTRODUCTION

It is important to identify the source of disturbance to improve power quality. Event source identification consists of event source locating and event source kind identification. For event source locating, the event direction must be identified before. Direction finding method has been proposed in (Parsons, *et al.*, 1998, 1999, 2000). These studies used the concept of disturbance energy and dealt with voltage variation and capacitor switching, but they have not considered the kind of event source in event direction identification. However, because the direction of event can be identified by different ways according to the kind of event source, the kind of event cause must be considered to the identification of the direction of event.

Voltage sag is a short duration reduction in the RMS voltage due to the short circuits, overloads or starting of large motors. The interests in voltage sags are increasing because they cause the detrimental effects on several sensitive equipments. There are far more voltage sags than interruptions and the total damage is still larger (Bollen, 2000). For these reasons, it is important to find the location of the source of sag accurately.

This paper presents a method that can determine the relative location of voltage sag source according to

the cause of event. First, the definition of the relative location of event source at a monitor is stated and then, the relation between the relative location and the cause of voltage sag is investigated. And the rules to determine the relative location are proposed for each cause. Finally, the overall algorithm to identify the relative location and kind of event source is constructed and a simple example is illustrated.

2. FUNCTIONS OF POWER QUALITY MONITORING AND DIAGNOSIS

Power quality data management system consists of three major components like PQMS, GUI system, and PQ diagnosis system (Chung, *et al.*, 2003). PQMS evaluates power quality trends and detects power quality events after it analyzes the sampled voltage and current obtained from power line. The power quality data made by PQMS are transferred to GUI system through network line. GUI system receives the data from several PQMSs and stores the data to suitable database. In addition, GUI system shows the event data, trend data, and waveform on monitor screen and alerts event happening. The data in the database are used as the input of PQ diagnosis system. PQ diagnosis system is offered as an optional function of GUI system. Therefore, when this system is installed, PQ diagnosis menus are added and activated to main menus of GUI software. This

system makes a diagnosis of power quality in many ways such as predicting probability of event, identifying event cause and location, proposing counter measures, and so forth.

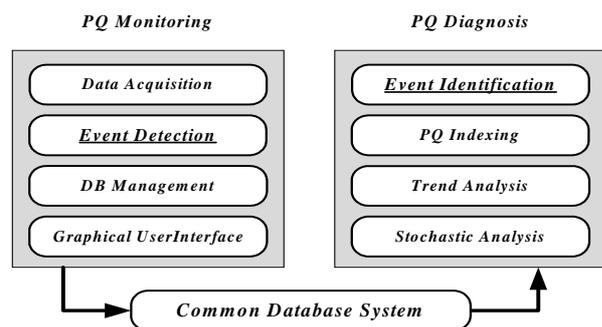


Fig. 1. Functions of power quality monitoring and diagnosis

2.1 Power Quality Monitoring

Power quality monitoring has four main functions as shown in Fig. 1. At data acquisition, the line voltage and currents are measured, sampled and converted to digital signals. From the measured data, the basic characteristics such as RMS value of voltage and current, harmonic contents and frequency are calculated. The basic characteristics are analyzed and power quality events are detected. Each time the event is detected, event data are stored in the database and displayed in the GUI. Each event data consists of event duration, event kind, start time, end time, mean value, and min or max value of RMS voltage or current. Event direction, key information for the event source location identification, is added to the event data for some power quality events such as voltage sag, interruption and harmonic event.

2.2 Power Quality Diagnosis

Main functions of diagnosis are event trend diagnosis, stochastic analysis, power quality indexing, and event identification as shown in Fig. 1. As above-mentioned, the input of diagnosis system is the database that stores power quality event data.

Event trend diagnosis function consists of hourly plot, weekly plot, monthly plot and time plot. These plots show the trend of events according to time, weekday, and month, respectively. With these plots, customers are assisted to identify the main cause of PQ events. Additionally, customers can modify the patterns of the power consumption to improve the PQ level of their site. Stochastic diagnosis function proffers standard charts, voltage event graph, and harmonic event graph. CBEMA, ITIC, and SEMI charts are generally used as the standard of voltage supplied to computer based devices or semiconductor manufacturing equipments. To evaluate PQ level, a number of PQ indices have been developed. PQ indices can quantify complicated PQ problems and help customers understand PQ level simply. Event identification function has three categories as

illustrated in Fig. 2.

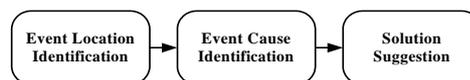


Fig. 2. The categories of event identification

Event location identification that is to find the position of event source is very important to solve PQ problems because this function makes it possible to remove the faults rapidly and to find more suitable compensating method. To identify event location, PQ diagnosis system uses the event direction data generated by PQMSs that are stored in database and system configuration data. The more PQMSs are installed in the local system, the more exact location can be obtained. Event source identification is also significant because this function gives the solution of improving PQ level. PQ diagnosis system suggests the various solutions to improve PQ level like the sort and rating of various PQ compensating devices. This system helps users compare the PQ compensating devices and select the best way they can use.

3. DEFINITION OF UP/DOWN AREA

If a monitor is installed in power system, the monitor can identify the relative location of event source. In other words, the monitor can determine whether the event has come from up area or down area. The relative location of event source is classified into *UP* area and *DOWN* area.

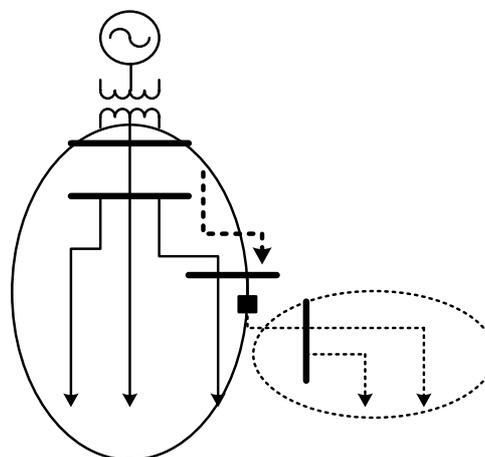


Fig. 3. Definition of *UP* area and *DOWN* area considering monitor location

The determination of relative location of event source is closely related to the flow of electric energy at the monitor. The components of the system can be divided into three different sections according to the energy flow. One of them is the section through which the energy flows into the monitor like L_1 and L_5 . Another is the section to which the energy flows from the monitor like L_6 , L_7 , and L_8 . The other is the section which has nothing to do with the energy flow at the monitor like L_2 , L_3 , and L_4 . These three sections can be classified into two areas again as shown in Fig. 3.

The **DOWN** area is named as **DOWN** in the facts that the area is located at downward side of the monitor in view of energy flow. On the other hand, the **UP** area is defined as **UP** in the fact that the area is the path located at upward side in view of energy flow from source. The **UP** area also includes the sections which are not related to the energy flow at the monitor.

4. RULES TO DETERMINE THE RELATIVE LOCATION FOR EACH CAUSE

Many papers such as (Bollen, 2001; Gomez and Morcos, 2002) have stated that voltage sag happens when high inrush current flows in the power system. This inrush current results in large voltage drop in the system and the event origin act as an energy sink (Parsons, *et al.*, 1999, 2000). These inrush currents mainly happen when the line experiences a short circuit. Besides, when a large induction motor starts to operate or a transformer is saturated, they absorb high inrush current (Bollen, 1995; Bollen and Dirix, 1996; Bollen, *et al.*, 2003). Therefore these three events are classified as the cause of voltage sag and their characteristics will be discussed.

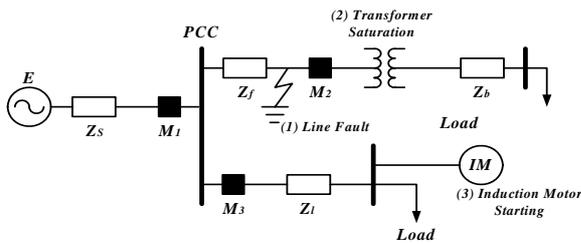


Fig. 4. Example system to find the rules to determine the relative location

Simple example system as shown in Fig. 4 is constructed using the PSCAD/EMTDCTM. In the example system, three different events are simulated to investigate the relation between the relative location and the cause of voltage sag. From the investigations, the rules to determine the relative location of voltage sag are proposed for each cause.

4.1 Line faults

Once the line is short-circuited for various reasons, the impedance at the fault location becomes low. A large fault current flows through the path from source to fault, so the voltage drops in the vicinity of the fault location. The waveform due to line fault can be characterized as sharp drop and rise compared to other causes (Styvaktakis, *et al.*, 2002). This rectangular property due to line fault will be used for identification of the relative location and the cause of event. Because the impedance at the fault location becomes low, the energy converges into the fault location. Therefore a large fault current flows through the path from source to fault location. Using these characteristics, the direction of line fault event can be identified.

The difference of current magnitude before and during line fault is critical factor to determine the relative location. The ratio of current at the monitor that detects **DOWN** event is definitely discriminated from others. Using this result, the relative location of event source can be determined as follows.

$$\begin{cases} \text{DOWN} & \text{if } \frac{I_{sag}^1}{I_{ss}^1} \geq Thr_{LF} \\ \text{UP} & \text{if } \frac{I_{sag}^1}{I_{ss}^1} < Thr_{LF} \end{cases} \quad (1)$$

where,

I_{ss}^1 : fundamental frequency component of the current before line fault

I_{sag}^1 : fundamental frequency component of the current during line fault

Thr_{LF} : threshold of the ratio I_{sag}^1 / I_{ss}^1

If the ratio exceeds the threshold, the event is determined as a **DOWN** event. On the contrary, if the ratio is under the threshold, **UP** event is determined. Because the magnitude of fault current differs according to the system strength and fault impedance, the threshold Thr_{LF} may also differ. Therefore Thr_{LF} must be carefully tuned considering these parameters.

4.2 Induction motor starting

When a motor starts, inrush current which is 5~10 times of rational current is absorbed into the motor and it lasts until the motor reaches steady state. The occurrence of inrush current makes the motor as an energy sink. Therefore the voltage drops and voltage sag happens. The waveform at PCC during induction motor starting has a sharp drop but voltage recovers gradually, which is the main difference compared to the line fault. It is because the inrush current disappears slowly. The voltage waveform is balanced for the induction motor is a kind of balanced load. This property differentiates the induction motor starting from transformer saturation.

In case of induction motor starting, the magnitude of inrush current is not so large compared to the fault current during line fault and it decays exponentially. Therefore the ratio of current used in case of line fault cannot be utilized here. The main characteristic, in this case, is that the active power of the monitors which detect the **DOWN** event reaches a new steady state with increasing value. It is because the induction motor is a kind of load and the starting of induction motor acts as an increase of load. Therefore the difference of active power before and after induction motor starting can be used to determine the relative location in case of induction motor starting.

$$\left\{ \begin{array}{ll} \text{DOWN} & \text{if } \frac{P_{post} - P_{pre}}{P_{pre}} \geq Thr_{im} \\ \text{UP} & \text{if } \frac{P_{post} - P_{pre}}{P_{pre}} < Thr_{im} \end{array} \right. \quad (2)$$

where,

P_{pre} : steady state active power before induction motor starting

P_{post} : steady state active power after induction motor starting

Thr_{LF} : threshold of the ratio $(P_{post} - P_{pre})/P_{pre}$

In case of the sag due to the starting of induction motor, the ratio $(P_{post} - P_{pre})/P_{pre}$ is used in (2) instead of P_{post}/P_{pre} . If the ratio exceeds the threshold, the event is thought as a **DOWN** event. Otherwise, **UP** event is determined. Because the increase in active power differs according to the system loads and induction motor kind and rating, the threshold Thr_{im} may also vary. Therefore Thr_{im} must be carefully tuned considering the system loads of the site where the monitor is installed and the motor rating.

4.3 Transformer saturation

When the transformer is energized or the transformer voltage changes transient flux happens in the core of transformer. In most cases, these transient flux exceed the saturation value. This temporary over-fluxing of transformer results in a high magnetizing current. It is called '*magnetizing inrush current*' and the magnitude of magnetizing inrush current is determined by the time of switching and residual flux (Bhattacharya, *et al.*, 2001; Smith, *et al.*, 1999; Paul, *et al.*, 1988). The waveform is somewhat similar with that of induction motor starting. It has a sharp drop and slow rise in RMS voltage. However, transformer saturation is different from induction motor starting in that the three phase voltages are not balanced and the waveform has much harmonic contents.

The characteristics at the monitors that detect **DOWN** event have been summarized as the increase in the current of fundamental frequency and the existence of harmonic contents. However, the magnitude of inrush current at the monitor that detects **DOWN** event is not so large compared to the fault current during line fault. It is because the current increase rapidly and restore gradually. Therefore the more delicate ratio should be used to determine the direction of transformer saturation event.

Another characteristic that discriminates transformer saturation event from others is the existence of harmonic contents during the event. When the sag is caused by the transformer saturation, THD (Total Harmonic Distortion) in the current is increasing. Especially, second order harmonic is relatively large

in this case (Bronzeado, *et al.*, 1996). The magnitude of second order harmonic grows rapidly in the beginning of event. It reaches up to 30%~50% of total harmonic contents. Therefore this characteristic can be utilized to identify the transformer saturation event.

$$\left\{ \begin{array}{ll} \text{Transformer saturation} & \text{if } \frac{\Delta I_2}{\sum_{h=2}^7 \Delta I_h} \geq Thr_H \\ \text{Other causes} & \text{if } \frac{\Delta I_2}{\sum_{h=2}^7 \Delta I_h} < Thr_H \end{array} \right. \quad (3)$$

where,

h : order of harmonic contents

ΔI_h : change of harmonic current whose order is h

Thr_H : threshold of the ratio $\Delta I_2 / \sum_{h=2}^7 \Delta I_h$

After the cause of event is identified as transformer saturation by (3), the relative location is identified next. The rule is similar to that of line fault except that the threshold Thr_{TR} is adapted to the system including transformer.

$$\left\{ \begin{array}{ll} \text{DOWN} & \text{if } \frac{I_{ss}^I}{I_{ss}^I} \geq Thr_{tr} \\ \text{UP} & \text{if } \frac{I_{sag}^I}{I_{ss}^I} < Thr_{tr} \end{array} \right. \quad (4)$$

where,

I_{ss}^I : fundamental frequency component of the current before transformer saturation

I_{sag}^I : fundamental frequency component of the current during sag caused by the transformer saturation

Thr_{TR} : threshold of the ratio I_{sag}^I / I_{ss}^I in transformer saturation event

5. OVERALL ALGORITHM TO DETERMINE THE RELATIVE LOCATION AND THE CAUSE OF EVENT

In the previous section, methods to determine the relative location for each cause of voltage sag are discussed. From each method, only one method must be applied to identify the relative location. Therefore the event cause identification must be performed before the determination of the relative location. Because the decision rules are based on the characteristics of **DOWN** event, **DOWN** event is identified first. **UP** event is identified as the event that is not **DOWN** event.

The overall algorithm is as shown in Fig. 5. Following the algorithm, the cause of event source is identified first. And according to these causes, appropriate rule to determine the direction is applied. In this manner, the cause of event can be identified as well as the relative location. It will be very useful to

pinpoint the location of event source in the whole system.

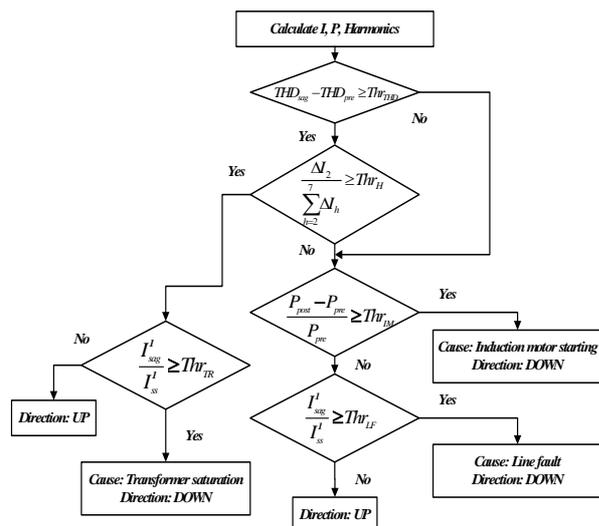


Fig. 5. Algorithm to identify the direction and cause of event source

6. CASE STUDY

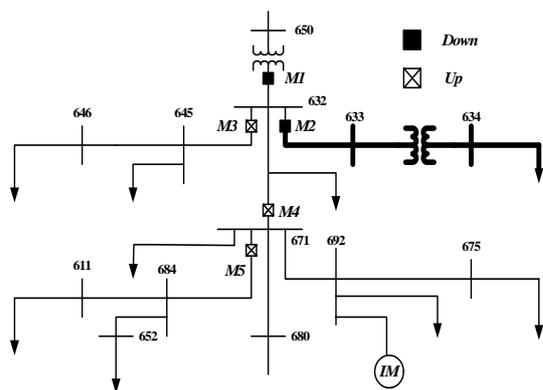


Fig. 6. Schematics of IEEE 13 bus test system

Fig. 6 shows the schematics of IEEE 13 bus test system. The system is constructed using PSCAD/EMTDC™ and the data are collected from the five monitors as shown in Fig. 6.

In the test system, the energizing of the transformer between bus #633 and bus #634 is simulated. As shown in Fig. 7, three phase voltages drop unequally and voltage sag occurs only in phase A. Therefore the direction identification is performed only in phase A.

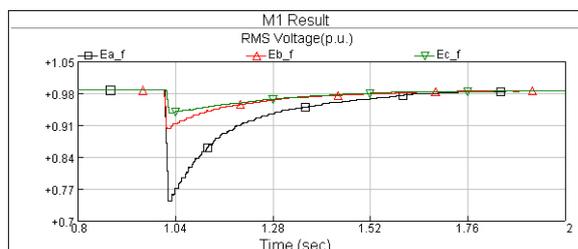


Fig. 7. Voltage Profile at M1 during the voltage sag due to the transformer saturation

The thresholds used in this case and the results are summarized in Table 1 ~ Table 4.

Table 1. Thresholds used in this case

Thr_{LF}	Thr_{IM}	Thr_{TR}	Thr_H	Thr_{THD}
3.0	0.1	1.2	0.3	0.1

Table 2. THD at each monitor

Monitor	ΔTHD	$\Delta I_2 / \sum_{h=2}^7 \Delta I_h$	Result
M1	0.236	0.556	Cause_TR = 1
M2	0.503	0.533	Cause_TR = 1
M3	0.136	0.481	Cause_TR = 1
M4	0.102	0.183	Cause_TR = 0
M5	0.106	0.188	Cause_TR = 0

Cause_TR = 1 : Cause is transformer saturation

Cause_TR = 0 : Another causes

Table 3. Active power at each monitor

Monit or	P_{pre}	P_{post}	$\Delta P / P_{pre}$ (%)	Result
M4	1.008	1.008	-0.012	<i>Down_IM</i> = 0
M5	0.78	0.784	0.104	<i>Down_IM</i> = 0

Down_IM = 1 : Cause is Induction motor starting and the direction is **DOWN**

Down_IM = 0 : Cause is not Induction motor starting or the direction is **UP**

Table 4. Current at each monitor

Monitor	I_{sag}^1 / I_{ss}^1	Result
M1	1.364	DOWN , Cause = TR
M2	6.774	DOWN , Cause = TR
M3	0.766	UP
M4	0.979	UP
M5	0.991	UP

From Table 2, at M1, M2, and M3 it is decided that the voltage sag is caused by the transformer saturation. Therefore, in these monitors the current ratio is calculated and the direction is determined using the threshold Thr_{TR} . On the contrary, at M4 and M5, it is thought that the sag is not caused by the transformer saturation because the portion of second harmonic contents does not exceed the threshold Thr_H . These results arise because the fault location is far from M4 and M5 and is not in the **DOWN** area of these monitors. However, in this algorithm, the cause at the monitors that detect **UP** events is not important. In case of M4 and M5, the active power variation is calculated and the results are listed in Table 3. Because the increase is smaller than the threshold Thr_{IM} , the current ratio is calculated and the direction is determined based on the threshold Thr_{LF} .

The final results are listed in Table 4 and Figure 6. At M1 and M2 it is concluded that the voltage sag is occurred by the transformer saturation and the direction is **DOWN**. And the direction at the other monitors is determined as **UP**. In Figure 6, the direction at the monitor is expressed using different symbols and the possible location of the event source is indicated by the bold lines. The transformer, the

real event source, is in the possible location. From the cause identification, we can pinpoint the accurate location of the event source in this case.

7. CONCLUSION

This paper proposed a method to determine the relative location of voltage sag source according to its cause. Three main causes of voltage sag are classified and their characteristics are investigated. Using these characteristics, rules to determine the relative location are proposed. For the sag due to line fault, the ratio of the current magnitude during fault to that before fault is used to determine the relative location. If a cause of the sag is the starting of an induction motor, increase in active power at the monitor is utilized to detect the **DOWN** event. Finally, in case of the sag due to the transformer saturation, the cause is identified by the dominance of the second harmonic in the current. And the current ratio with an adapted threshold is utilized to determine the relative location. And then, this paper presented an overall algorithm to determine not only the relative location but also the cause of sag. Moreover, from the simple case study, the decision making sequence of the proposed algorithm is illustrated.

ACKNOWLEDGEMENT

For the research presented in this paper the authors gratefully acknowledge the generous financial support provided by Electrical Industry Research Center (EIRC) of Ministry of Commerce, Industry and Energy of Korea (MOCIE) through Electrical Power Reliability / Power Quality Research Center (homepage - <http://eprrc.snu.ac.kr>)

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