A New Approach to Determine the Direction and Cause of Voltage Sag

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Abstract – Event source locating is very important to improving the power quality level. This paper presents a method to determine the relative location of the voltage sag source according to the cause. For this, the concept of the relative location of the source is defined first. Then, the main causes of voltage sag are classified and their characteristics are discussed. From these investigations, the rules to determine the relative location of event source are proposed for each type and the overall algorithm to identify the relative location and the kind of event source is presented. Finally, the proposed method is applied to the IEEE 13-bus test system and it is verified that the method can help to pinpoint the accurate location of the event source.

Keywords: Diagnosis, Event source location, Power quality, Relative location, Voltage sag

1. Introduction

Voltage sag is a short duration reduction in the RMS voltage magnitude due to short circuits, starting of large motor, and transformer energizing. It is the most significant power quality problem facing many customers since sensitive loads such as IT devices, adjustable-speed drives, and computers have increased. These devices may suffer failure, malfunction, or hardware damage during voltage sags [1].

In order to mitigate voltage sags and improve the power quality (PQ) level, identifying the source of voltage sag is very important. Event source identification comprises event source locating and event cause identification. The former determines where the event originates and the latter defines what kind of device or fault brings about the event. In the distributed PQ monitoring system [2], PQ information is acquired from multiple monitors and analyzed together for adequate diagnosis. It is a matter of course that more monitors will provide more accurate result. However, the number of monitors is commonly restricted because of the economical efficiency. Therefore, it is still difficult to pinpoint the event location even though the relative location of source can be correctly identified by the monitors. Event cause identification can help to find the exact event location especially in case of sag due to the large motor starting or transformer energizing.

Recently, some researchers have proposed various methods to locate the sources of voltage sags [3-6]. A method using the directions of the disturbance energy and disturbance power has been introduced in [3]. Another method using the line-fitting parameters of current and voltage during voltage sag is proposed for sag direction detection [4]. N. Hamzah et al. [5] has proposed another approach to locate the voltage sag source using the magnitude of currents and the phase angles of voltage and current, and the method using the seen impedance and its angle before and after the sag is proposed in [6]. The previous studies, however, have only dealt with the sag caused by short circuit faults.

This paper proposes a new method to identify the direction of voltage sag source considering the cause of event. To improve the ability in event location, the proposed method uses several different rules depending on event types because each type of event has different characteristics.

This paper is organized as follows. In Section 2, the definition of the relative location of event source at a monitor is stated. The characteristics according to the direction and the cause of voltage sag are investigated and the rules to determine the relative location are proposed for each type of sag in Section 3. Section 4 presents the overall algorithm to identify the relative location and kind of event source. Finally, test results and some relevant conclusions are reported.

2. Definition of Up/Down Area

If a monitor is installed in a power system, the relative location of event source can be identified using the recorded data. In other words, it is possible to determine which side

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of the monitor the event has come from. In this paper, the terms 'UP/DOWN area of a monitor' and 'UP/DOWN event' will be used to represent the relative location. The definition of the terms is explained in detail in Fig. 1 using the example system.

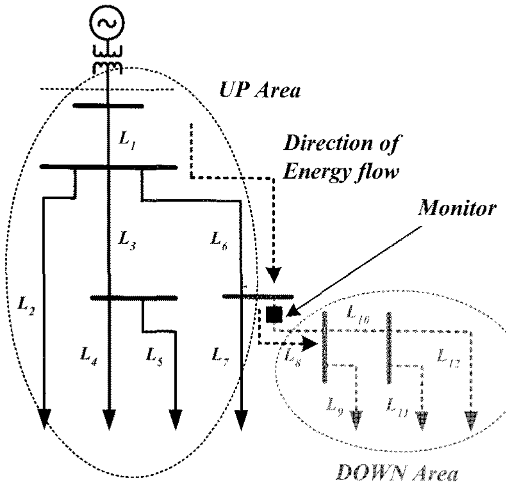

Fig. 1. Definition of UP and DOWN area considering the monitor location

The determination of the relative location of event sources is closely related to the flow of electric energy at a monitor. In the radial distribution system, it is assumed that the energy at a monitor always flows from the source to the load. Therefore, 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_6. Another is the section to which the energy flows from the monitor like L_8, L_9, L_{10}, L_{11}, and L_{12}. The last one is the section that is not directly related to the energy flow at the monitor like L_2, L_3, L_4, L_5, and L_7. These three sections can be classified into two areas again as shown in Fig. 1. The DOWN area can be defined as the area to which the energy flows from the monitoring point. On the other hand, the UP area is the rest area that is not included in the DOWN area, that is, the area from which the power flows to the monitor and the neighboring area.

3. Rules to Determine the Relative Location

Voltage sag happens when high inrush current flows in the power system [7, 8]. This inrush current prompts a large voltage drop in the system and the event origin acts as an energy sink [3]. These inrush currents mainly occur when the line experiences a short circuit fault. Additionally, when a large induction motor starts to operate or a transformer is energized, high inrush current flows in the system [9-11]. Therefore in this paper, sag events are classified into line fault initiated sag (LFIS), induction motor initiated sag (IMIS), and transformer energizing initiated sag (TEIS). To investigate how the distinctive characteristics for each type of voltage sag can be extracted, we simulated the events using PSCAD/EMTDC^{TM}. A diagram of the test system used for the simulation is shown in Fig. 2, where the locations of monitors and event origins are indicated. The simulated events are as follows.

- E1: Three phase line to ground fault between 0.2 s and 0.35 s
- E2: Induction motor starts at 1.0 s
- E3: Transformer is energized at 1.0 s

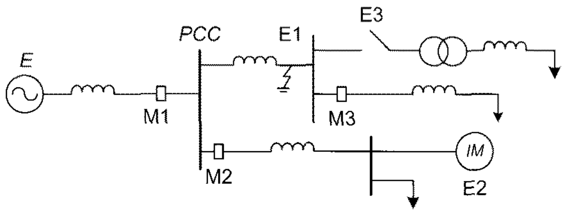

Fig. 2. Example system to develop the decision rules

Voltage magnitudes, current magnitudes before and during the sag, active power flows before and after the sag, and total harmonic distortions (THDs) before and during the sag are measured at three monitors and the results are summarized in Table 1. The waveforms of the selected parameters are presented in Figs. 3-5. From the results, we can find the distinctive rules to determine the relative location for three different types of sag.

3.1 Rules for the LFIS

As revealed in Fig. 3(a), the voltage waveform of the LFIS can be characterized as a sharp drop and rise compared to other types of events. This is because the voltage recovers immediately when the appropriate protection device operates. Large fault current flows through the path from the source to the fault location because the impedance at the fault location becomes low. The current magnitude during the sag at M1 increases about 8 times, while it decreases at the other two monitors.

As indicated in Table 1, the difference of the current magnitude before and during line fault is a critical factor to determine the relative location. The ratio of M1 that only should detect a DOWN event is definitely distinguished from any other.

This means that the current ratio can be used to determine the relative location for the LFIS. The relative location in case of the LFIS can be determined as follows:

Table 1. Result summary for the example system

Sag Type	Monitor	Direction	Current Before	Current During	Current Ratio	Active Power Before	Active Power After	Harmonic (THD) Before	Harmonic (THD) During
LFIS	M1	Down	0.566	4.345	7.68	10.01	9.97	0.00018	0.0013
	M2	Up	0.484	0.179	0.37	8.47	8.47	0.00024	0.0041
	M3	Up	0.081	0.027	0.33	1.41	1.41	0.0002	0.0026
IMIS	M1	Down	0.566	0.934	1.65	10.01	11.61	0.00018	0.045
	M2	Down	0.484	0.868	1.79	8.47	10.24	0.00024	0.051
	M3	Up	0.081	0.073	0.9	1.41	1.39	0.0002	0.0048
TEIS	M1	Down	0.566	0.936	1.65	10.01	10.32	0.00018	0.313
	M2	Up	0.484	0.447	0.92	8.47	8.49	0.00024	0.127
	M3	Up	0.081	0.075	0.93	1.41	1.41	0.0002	0.133

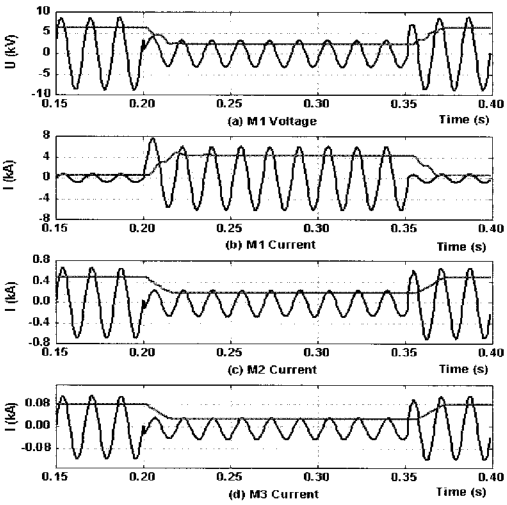

Fig. 3. Measured voltage and current in case of the LFIS

$$\begin{cases} DOWN & if \ \dfrac{I^1_{sag}}{I^1_{pre}} \geq Thr_{LF} \\ UP & if \ \dfrac{I^1_{sag}}{I^1_{pre}} < Thr_{LF} \end{cases} \quad (1)$$

where, I^1_{pre} : the fundamental frequency component of the current before line fault, I^1_{sag} : the fundamental frequency component of the current during line fault, Thr_{LF} : the threshold of the ratio I^1_{sag}/I^1_{pre} . If the ratio exceeds the threshold, the event is determined as a DOWN event. Otherwise, an UP event is determined.

3.2 Rules for the IMIS

When an induction motor starts, inrush current, which is 5–10 times greater than rational current, is absorbed into the motor. This inrush current lasts until the motor reaches steady state. The incidence of inrush current during induction motor starting makes the motor as energy sink like line fault. The waveform at the PCC during the IMIS has a sharp drop like the LFIS but the voltage recovers gradually, which is the main difference compared to the LFIS. This is because the inrush current disappears slowly. The voltage waveform is balanced because the induction motor is normally a balanced load. This property differentiates the IMIS from the TEIS. The starting of the induction motor results in voltage sag but the magnitude of the 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 the LFIS is not suitable for the IMIS.

In this test system, monitors M1 and M2 are thought to detect DOWN events with M3 detecting an UP event. As shown in Fig. 4(b) and (c), the active powers of M1 and M2 reach new steady states with increasing values. This is because the induction motor is a load and the starting of the induction motor acts as an increase of load. Therefore the difference of active power before and after the sag can be used to determine the relative location in case of the IMIS. The rule for the IMIS can be summarized as follows:

$$\begin{cases} DOWN & if \ \dfrac{P_{post} - P_{pre}}{P_{pre}} \geq Thr_{IM} \\ UP & if \ \dfrac{P_{post} - P_{pre}}{P_{pre}} < Thr_{IM} \end{cases} \quad (2)$$

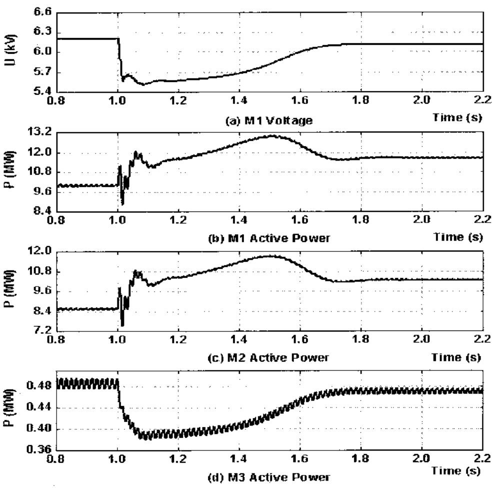

Fig. 4. Measured voltage and active power in case of the IMIS

where, P_{pre} : the steady state active power before induction motor starting, P_{post} : the steady state active power after induction motor starting, Thr_{IM} : the threshold of the ratio $(P_{post} - P_{pre})/P_{pre}$.

3.3 Rules for the TEIS

Transient flux happens in the core of a transformer when the transformer is energized or its voltage changes. In most cases, this transient flux exceeds the saturation value. This temporary over-fluxing of a transformer results in a high magnetizing current. This is known as 'magnetizing inrush current' and its magnitude is determined by the time of switching and residual flux [12-14]. This inrush current also results in voltage sag. The waveform of the voltage in case of the TEIS is somewhat similar with that of the IMIS. It has a sharp drop and slow recovery. The shape of voltage in case of the TEIS is different from that of the IMIS in that the three phase voltages are not balanced and contain numerous harmonic contents.

The characteristics at the monitors that detect DOWN events have been summarized as the increase in the current of fundamental frequency and the existence of harmonic contents. In the test system, the monitor M1 is thought to detect a DOWN event with M2 and M3 detecting UP events.

As shown in Fig. 5(b), the current at M1 increases rapidly but is restored gradually. Furthermore, the magnitude of the inrush current is not very large compared to the fault current during the line fault. Therefore, a more delicate ratio should be applied to the TEIS and another characteristic that distinguishes the TEIS from others is necessary. The unique characteristic that discriminates the TEIS from others is the existence of harmonic contents during the event. Especially, the ratio of the second order harmonic current is relatively high in this case [15]. This fact can also be verified by the harmonic analysis as shown in Fig. 6. The magnitude of the second order harmonics grows rapidly at the beginning of the event. It reaches up to 30–50% of the total harmonic contents. Therefore, we can use this characteristic to identify the TEIS as follows:

$$\begin{cases} TEIS & if \ \dfrac{\Delta I_2}{\sum_{h=2}^{7} \Delta I_h} \geq Thr_H \\ Other\ Types & if \ \dfrac{\Delta I_2}{\sum_{h=2}^{7} \Delta I_h} < Thr_H \end{cases} \quad (3)$$

where, h : the order of harmonic contents, ΔI_h : the change in the h^{th} order harmonic current, Thr_H : the threshold of the ratio $\Delta I_2 / \sum_{h=2}^{7} \Delta I_h$.

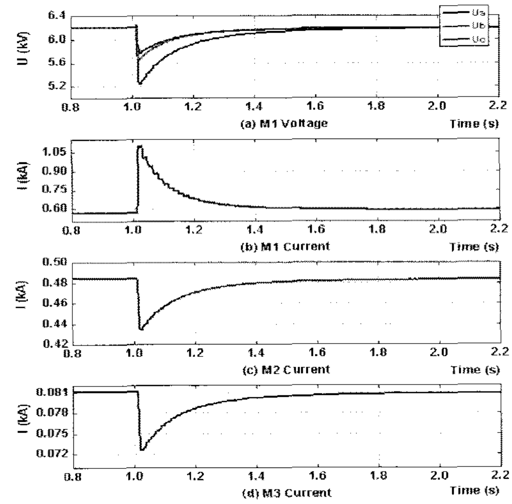

Fig. 5. Measured voltage and current in case of the TEIS

As shown in Table 1, the increase of the THD in case of the LFIS and IMIS is very small compared to that of the TEIS. Therefore, for the LFIS and IMIS the ratio in (3) cannot provide significant information or may result in misjudgment at times. In order to avoid these errors, the rule is applied when the THD during the sag increases more than the threshold (Thr_{THD}).

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

$$\begin{cases} DOWN & if \ \dfrac{I_{sag}^1}{I_{pre}^1} \geq Thr_{TR} \\ UP & if \ \dfrac{I_{sag}^1}{I_{pre}^1} < Thr_{TR} \end{cases} \quad (4)$$

Where, I_{pre}^1 : the fundamental frequency component of the current before transformer energizing, I_{sag}^1 : the fundamental frequency component of the current during sag caused by the transformer energizing, Thr_{TR} : the threshold of the ratio I_{sag}^1 / I_{pre}^1 in transformer energizing event.

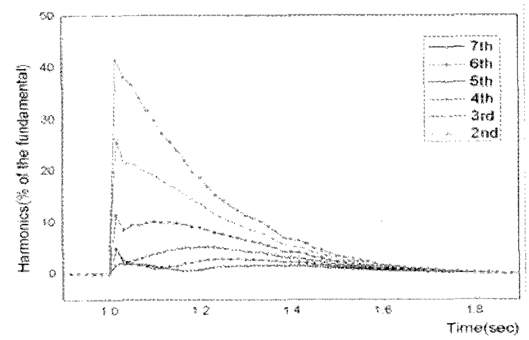

Fig. 6. Harmonic contents of current during the TEIS

4. Overall Algorithm and Its Implementation

4.1 Overall Algorithm

In the previous section, the methods to determine the relative location for each type of voltage sag are discussed. The characteristics appeared in the monitors that detect DOWN events according to the decision rules and sag types are summarized in Table 2. The overall algorithm to determine the event direction and cause based on the above characteristics is described in Fig. 7. For the events occurred in the DOWN area, the event cause as well as the direction can be identified using the proposed algorithm. When the events are occurred in the UP area of the monitor, the event cause cannot be classified because the algorithm is based on the characteristics appeared in the DOWN monitors. However, the information at multiple monitors is analyzed together in order to determine the accurate location and cause of the event, therefore the event cause can be identified using the information from the monitors that detect DOWN events.

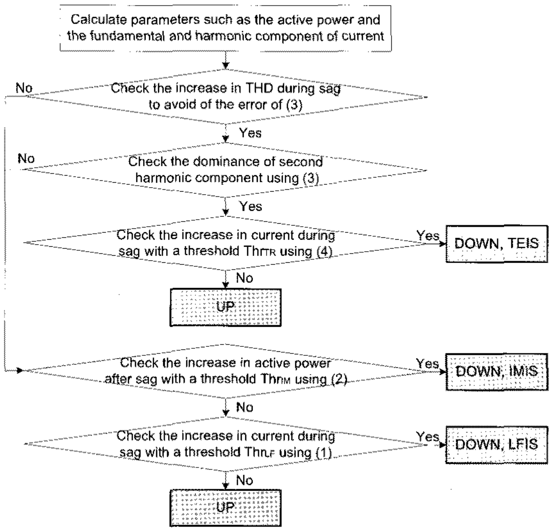

Fig. 7. Overall algorithm to identify the direction and cause of the voltage sag source

4.2 Principles to Select Appropriate Threshold Values

The selection of appropriate threshold values is a significant factor in order that the proposed algorithm works well. Therefore, before the monitors are installed, the threshold values should be tuned according to the characteristics of the system, the location of the monitor, and so on. Thus, this paper presents a few factors that should be reflected on the determination of threshold and/or suggests ranges within which the threshold values normally lie.

Thr_{LF} used in the rule for the LFIS is dependent mainly on the magnitude of the short circuit current flowing through the monitor. Therefore the short circuit level of the system, the location of the monitor, and the fault impedance should be considered and some techniques used in the overcurrent relay design can be applied to the determination of this threshold. The rating and type of induction motor, starting method of the motor, and the load level can be the critical factors used to determine Thr_{IM}. The crucial factor to decide Thr_{TR} is the magnitude of the magnetizing inrush current and it is governed by the following factors [14]: the resistance of the primary winding circuit; the inductance of the air core in between the energizing winding and the transformer core; the geometry of the transformer core; the maximum flux-carrying capability of the core materials, and so on. In general, the inrush current is smaller than the short circuit current and decreases gradually, thus Thr_{TR} has a smaller value than Thr_{LF}. Thr_{H} and Thr_{THD} which are used to distinguish the TEIS from others and can be determined experimentally. According to the harmonic analysis in our study, the typical values for the thresholds are 0.3 and 0.1, respectively.

4.3 Implementation

We have developed a prototype of a power quality management system and the proposed algorithm is implemented in the power quality monitoring system (PQMS). The sampling

Table 2. Characteristics according to the decision rule and sag type

Identification method / Cause	Current increase during sag	Active power increase after sag	Increase in harmonic contents
LFIS	*Very Large*	*No*	*No*
IMIS	*Small*	*Yes According to IM rating*	*Small, Almost identical in all harmonic contents*
TEIS	*Small*	*No*	*Large, Dominant in 2^{nd} harmonic*

rate of the developed PQMS is 128 samples per cycle and the sampling resolution is 16 bits per sample [16, 17]. In the PQMS, the RMS values of voltage and current are updated every cycle. Active and reactive power and 0 ~ 50th harmonic components of current are also calculated. In normal time, the calculated active power, the fundamental and 2~7th harmonic component of current, and THD are stored in the FIFO buffer. The size of the buffer is 10 and the mean value of the stored data is used as a normal or steady state value of each parameter. When the voltage sag event is detected at the monitor, the parameters are stored in the temporary memory and these data are used to calculate the during-sag values.

5. Case Studies

5.1 System Configuration and Event Description

The proposed method is applied to the IEEE 13-bus system, which is modified for the generation of PQ events. The diagram of the network is shown in Fig. 8 and the location of monitors and event sources are also indicated in the same figure. The load and line data of the test system are summarized in [18]. The PSCAD/EMTDC™ is used to model the system, simulate the PQ events, and generate the data. The data obtained from the simulation is analyzed using the developed PQMS. For the case study, three different events summarized in Table 3 are assumed to happen in the test system.

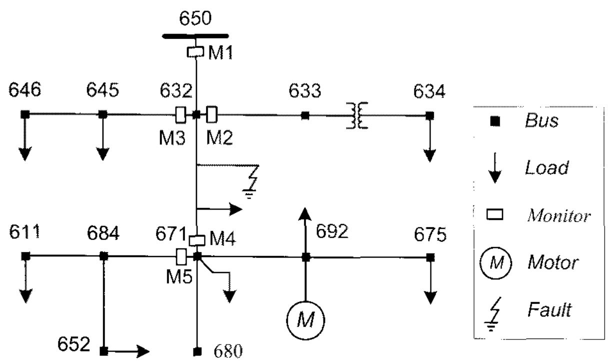

Fig. 8. Schematics of IEEE 13-bus test system

Table 3. Event description used in the case studies

Case	Event Description
1	3 phase L-G fault at the center of Line 632-671
2	Induction motor installed at 692 starts to operate
3	Transformer between 633 and 634 is connected to system

Table 4. Threshold values used in the test case

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

5.2 Results and Analysis

The threshold values used in the case study are as listed in Table 4 and the results of the case study are summarized in Table 5 ~ Table 7.

Case 1: 3 phase L-G fault at Line 632-671

The calculated values at each monitor are summarized in Table 5. Because the increase in the THD is smaller than the threshold 0.1 at all monitors, the variation in the active power after sag is investigated. The active power after sag is slightly increased but the variation is smaller than the threshold (Thr_{IM}). Therefore, the increase in the current during sag is examined. Because the current ratio at M1 exceeds the threshold (Thr_{LF}), the event cause becomes line fault and the direction is DOWN at M1. At the other monitors, however, the current decreases slightly during sag. Therefore, the direction at M2, M3, M4, and M5 are identified as UP. If we analyze the results synthetically we can conclude that the voltage sag is caused by the fault at the line between 650 and 671 where the real event source is located.

Table 5. Result summary for test case 1

	ΔTHD	$I_2 / \sum_{h=2}^{7} I_h$	$\Delta P/P_{pre}$	I^1_{sag} / I^1_{pre}
M1	0.0007	-	0.022	***4.678***
M2	0.0069	-	0.023	0.892
M3	0.0074	-	0.022	0.921
M4	0.0047	-	0.003	0.780
M5	0.0042	-	0.011	0.807

Case 2: Starting of the induction motor installed at 692

As shown in Table 6, the increase in the steady state active power after sag at M1 and M4 exceed the threshold. Therefore, the event cause is identified as induction motor starting and the direction is DOWN at the two monitors. On the other hand, at M2, M3, and M5 the active power slightly increases or somewhat decreases. Therefore, the increase in the current during sag is investigated. Because the current ratios are smaller than the threshold, the direction at the three monitors is determined to be UP. According to the results, the source of the sag is identified as the induction motor at 692. If there are two or more motors installed in the suspicious area, the rating of motor and the increased value of power can be utilized to determine the exact source of event [19].

Table 6. Result summary for test case 2

	ΔTHD	$I_2 / \sum_{h=2}^{7} I_h$	$\Delta P/P_{pre}$	I^1_{sag} / I^1_{pre}
M1	0.0042	-	***0.2569***	-
M2	0.0019	-	0.0027	1.085
M3	0.0018	-	0.0047	1.085
M4	0.0093	-	***0.2031***	-
M5	0.0074	-	-0.0035	1.086

Case 3: Transformer between 633 and 634 energizing

The results of this case are summarized in Table 7. At all monitors the increase in THD exceeds the threshold (Thr_{THD}) then, the harmonic components in the current are analyzed. At M1, M2, and M3, because the ratio of the 2nd harmonic exceeds the threshold (Thr_H), the current ratio is calculated and the direction is determined using the threshold (Thr_{TR}). At M4 and M5, the ratio of the 2nd harmonic is smaller than the threshold. Therefore, the decision rules using the active power variation and the current ratio (with the threshold Thr_{LF}) are used in these monitors. Consequently, at M1 and M2 it is concluded that the voltage sag is caused by the transformer energizing and the direction is DOWN and the direction at the other monitors is determined as UP.

A topological locating algorithm using the direction information in order to systematically determine the event source is proposed in [19] and implemented in the developed prototype system. The developed system is now under the course of commercialization. Therefore, the proposed algorithm can be tested using the field-measurement in the near future.

Table 7. Result summary for test case 3

	ΔTHD	$I_2 / \sum_{h=2}^{7} I_h$	$\Delta P/P_{pre}$	I^1_{sag} / I^1_{pre}
M1	0.236	0.556	-	***1.364***
M2	0.503	0.533	-	***6.774***
M3	0.136	0.481	-	0.766
M4	0.102	0.183	-0.0001	0.979
M5	0.106	0.188	0.00104	0.991

6. Conclusion

This paper proposed a method to determine the relative location of the voltage sag source according to its cause. Three main causes of voltage sag are classified and their characteristics are investigated. Using these characteristics, the rules to determine the relative location are proposed. For the LFIS, the ratio of the current magnitude during fault to that before fault is used to determine the relative location. If the cause of the sag is the starting of an induction motor (IMIS), increase in active power at the monitor is utilized to detect the DOWN event. Finally, in case of the TEIS, 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. This paper also presented the overall algorithm to determine the direction and cause of the sag together. The proposed algorithm was implemented in the prototype PQ management system and tested using the simulation data.

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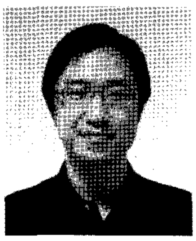

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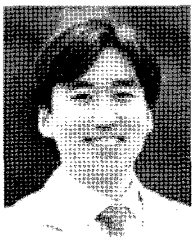

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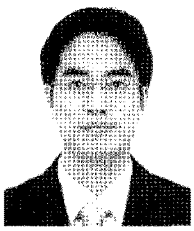

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