An Intranet-based Transmission Grid Fault Location Platform Using Synchronized IED Data for the Taiwan Power System

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Abstract **—In this paper, we propose an application of a developed fault location platform to the Taiwan transmission grid using transmitted synchronized IED (Intelligent Electronic Device) data as inputs to the platform via Ethernet. The proposed fault location platform can also be applied to utilities with IEDs around the world. IED measurements are synchronized with embedded phasor measurement unit (PMU) function in IEDs or with unsynchronized measurements correction method in the platform. The functions of the fault location platform consist of COMTRADE file converter, faulted waveform display function, digital filter, two-terminal and three-terminal transmission line fault location algorithms, unsynchronized measurements correction method, and graphical display of fault location. Due to the high accuracy and fast analysis features of the platform, utilities can reduce large amount of manpower cost and power interruption cost during a fault searching period. Field event results of the platform over the Taiwan power system are provided to demonstrate the claimed features.**

Index Terms **— Intelligent Electronic Device (IED), phasor measurement unit, Transmission Line Fault Location Platform**

I. INTRODUCTION

In power systems, transmission grids are vital links that achieve the essential continuity of service from the generating plants to the end users. Accurate fault location information for transmission lines is very important for quickly restoring power service, reducing outage time and saving large maintenance manpower demands. As a result, the development of a robust and accurate fault location technique is a highly important research area.

Intelligent electronic devices (IEDs) nowadays are replacing traditional relays to meet demands because of their self-checking ability, flexibility, scalability, recording ability, and communication capability. IEDs sample voltage and current waveforms of transmission lines into digital data to determine the proper protective actions by internal relaying algorithms. Furthermore, the sampled data can be downloaded to a remote server via Ethernet for fault location calculation to identify the exact position of transmission line faults.

Since the Global Positioning System (GPS)-based synchronously measuring units, including phasor measurement units (PMUs) and digital relays, were developed in the early 1990s, fault location estimation techniques using synchronized phasor measurements have rapidly become well-known techniques. Owing to the availability of synchronized data obtained by GPS-based techniques, the accuracy of fault location is unaffected by the variations of fault impedances and source impedances. In our previous work [10]-[14], the GPS-based fault location/detection techniques for transmission lines have been proposed.

Fault location/detection techniques are also used for transmission line protection [15, 16], which form the basis of our work. Brahma [2] respectively utilized synchronized pre- and post-fault voltage measurements to obtain the fault location. Meanwhile, Izykowski *et al.* [4] locate faults by using synchronized current samples and an additional voltage phasor from the terminal at which a fault locator had been installed. Their work considered the use of incomplete synchronized signals for fault location. However, most commercially available digital relays are still not time synchronized by GPS-based techniques. Instead, numerical methods for serving this purpose were proposed by Girgis *et al.* [18] where they adopted an iterative method with post-fault data to synchronize the time measured errors.

In this paper, an application of a developed fault location platform to the Taiwan power (TAIPOWER) transmission grid using transmitted synchronized IED (Intelligent Electronic Device) data as inputs to the platform via Ethernet was established. The proposed fault location platform can also be applied to utilities with IEDs around the world. IED measurements are synchronized with embedded phasor measurement unit (PMU) function in IEDs or with unsynchronized measurements correction method in the platform. The proposed fault location platform can locate both short circuit faults and arcing faults for various kinds of transmission grids such as multi-terminal transmission lines [11], double-circuit transmission lines [14], multi-section compound transmission lines [21, 22], and series compensated transmission lines [12]. The proposed fault location platform includes a friendly graphical user interface and multiple access function. Due to the high accuracy and fast analysis features of the platform, utilities can reduce large amount of manpower cost and power interruption cost during a fault searching period.

II. ARCHITECTURE OF THE FAULT LOCATION PLATFORM

The goal of this research is to develop a human-friendly interactive transmission line fault location platform. The plat-

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form architecture for the Taiwan Power System shown in Fig.1 can be divided into three layers. Layer 1, where IEDs are placed, is called Data Acquisition Layer. Layer 2 is Network layer, which includes TAIPOWER company intranet system. All the computing functions are built in Layer 3, Application Layer. IED data (sampled voltage and current waveform) are collected constantly and stored in its own memory, which will not be rewritten within several days. Once a fault occurs, TAIPOWER engineers will capture the fault data through intranet and then import it into the fault location platform to calculate fault location.

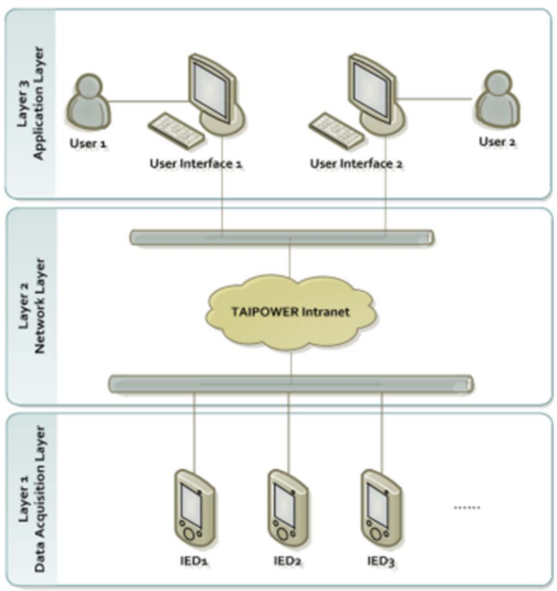

Fig. 1 Architecture of the fault location platform

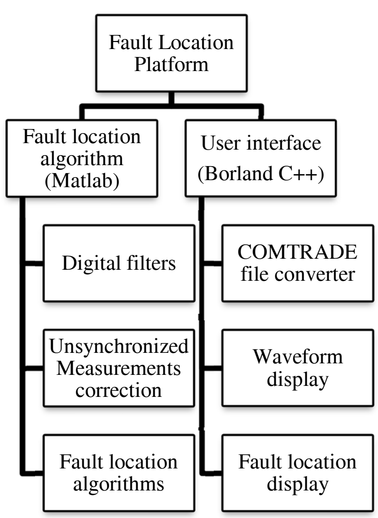

Fig. 2 Overview of fault location platform functions

The overview of the fault location platform functions is shown in Fig. 2. The user interface of the fault location platform was designed in Borland C++. Users first choose transmission line terminal names from built-in list and then import COMTRADE files into the platform. Once the fault records are given and substation names are chosen, the program will automatically load the line parameters from built-in data and also display transient voltage and current waveforms of each terminal. The main fault location calculation functions of the platform were coded in MATLAB and simulated in MATLAB SIMULINK®. After loading the COMTADE files, fault location functions will be called to execute the fault location calculation and send the results back to the user interface in order to be displayed.

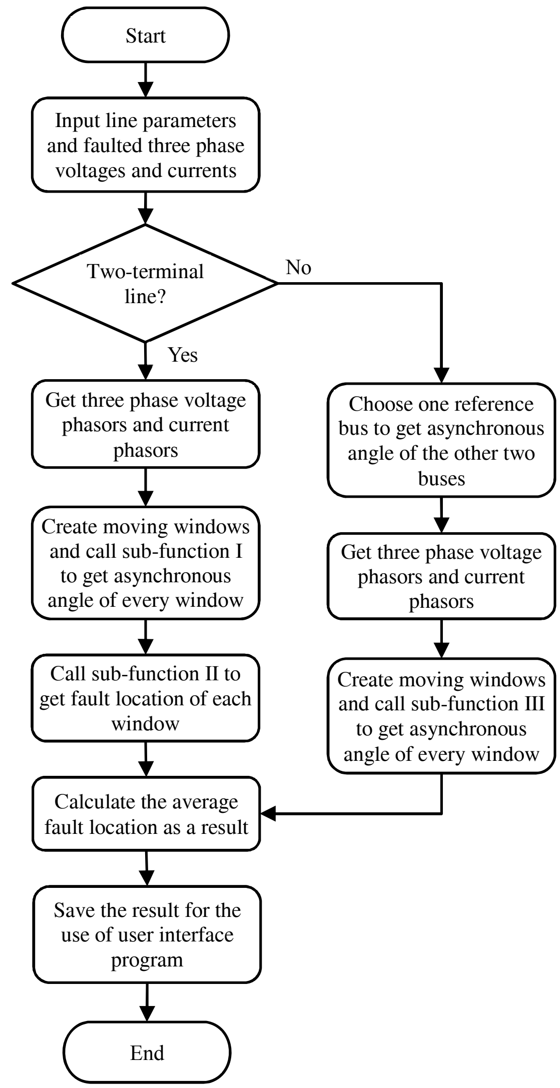

Fig. 3 Flowchart of the implementation of the fault location algorithm

A. *Fault location algorithm implementation*

The fault location algorithm was implemented in MATLAB. Our implementation contains one main function and three subroutines. Figure 3 shows the flowchart of the implementation of the fault location algorithms. The main function reads a file which contains the parameters of the transmission line and the raw data of three phase voltages and currents created by the user interface program. The main function will then call the three subroutines to calculate the fault location of the faulted transmission line. Subroutine I is called by the main function to calculate the asynchronous angle using the modified secant iteration algorithm [19] for two-terminal lines. Subroutine II is called by subroutine I to calculate the faulted section and the fault location for two-terminal lines using the proposed compound-line fault location algorithm [21]. Subroutine III is called by the main function to calculate the faulted line branch, faulted section, and fault location using the suggested fault location algorithm [22] for three-terminal lines.

B. User interface implementation

The user interface was built with Borland C++ under Windows XP. The purpose of the user interface is to create a user friendly environment which allows end users to locate fault locations easily. Figure 4 shows the main page of the fault location platform. Users can choose two-terminal or three-terminal fault location function from the navigation bar on top of the window. Figure 5 shows the faulty data importing blocks and waveform display block. Figure 6 shows the result of fault location calculation. Numerical information of fault locations are shown along with a graph in order to make maintenance engineers quickly understand the exact fault position with respect to the whole transmission line.

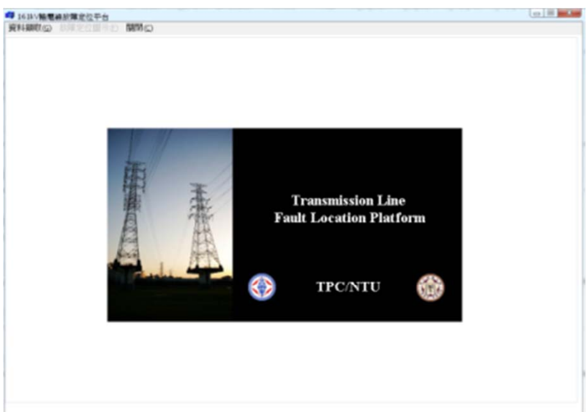

Fig. 4 Main page of the transmission line fault location platform

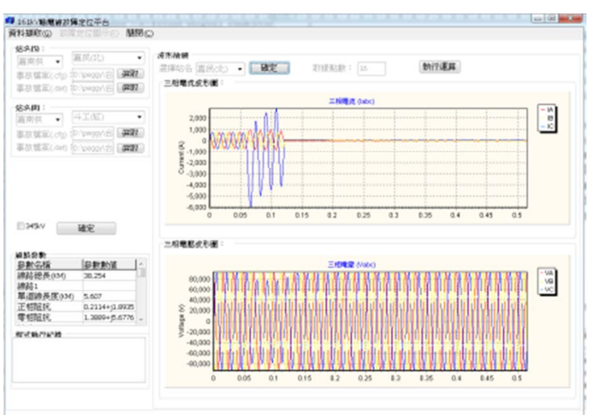

Fig. 5 Faulty data importing blocks and waveform display function

Fig. 6 Graphical display of the fault location estimation result

III. Fault Location Algorithms

In this section, the principle of the core module of the platform, fault location algorithms, is briefly explained and detailed principles behind these algorithms are referred in [10-17, 21-22]. The transient voltage and current waveforms are sampled and filtered by Discrete Fourier Transform and digital Mimic filter to produce phasors as inputs to the fault location algorithms.

A. Two-terminal fault location technique for multi-section compound lines

Consider the two-section compound transmission line L shown in Fig. 7. Line L includes an overhead line section with length L_S and an underground power cable section with length L_R, therefore the multi-section fault location algorithm is needed in this scenario. Assume IEDs are installed on Bus S and Bus R, two-terminal synchronized voltage and current phasors of this transmission line are obtainable.

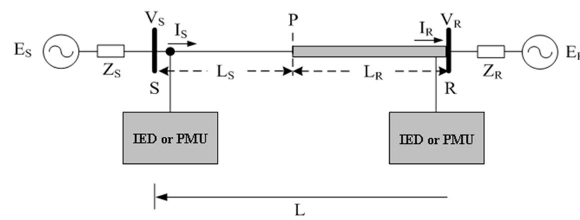

Fig. 7 One line diagram of a two-section compound transmission line; the thin line denotes the overhead line and the bold line denotes the power cable.

The two-terminal multi-section fault location technique for this case is expressed in the following steps:

Step 1: Assume the fault is on the right side of tap point P

As shown in Fig. 8, the fault is situated on the underground power cable L_R. Since the overhead line L_S is healthy, the voltage and current at any point of the overhead line can be derived by applying boundary conditions at Bus S. Consequently, the voltage and current phasors at tap point P can be obtained in terms of (V_S, I_S) as:

$$V_{P,S} = \frac{1}{2}e^{-\Gamma_s L_s}\left(V_s + Z_{C,S}I_s\right) + \frac{1}{2}e^{\Gamma_s L_s}\left(V_s - Z_{C,S}I_s\right) \tag{1}$$

$$I_{P,S} = \frac{1}{Z_{C,S}}\left[\frac{1}{2}e^{-\Gamma_s L_s}\left(V_s + Z_{C,S}I_s\right) - \frac{1}{2}e^{\Gamma_s L_s}\left(V_s - Z_{C,S}I_s\right)\right] \tag{2}$$

where $Z_{C,S} = \sqrt{Z_S / Y_S}$ and $\Gamma_s = \sqrt{Z_s Y_s}$ denote the characteristic impedance and the propagation constants of the overhead line section. Z_S and Y_S are the positive sequence impedance and admittance of the L_S, respectively.

The fault location index D_1 of this section is derived by voltage and current phasors at tap point P and Bus R. After equation manipulations, the fault location index D_1 can be expressed as follows:

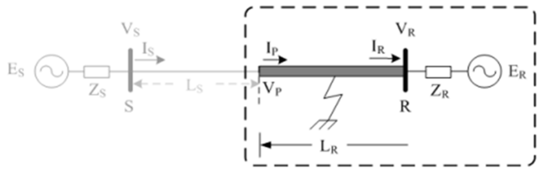

Fig. 8 Fault occurs in the underground power cable section.

$$D_1 = \frac{\ln(N_R / M_R)}{2\Gamma_R L_R} \tag{3}$$

where $\Gamma_R = \sqrt{Z_R Y_R}$, Z_R is the positive sequence impedance ,and Y_R is the admittance of the underground power cable L_R. M_R and N_R are given by:

$$M_R = \frac{1}{2}(V_{P,S} + Z_{C,R} I_{P,S}) e^{-\Gamma_R L_R} - \frac{1}{2}(V_R + Z_{C,R} I_R) \tag{4}$$

$$N_R = \frac{1}{2}(V_R - Z_{C,R} I_R) - \frac{1}{2}(V_{P,S} - Z_{C,R} I_{P,S}) e^{\Gamma_R L_R} \tag{5}$$

where $Z_{C,R} = \sqrt{Z_R / Y_R}$.

Step 2: Assume the fault is on the left side of tap point P

Assume that the fault occurs in the overhead line section L_S as shown in Fig. 9. The voltage and current phasors at tap point P can be derived similarly in terms of (V_R, I_R):

$$V_{P,R} = \frac{(V_R + Z_{C,R} I_R)}{2} e^{\Gamma_R L_R} + \frac{(V_R - Z_{C,R} I_R)}{2} e^{-\Gamma_R L_R} \tag{6}$$

$$I_{P,R} = \frac{1}{Z_{C,R}} [\frac{(V_R + Z_{C,R} I_R)}{2} e^{\Gamma_R L_R} - \frac{(V_R - Z_{C,R} I_R)}{2} e^{-\Gamma_R L_R}] \tag{7}$$

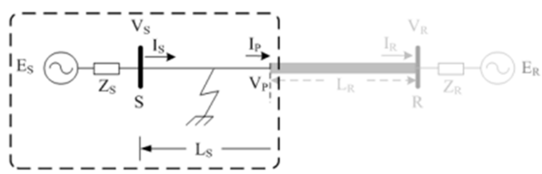

Fig. 9 Fault occurs in the overhead line section

The fault location index D_2 of this section can be obtained using voltage and current phasors at tap point P and Bus S. By applying similar equation manipulations in step one, the fault location index D_2 can be expressed as:

$$D_2 = \frac{\ln(N_S / M_S)}{2\Gamma_S L_S} \tag{8}$$

where

$$M_S = \frac{1}{2}(V_S + Z_{C,S} I_S) e^{-\Gamma_S L_S} - \frac{1}{2}(V_{P,R} + Z_{C,S} I_{P,R}) \tag{9}$$

$$N_S = \frac{1}{2}(V_{P,R} - Z_{C,S} I_{P,R}) - \frac{1}{2}(V_S - Z_{C,S} I_S) e^{\Gamma_S L_S} \tag{10}$$

Step 3: Faulted section identification/fault location estimation

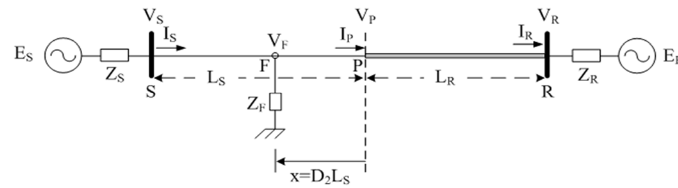

Fig. 10 A fault occurs at a distance $x = D_2 L_S$ away from tap point P

Suppose that a fault occurs on the transmission line shown in Fig. 10 at point F with distance $x=D_2L_S$ km away from tap point P in section L_S. As discussed and proved in [21], if the index D_2 is in the interval [0, 1] and the index D_1 is greater than 1, the fault can be identified occurring in section L_S of a two-section compound line as the one shown in Fig. 10. In a similar manner, the relationships between the two indices, D_1 and D_2 can be determined while dealing with a fault in section L_R or at tap point P. All the specific relationships between the two indices D_1 and D_2 and the method of how to identify the fault location are summarized in Table I. The general identification technique of the faulted section/fault location for multi-section compound lines is developed based on the similar procedure.

TABLE I
THE FAULTED SECTION/FAULT LOCATION IDENTIFICATION FOR TWO-SECTION COMPOUND TRANSMISSION LINES

(1) $D_2 < 0$ and $0 \leqq D_1 < 1$: the fault occurs on L_R and D_1 is the actual fault location away from bus R.
(2) $0 < D_2 \leqq 1$ and $D_1 > 1$: the fault occurs on L_S and $(1\text{-}D_2)$ is the actual fault location away from bus S.
(3) $D_2 = 0$ and $D_1 = 1$: the fault occurs at the point P.

B. Fault location technique for three-terminal homogenous lines

The one-line diagram of a three-terminal transmission line is shown in Fig. 11.

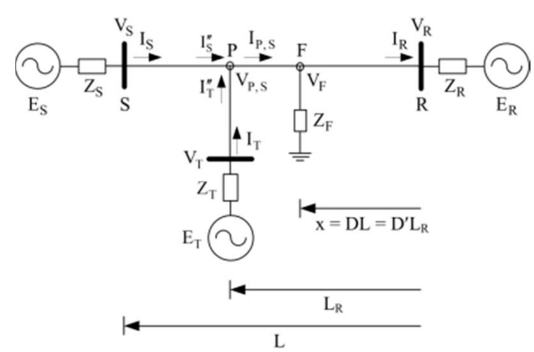

Fig. 11 One-line diagram of a three-terminal transmission line under a faulted condition.

The IEDs are installed at Buses S, R, and T; therefore the three-terminal synchronized voltage and current phasors can be obtained. The injective currents coming from the tap branch of multi-terminal lines are considered. The line section length

L_R is defined as the reference length of the fault location indices. The voltage and current phasors at tap point P can be derived and expressed in terms of the data sets (V_S, I_S):

$$V_{P,S} = \frac{1}{2}e^{-\Gamma L_R}(V_S + Z_C I_S) + \frac{1}{2}e^{\Gamma L_R}(V_S - Z_C I_S) \quad (11)$$

$$I''_S = [\frac{1}{2}e^{-\Gamma L_S}(V_S + Z_C I_S) - \frac{1}{2}e^{\Gamma L_S}(V_S - Z_C I_S)]/Z_C \quad (12)$$

According to Kirchhoff's law, the current phasors at tap point P is:

$$I_{P,S} = I''_S + I''_T \quad (13)$$

where I''_T is the injective current of the tap branch, which is given by

$$I''_T = [\frac{1}{2}e^{-\Gamma L_T}(V_T + Z_C I_T) - \frac{1}{2}e^{\Gamma L_T}(V_T - Z_C I_T)]/Z_C \quad (14)$$

Similarly, the fault location index D_S, and also the fault location $x = D_S L_R$ away from Bus R can be derived by (15-17),

$$D_S = \frac{\ln(N_S/M_S)}{2\Gamma L_R} \quad (15)$$

where

$$M_S = \frac{1}{2}e^{-\Gamma L_R}(V_{P,S} + Z_C I_{P,S}) - \frac{1}{2}(V_R + Z_C I_R) \quad (16)$$

and

$$N_S = \frac{1}{2}(V_R - Z_C I_R) - \frac{1}{2}e^{\Gamma L_R}(V_{P,S} - Z_C I_{P,S}) \quad (17)$$

By applying the same method, the voltage and current phasors at tap point P can also be derived and expressed in terms of the data sets (V_T, I_T). The fault location index D_T is given by (18-20) and the fault location x can be obtained $D_T L_R$, away from Bus R.

$$D_T = \frac{\ln(N_T/M_T)}{2\Gamma L_R} \quad (18)$$

where

$$M_T = \frac{1}{2}e^{-\Gamma L_R}(V_{P,T} + Z_C I_{P,T}) - \frac{1}{2}(V_R + Z_C I_R) \quad (19)$$

and

$$N_T = \frac{1}{2}(V_R - Z_C I_R) - \frac{1}{2}e^{\Gamma L_R}(V_{P,T} - Z_C I_{P,T}) \quad (20)$$

Therefore, both indices D_S and D_T can be used to determine whether the fault occurs in section L_R, L_S, or L_T, and also locate faults; the determination rules are summarized and listed in Table II.

In a similar manner, a fault location scheme for three-terminal compound transmission lines can be developed through a combination of the two-terminal compound line fault location algorithm and the three-terminal homogenous line fault location algorithm. Furthermore, a general form of the faulted section/fault location identification of two- or three-terminal multi-section transmission lines can be obtained [11].

TABLE II
THE FAULTED SECTION/FAULT LOCATION IDENTIFICATION FOR THREE-TERMINAL LINES

(1) $0 < D_S < 1$ and $0 < D_T < 1$: the fault occurs in L_R. Then, $D_S = D_T$, and both of them are accurate fault locations.
(2) $D_S > 1$ and $D_T = 1$: the fault occurs in L_S and D_S is the actual fault location away from bus R.
(3) $D_S = 1$ and $D_T > 1$: the fault occurs in L_T and D_T is the actual fault location away from bus R.
(4) $D_S = 1$ and $D_T = 1$: the fault occurs in point P.

C. Unsynchronized Measurements Correction Method

Another core function of the platform, unsynchronized measurement correction method, is explained in this section. If the clock of IED failed to be synchronized with time synchronization sources, the proposed fault location platform has the capability to synchronize IED measurements automatically [19, 21-22].

IV. FIELD EVENT RESULTS

A. Practical implementation issues

The proposed fault location platform has already been implemented in TAIPOWER 345 kV and 161 kV transmission grids since 2008. More than 40 field event cases during the period from Jan. 2008 to Sep. 2011 including two/three-terminal compound lines (which include overhead transmission lines and underground power cables) were tested. Most of the transmission lines in Taipower system are protected by unsynchronized IEDs (GE, SEL, and TOSHIBA IEDs are used in field events) except a few 345kV substations with PMUs.

All measured data from unsynchronized IEDs and/or PMUs which failed to synchronize with GPS are synchronized by the unsynchronized measurement correction module of the platform. However, there are still some cases that cannot be corrected by the platform due to the huge unsynchronized time differences between the two terminals. Apart from the phasor synchronization issues, some other data issues were encountered as well. For example, there were several three-terminal transmission line cases missing data from one of the terminals. Furthermore, current transformer (CT) ratio was wrongly set in some installed IEDs. The problems mentioned above were reported to TAIPOWER Company, and the incomplete data was discarded in fault location calculation for the moment. However, some auto-calibration functions of CTs and generation of virtual data to replace missing terminal data are under investigation to enhance the strength of the platform.

B. Performance evaluation

For two-terminal compound transmission lines, the average fault location error percentage of the total field event cases of the proposed platform is about 1.878% which is less than 10.927% that of the built-in IED fault location function. Meanwhile, for three-terminal compound transmission lines, the average error of the total field event cases of the proposed platform is about 1.356%, less than 38.431%, that of the IED built-in fault location function.

V. Conclusion

A human-friendly fault location platform for transmission grids using synchronized IED measurements as inputs with graphical user interface is developed and proposed in this paper. The fault location algorithms were tested with various transmission line fault types in Taiwan power system to verify the accuracy. By the use of the transmission line fault location platform, maintenance engineers are able to check the fault voltage and current waveforms and obtain fault location with graphical view in a very short time. Therefore the tiring and time-consuming line patrolling work can be cut down significantly.

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