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Rearrangement Method of Reducing Fault Location Error in Tied Uncompleted Parallel Lines

Hooman Torkaman¹, Ehsan Zeraatkar², Nasim Deyhimi³,
Hassan Haes Alhelou⁴, (Senior Member, IEEE),
AND Pierluigi Siano^{5,6}, (Senior Member, IEEE)

¹Fars Regional Electric Company, Shiraz 7134694715, Iran

²Shiraz Urban Railway Organization, Shiraz 1651637969, Iran

³Parsia Afzar Fara Andishan Novin, Shiraz 1577936615, Iran

⁴Department of Electrical Power Engineering, Tishreen University, Lattakia 2230, Syria

⁵Department of Management and Innovation Systems, University of Salerno, 84084 Salerno, Italy

⁶Department of Electrical and Electronic Engineering Science, University of Johannesburg, Johannesburg 2092, South Africa

Corresponding author: Hassan Haes Alhelou (alhelou@ieee.org)

ABSTRACT In Tied Uncompleted Parallel (TUP) line, locating faults via single-ended fault location algorithm leads to a considerable final error yielding unacceptable outage time. On the other hand, utilizing modern techniques such as Two-ended Protection method, in these temporarily transmission lines are not economically justified. This paper proposes a rearrangement method of tied uncompleted transmission lines to improve the protection coordination and fault location via single ended fault location. This novel method aims to reduce the error of fault location in the line without imposing an unnecessary financial burden or installing new devices. The proposed technique can locate a fault online, resulting less outage time and more reliability of the network. The simulation results, as well as those of field test, indicate the effectiveness of the proposed method in locating fault according to different constraints such as the protection coordination. This method has already been implemented in the Fars-Iran power system since 2018, and it has yielded outstanding results in practice. The technique is easy to execute and considerably reduces the fault location error and the outage time. Having derived the factors of fault location error, the rearrangement technique suggests a new arrangement based on the fault location error factor reduction. In this paper, it is approved that the proposed algorithm can effectively locate faults in uncompleted transmission lines via simulation results as well as practical experience.

INDEX TERMS Power fault location, protection coordination, single-ended protection, transmission line rearrangement.

NOMENCLATURE

Z_{LN} impedances of the line section LN (Ω).

Z_{LP} impedances of the line section LP (Ω).

Z_{LM} impedances of the line section LM (Ω).

Z_R, Z_P Source impedances behind terminals R and P (Ω).

Z_{L1} positive sequence impedance of the line (Ω).

Z_{Relay} The apparent impedance to the fault (Ω).

V_R, V_P Line-to-ground voltages recorded during the fault at terminals R and P (kV).

I_R, I_P Line currents in the parallel transmission line at terminals R and P (kA).

I_F Current at the fault point F (kA).

R_F Fault resistance (Ω).

SLG Single line to ground fault.

LLL Three phase short circuit fault.

LL Line to line fault.

LLG Double line to ground fault.

m Distance to the fault (pu).

I'_R, I'_P Line currents in the divided branches (Section A) of transmission line (kA).

I''_R, I''_P Line currents in the divided branches (Section B) of transmission line (kA).

$I_{S.C3PH.R}$ Three phase short circuit currents measured by the relay R (kA).

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$I_{S.C3PH.P}$	Three phase short circuit currents measured by the relay P (kA).
$I_{S.C1PH.R}$	Single phase short circuit currents measured by the relay R (kA).
$I_{S.C1PH.P}$	Single phase short circuit currents measured by the relay P (kA).
T_0, T_N	Dead-end towers' label.
T_M	The dead-end Tower under calculation.
$I_{KSS.R}, I_{KSS.P}$	The short circuit power at terminal R and P (mVA).
$FL_{relay R}$	Fault location calculated by relay R.
$FL_{relay P}$	Fault location calculated by relay P.
L_{AR}	Real distance from terminal R to the fault on the section A.
L_{AP}	Real distance from terminal P to the fault on the section A.

I. INTRODUCTION

Transmission lines are one of the most essential elements of power system deliveries. The accuracy of fault locating is a critical element in restoring power services, reducing the outage times as well as increasing the reliability and decreasing the maintenance cost.

Various types of techniques have been proposed for finding the location of the faults. Among those, there are some measures using single-ended fault location algorithms [1]–[6]. Being economical, simplicity of installation and low-cost maintenance are the main reasons that these techniques are widely applied in power systems. On the other hand, they can be affected by variations in source impedance, fault impedance, and angle. Nevertheless, due to economic factors, they are still widely used in power systems. Moreover, by using Global Positioning Systems (GPS) and Phasor Measurement Units (PMUs), it is now possible to monitor synchronous voltage and current of all ends of the transmission line to calculate the exact place of fault occurrence [7]. Afrasiabi used the features extracted from the signals measured by PMUs to train a Gabor Filter Convolutional Neural Network and developed a robust and accurate algorithm for fault localization system [8]. Guha developed a real time fault locating algorithm based on the complex voltage data derived from PMUs and the network topology. Guha and Flueck could locate the closest bus to the fault location without carrying out any computationally expensive calculations [9]. Moreover, an error model of the measurement chain including instrument transformers and PMUs developed to design measuring errors covariance matrix in the state estimation formulation. Using the state station calculation and the solution algorithm of Weighted Least Square [10]. On the other hand, Kezunovc used synchronized voltage and current samples at both ends of transmission line to estimate fault location yet it requires a significant high rate [11], [12]. Lee *et al.* used an algorithm based on zero and positive sequence with synchronized data at both ends of the line [13], but this method had error on three phase faults. Liu used a novel technique to locate the fault position in a multi-section line by online or

offline data [14]. Moreover, Minambres *et al.* used the unsynchronized data to simply detect the fault in three terminal transmission lines [15]. Girgis *et al.* [16] developed a three-terminal fault location algorithm by using synchronized and unsynchronized voltages and currents to estimate the fault location. He *et al.* [17] developed a dynamic fault locator for three-terminal lines based on Newton iterative technique but these methods [16], [17] are supposed to be computationally complex ones. Izykowski *et al.* [18] developed a non-iterative algorithm using of unsynchronized measurements without considered the effect of high resistance inter-phase faults. However, due to the high cost of using the PMUs and GPS system, these techniques cannot be applied in all stations, let alone in temporary schemes.

Furthermore, there are some papers investigating Artificial Intelligence methods in fault locating problem. Parsi studied four different techniques, time domain, impedance, visual inspection and wavelet-based technique applied to the travelling fault wave [19]. Dashtdar extracted the fault characteristics from zero-sequence current using discrete wavelet transform to train an artificial neural network [20]. By the trained network, he could estimate the fault distance based on the type of the fault in different conditions. Kumar proposed a Neural Network approach using the voltage and current of single end of line processed by Discrete Fourier Transform and trained using Levenberg-Marquardt method [21]. Mukherjee deployed a Principle Component Analysis (PCA)-based method using fault signals of ten different types of seven intermediate locations [10].

Meanwhile, some have developed phase-based methods to locate the fault in power grids. By introducing the fault location as an additional state of the overall model and using state estimation algorithm to identify the fault location, Liu developed a phase-based method in fault location problem for non-homogeneous transmission lines [22].

A Significant number of power grid expansion projects in Fars province in Iran have not been completed due to several reasons, mainly economic issues. A typical scheme of these uncompleted projects is illustrated in Fig. 1. Although there is no certain time to complete the future scopes, the completed sections, which are mainly the transmission line, are currently under operation as shown in Fig. 1. These TUP lines are connected to the main power transmission line using jumpers as shown in Fig. 1, so as to reduce power loss. However, it can provoke a protection error in detecting the accurate place of the fault occurrence. This problem can increase not only the outage time but also the expenses of repairing the power

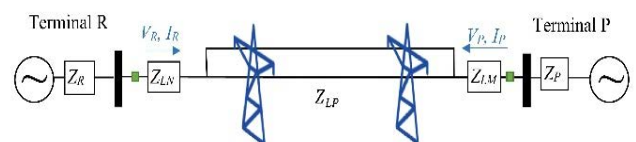


FIGURE 1. Conventional scheme of uncompleted parallel lines.

line, especially those installed in harsh environments such as mountains or valleys. On the other hand, in the majority of cases, using PMUs and GPS in such temporarily schemes impose a considerable financial burden.

The main contributions of this paper are as follows:

- Proposing a novel and practical rearrangement method in a TUP line to reduce the inaccuracy of fault location in the single-ended fault location algorithms.
- Online fault locating without installing high expensive devices.
- Reducing the outage time as well as the maintenance cost by easing finding the fault location which accordingly, will increases the reliability.

This paper is organized as follows: In section II, fault locating problems in TUP lines using single-ended fault location techniques, as well as previous fault locating ones are described. Section III discusses the proposed rearrangement method, which is evaluated using the practical network described in section IV. The experimental results are illustrated in section V, and a comparative study is conducted in section VI. Finally the conclusion is reached in section VII.

II. FAULT LOCATING PROBLEMS IN TUP LINES USING SINGLE-ENDED TECHNIQUES

A. REVIEW OF SINGLE-ENDED FAULT LOCATION TECHNIQUES

Single-ended impedance-based fault location algorithms estimate the location of a fault based on the voltage and the current of one terminal. Consider the two-terminal transmission network shown in Fig. 2, where the positive sequence impedance is Z_{L1} between two terminals R and P. Thevenin equivalents, having impedances Z_R and Z_P . When a fault occurs at the m percentage of the line with the resistance of R_F , both sources contribute to the total fault current I_F . Using Kirchhoff's law, the voltage drop from terminal R can be derived as:

$$V_R = mZ_{L1}I_R + R_F I_F \tag{1}$$

where, the form taken by V_R and I_R depends on the fault type which are expressed in table 1 [1].

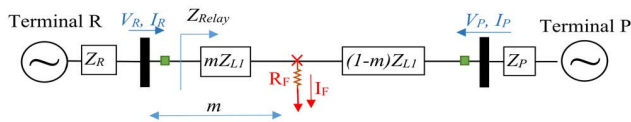


FIGURE 2. A single diagram of a simple two terminal transmission line.

TABLE 1. Definition of V_R and I_R for different fault types.

Fault Type	V_R	I_R
SLG	V_{AF} or V_{BF} or V_{CF}	$(I_{AF}$ or I_{BF} or $I_{CF}) + KI_0$
AB-ABG-ABC	$V_{AF} - V_{BF}$	$I_{AF} - I_{BF}$
BC-BCG-ABC	$V_{BF} - V_{CF}$	$I_{BF} - I_{CF}$
CA-CAG-ABC	$V_{CF} - V_{AF}$	$I_{CF} - I_{AF}$
	$K = (Z_{L0}/Z_{L1}) - 1$	

The apparent impedance to the fault Z_{Relay} can be expressed as:

$$Z_{Relay} = \frac{V_R}{I_R} = mZ_{L1} + R_F \frac{I_F}{I_R} \tag{2}$$

The fundamental equation that governs single-ended impedance-based fault location is equation (2) with the three unknowns of m , I_F , and R_F . Various fault location techniques are developed to eliminate or address the impact of R_F and I_F in finding the location of a fault [23]. While a considerable number of installed relays in Fars province located in Iran use Simple Reactance Method to determine the fault location, none of these techniques can estimate a reliable fault location at TUP lines. Briefly, these techniques are described in the following sections.

1) SIMPLE REACTANCE METHOD

This technique gains advantage from the fact that R_F is naturally resistive [1]. Furthermore, by assuming that I_R and I_P are in phase, the impact of $R_F(I_F/I_R)$ can be ignored. This result can be derived by considering the imaginary components of (2) as:

$$m = \frac{Im(\frac{V_R}{I_R})}{Im(Z_{L1})} \tag{3}$$

However, this technique can be affected by various reasons such as load current and difference between the phases of I_R and I_P .

2) TAKAGI METHOD

This technique improves the Simple Reactance Method by subtracting out the load current from the total fault current. This technique uses the superposition principle and estimates the fault Current I_F . Having estimated I_F , an angle β can be derived so as to reduce the impact of $R_F(I_F/I_R)$ by changing the angle of I_F . However, if the system is not uniformed or the load model is not a constant current, the results might not be valid [2].

3) MODIFIED TAKAGI METHOD

Depending on the relay types, the availability of the pre-fault current is under question. Having considered this fact, the modified Takagi method uses I_{R0} to change the phase of I_F current so as to reduce the impact of $R_F(I_F/I_R)$ in fault location finding process. Although this technique has superior performance over Takagi method [3]–[5], it is highly dependent on accurately knowing the source impedance.

4) ERIKSSON METHOD

Eriksson method uses the source impedance parameters to eliminate the effect of any reactance errors such as load or fault resistance with high accuracy. This technique can calculate the value of R_F , which is not possible in any other methods, but is unable to estimate the fault location in 3 terminals line or in TUP lines. [6]

B. FAULT LOCATION ERROR IN TUP LINES USING SINGLE-ENDED TECHNIQUE PROTECTION SCHEME

First, we consider the described TUP line in which the parallel lines are connected at both ends shown in Fig. 3.

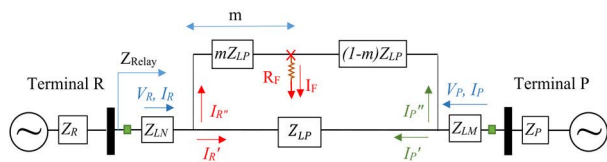


FIGURE 3. A fault at TUP line in the conventional scheme.

In both terminals *R* and *P*, distance relays are installed, and their short circuit current is I_R and I_P , respectively. Moreover, m is the percentage of L'_P , where the fault takes place. The conventional arrangement of TUP line leads to a non-uniform line impedance due to its arrangement, and it is of great importance to calculate the error in fault location in the single-ended fault technique. For calculating this error, assume a fault takes place in the location of m . The I_R , V_R and I_P and V_P are measured by relays in terminals *R* and *P*, respectively. The I_R and I_P are divided into I_R' , I_R'' , I_P' , and I_P'' in the branches. The measuring fault location relay error in the relay located at terminal *R* is calculated according to Fig. 3:

$$I_R = I_R' + I_R'' \tag{4}$$

$$\frac{I_R'}{I_R''} = \frac{m}{2 - m} \tag{5}$$

$$I_R = \frac{2}{2 - m} I_R'' \tag{6}$$

$$I_P = I_P' + I_P'' \tag{7}$$

$$\frac{I_P'}{I_P''} = \frac{1 - m}{1 + m} \tag{8}$$

$$I_P = \frac{2}{1 + m} I_P'' \tag{9}$$

$$V_R = I_R Z_{LN} + I_R'' m Z_{LP} + I_P' m Z_{LP} + R_F (I_P + I_R) \tag{10}$$

And the calculated impedance by the relay is:

$$Z_R = \frac{V_R}{I_R} = Z_{LN} + \frac{I_R''}{I_R} m Z_{LP} + \frac{I_P'}{I_R} m Z_{LP} + R_F \left(\frac{I_P}{I_R} + 1 \right) \tag{11}$$

By applying (5) and (8) into (10) it will be:

$$Z_R = Z_{LN} + \frac{2m - m^2}{2} Z_{LP} + \left(\frac{m - m^2}{2} \left(\frac{I_P}{I_R} \right) \right) Z_{LP} + R_F \frac{I_F}{I_R} \tag{12}$$

It is noteworthy to mention that the distance relays indicate the location of the fault based on the calculated reactance and the initial data of the line's parameters, such as X_0 , X_1 , R_0 , R_1 . Since the distance relays can only receive one line's parameters, the impedance of the parallel line is assumed as a

uniform line with half of its impedance. Assuming a uniform line, the impedance that the relay should calculate, $Z_{Correct}$, is as follows:

$$Z_{Correct} = Z_{LN} + \frac{m}{2} Z_{LP} \tag{13}$$

and Z_{Error} , which can be interpreted as the difference between the actual impedance that the relay must calculate and the apparent impedance that the relay sees, is derived as:

$$Z_{Error} = Z_{Correct} - Z_R = \left(1 + \frac{I_P}{I_R} \right) \left[\left(\frac{m^2 - m}{2} \right) Z_{LP} - R_F \right] \tag{14}$$

where, Z_{Error} is an error that might lead to miscoordination, as the relay apparent impedance might become bigger than $120\% (Z_{LN} + Z_{LP}/2 + Z_{LM})$ [24].

Moreover, another fault location related error is the difference between exact distances of the fault location and the one that the relay is programmed to calculate, which is called Distance Error, $Z_{Error_Distance}$. While there is an error in precisely locating the fault, the dispatched linemen have to patrol through the line to find the exact fault point. This is a time-consuming process and leads to a more outage time of the line. The distance error can be derived as:

$$Z_{Distance} = Z_{LN} + m Z_{LP} \tag{15}$$

$$Z_{Error-Distance} = Z_{Distance} - Z_R = \frac{m^2}{2} Z_{LP} + \frac{I_P}{I_R} \left[\left(\frac{m^2 - m}{2} \right) Z_{LP} - R_F \frac{I_F}{I_R} \right] \tag{16}$$

As shown in (14) and (16) the proportion of I_P/I_R leads to a considerable error, where I_P is much bigger than I_R . It is therefore obvious that the error of the relay installed in one end could be much higher than that of the other side. Moreover, the length of Z_{LP} is another dominant factor in both miscoordination and $Z_{Error-Distance}$, as the impedance of fault that the relay calculates could be more than $120\% Z_{Total}$ [24].

III. THE PROPOSED METHOD

A. REARRANGEMENT TECHNIQUE

The main goal of the proposed method is to reduce Z_{Error} and $Z_{Error-Distance}$ not only to ease the procedure of finding the exact location of the fault but to prevent miscoordination. The proposed method consists of two steps. The first one (as shown in Fig. 4) is to disconnect the points *A* or *B*, which leads to new Z_R as:

$$V_R = I_R Z_{LN} + (I_R + I_P) m Z_{LP} + R_F I_F \tag{17}$$

$$Z_R = \frac{V_R}{I_R} = Z_{LN} + \left(1 + \frac{I_P}{I_R} \right) m Z_{LP} + R_F \frac{I_F}{I_R} \tag{18}$$

According to the new topology, and as the line is now uniform, Z_{Error} and $Z_{Error-Distance}$ can be derived as: (if *B* is disconnected):

$$Z_{Correct} = Z_{LN} + m Z_{LP} = Z_{Correct-Distance} \tag{19}$$

TABLE 2. Selecting the correct fault location table.

o	Condition	Fault type:	Relay R	Relay P	Fault section
1	$FL_{relay R} + FL_{relay P} \approx L_{AR} + L_{AP}$	any type	✓	✓	A
2	$FL_{relay R} < L_{AR}$	SLG	✓	✗	B_R
3	$FL_{relay P} < L_{AP}$	SLG	✗	✓	B_P
4	$(FL_{relay R} - L_{AR}) < (FL_{relay P} - L_{AP})$	SLG	✓	✗	B_R
5	$(FL_{relay R} - L_{AR}) > (FL_{relay P} - L_{AP})$	SLG	✗	✓	B_P
6	$FL_{relay R} < L_{AR}$ and $I_{kss_R} > I_{kss_P}$	LLG,LLL,LL	✓	✗	B_R
7	$FL_{relay P} < L_{AP}$ and $I_{kss_R} < I_{kss_P}$	LLG,LLL,LL	✗	✓	B_P
8	$FL_{relay R} < L_{AR}$ and $I_{kss_R} < I_{kss_P}$	LLG,LLL,LL	✗	✗	B_P or B_R
9	$FL_{relay P} < L_{AP}$ and $I_{kss_R} > I_{kss_P}$	LLG,LLL,LL	✗	✗	B_P or B_R
10	$(FL_{relay R} - L_{AR}) < (FL_{relay P} - L_{AP})$ and $I_{kss_R} > I_{kss_P}$	LLG,LLL,LL	✓	✗	B_R
11	$(FL_{relay R} - L_{AR}) > (FL_{relay P} - L_{AP})$ and $I_{kss_R} < I_{kss_P}$	LLG,LLL,LL	✗	✓	B_P
12	$(FL_{relay R} - L_{AR}) < (FL_{relay P} - L_{AP})$ and $I_{kss_R} < I_{kss_P}$	LLG,LLL,LL	✗	✗	B_P or B_R
13	$(FL_{relay R} - L_{AR}) > (FL_{relay P} - L_{AP})$ and $I_{kss_R} > I_{kss_P}$	LLG,LLL,LL	✗	✗	B_P or B_R

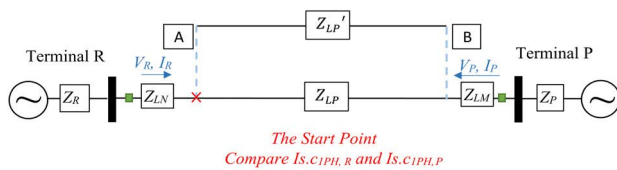


FIGURE 4. The first step of the proposed method.

$$Z_{Error-Distance} = Z_{Error} = \frac{I_P}{I_R} m Z_{LP} + R_F \frac{I_F}{I_R} \quad (20)$$

However, if A is disconnected then:

$$V_R = I_R(Z_{LN} + Z_{LP}) + (I_R + I_P)(1 - m)Z_{LP} + R_F I_F \quad (21)$$

$$Z_R = \frac{V_R}{I_R} = (Z_{LN} + Z_{LP}) + (1 + \frac{I_P}{I_R})(1 - m)Z_{LP} + R_F \frac{I_F}{I_R} \quad (22)$$

$$Z_{Correct} = Z_{LN} + Z_{LP} + (1 - m)Z_{LP} \quad (23)$$

$$Z_{Error} = \frac{I_P}{I_R} (1 - m)Z_{LP} + R_F \frac{I_F}{I_R} \quad (24)$$

On the other hand, $Z_{Error-Distance}$ is

$$\begin{aligned} Z_{Distance-Correct} &= Z_{LN} + mZ_{LP} \Rightarrow Z_{Error-Distance} \\ &= (m - 1)(2 + \frac{I_P}{I_R})Z_{LP} \\ &\quad + R_F \frac{I_F}{I_R} \end{aligned} \quad (25)$$

It is obvious that if a fault occurs at the sections L_N , L_M , or L_P in Fig. 4, the problem can be addressed as described by equation (2), and the effect of the other side's current on the impedance of the relays is negligible. Another advantage of this step is that the impedance of the line is uniformed regardless of the location of the fault.

Moreover, in the conventional scheme of connecting TUP lines, there would always be an error due to the settings of the relays, whether the fault occurs at sections L_N , L_M , or L_P .

However, by disconnecting one side the uniformity of the line will eliminate this error.

Nevertheless, whether A or B is disconnected two different $Z_{Error-Distance}$ can be derived according to equations (20) and (25). The best solution, thus, for minimizing the error of $Z_{Error-Distance}$ is to discard the result of one relay. Discarding a relay result is according to the $I_{short-circuit}$ of both ends, in a way that the relay associated with the lower $I_{short-circuit}$ will be ignored. The policy taken to discard any relay results is described in table 2.

It is important to note that the short circuit current is highly dependent on the type of the fault, and since a majority of fault's type are SLG ones, the rearrangement should be calculated accordingly. Consequently, for other types of faults, where the proportion of $I_{S.C3PH.R}/I_{S.C3PH.P} > 1$ and $I_{S.C1PH.R}/I_{S.C1PH.P} < 1$ the $Z_{Error-Distance}$ might not satisfy all the constraints.

In the next step of the proposed rearrangement, two main goals under two constraints are considered. The first goal is to minimize $Z_{Error-Distance}$ to be lower than the sight range of the linemen teams, and the other one is to maintain protection coordination. In the proposed algorithm, to reach these goals, Z_{LP} is reduced by dividing into multiple sections being briefly described in Fig. 6; yet, it is vitally important to describe the constraints described in the following.

1) PROTECTION CONSTRAINT (P.C)

Assume that a fault occurs at T_N shown in Fig. 5, and I_R is much bigger than I_P . It is obvious that $Z_{Error-Distance}$ in the Relay (R) is less than that of Relay (P). However, the impedance calculated by Relay (R) and (P), which are described in equations (18) and (22), should not exceed 120% ($Z_{LN} + Z_{LP} + Z_{LM}$) to prevent miscoordination for all fault types [24].

2) VISUAL CONSTRAINT (V.C)

Any linemen team whose job is to locate and repair the failed equipment of lines has a sight range depending on some fac-

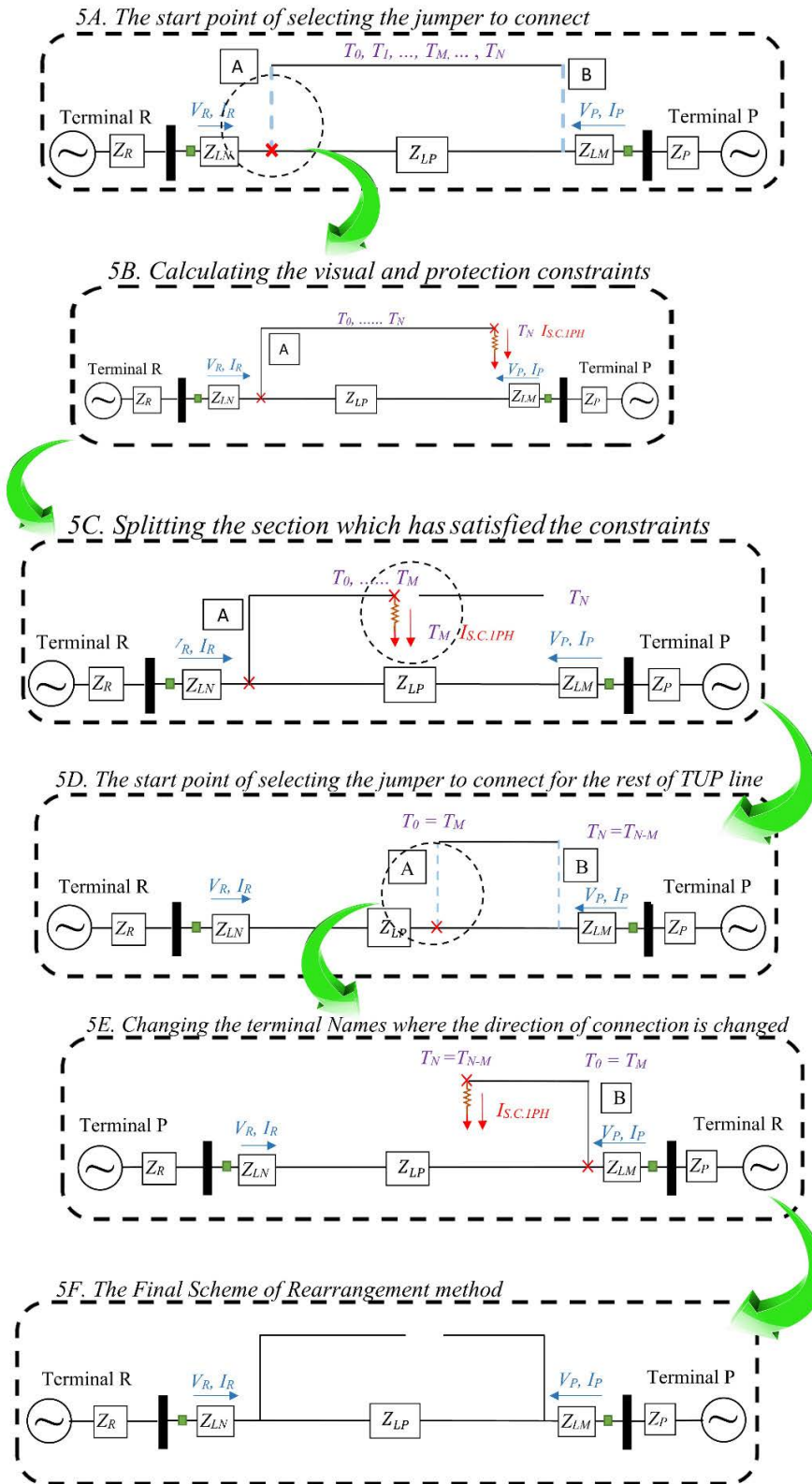


FIGURE 5. Rearrangement process illustration.

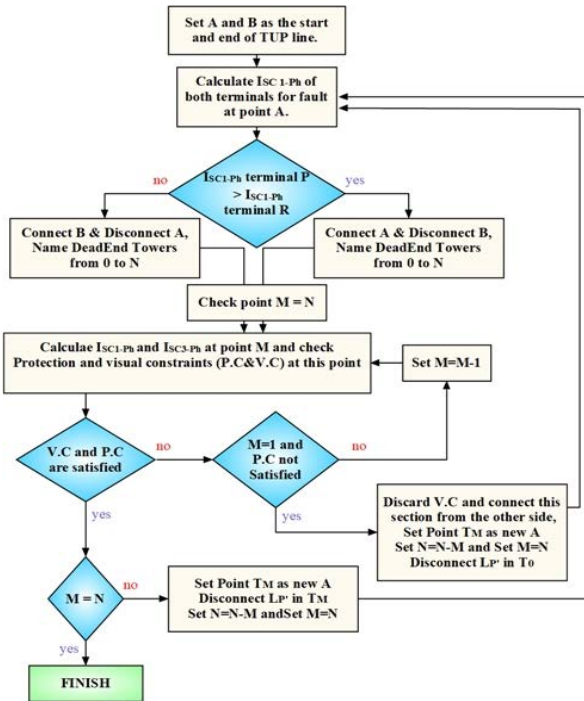


FIGURE 6. Flow chart of rearrangement method.

tors. These factors root from environmental conditions of the line’s surroundings and their equipment such as binoculars, drones and etc. If $Z_{Error-Distance}$ is less than this sight range, it is highly probable that the linemen team can locate the exact place of the fault occurrence as soon as they patrol to the point that the relay had determined.

3) LINE TOPOLOGY CONSTRAINT

As the second step of the proposed rearrangement, it is suggested to divide the TUP line into multiple sections, yet these changes can merely occur in dead-end towers, where donated as N_i in Fig. 5.

The second step of the rearrangement method starts from the first point of the TUP line near to the terminal, where $I_{S.C1.P.H.P}$ is bigger than the other side. An example of this process is illustrated in Fig. 5.

This procedure is described as follows:

- 1) If $I_{S.C1.P.H.R} > I_{S.C1.P.H.P}$ at T_0 , connect A, otherwise connect B. (Fig 5-A)
If B is connected then rename terminal P as R and terminal R as P for a fault at T_0 . (Fig 5-E)
- 2) Calculate $Z_{Error-distance}$ for Relay (S) and Z_{Error} All Faults Type for Relay (R and P). (Fig 5-B)
- 3) Compare $Z_{Error-distance}$ and Z_{Error} All Faults Type with visual constraints and protection constraint respectively.
- 4) If the constraints are satisfied disconnect T from the rest of TUP line. (Fig 5-C)
If the entire line is totally energized finish the process. (Fig 5-F)

If the entire line is not energized, Set $T_0 = T_M$ and start the processing from stage 1. (Fig 5-C)

- 5) If the constraints are not satisfied set T_M to the previous dead-end tower and start the processing from stage 2. (Fig 5-C)

If the visual and protection constraints cannot be both satisfied, only consider the protection constraint.

In the second step, the impact of Z_{LP} is reduced on the exact fault location error, while maintaining protection coordination. As mentioned before, in the faults occurring between terminal R and T_0 in Fig. 7, the relay (R) shows better results compared to the one on the other side. Similarly, for locations between T_0 and terminal P, relay (P)’s fault locator shows more accurate results for SLG faults compared to that of the other side. Moreover, in the faults occurring on the main line (section A in Fig. 7), both relays can show reliable answers for the fault location regardless of the fault type. In contrast, in the conventional arrangement schemes in the entire part of these sections, there is a considerable error causing both relays to show unreliable results for fault location with the possibility of miscoordination.

The flow chart of the proposed algorithm is shown in Fig. 6. According to Fig. 5 it is assumed that Terminal R is close to point A and Terminal P is close to point B, moreover the dead-end towers are named as T_0 to T_N .

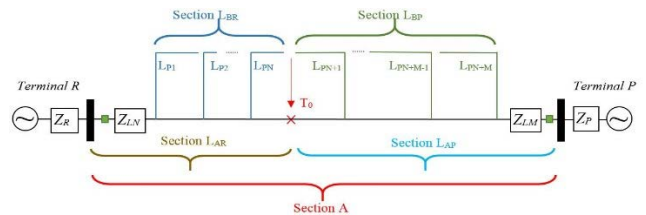


FIGURE 7. A single line diagram of a rearrangement TUP line.

B. SELECTING THE CORRECT FAULT LOCATION

As it is mentioned in 3.1 both relays might not indicate the correct fault location and it is of great importance to detect which relay is showing the reliable fault location under various conditions. This analysis is summarized in the table (2) for a single line diagram shown in Fig. 7.

If a fault occurs at the section A in Fig. 7 the scheme is like a typical line and based on the used fault location method, both relays can estimate a reliable fault location. On the other hand, since most of the faults’ type in power transmission systems are SLG, the proposed rearrangement method is based on this type of the fault; consequently, for this type of fault at least one of the relays can estimate the location of the fault as it is shown in table 2.

However, the proposed method can detect the other fault types such as LLG or LLL in a proportion of the line, where the $\frac{I_{S.C3.P.H.R}}{I_{S.C3.P.H.P}} > 1$ and $\frac{I_{S.C1.P.H.R}}{I_{S.C1.P.H.P}} > 1$.

IV. SIMULATED CASES EVALUATION

The simulated system was developed using Matlab software Version 2019 b, with the use of the line’s parameters which are shown in table 3.

TABLE 3. Parameters of a TUP transmission line.

System Voltage: 66KV		System Frequency: 50Hz	
Source		Source Impedance	
$E_R = 1\angle 0^\circ pu$		$Z_{SR} = 0.27 + 2.96j$	
$E_P = 1\angle -2.5^\circ pu$		$Z_{SP} = 10.05 + 23.54j$	
Section length of transmission line in old scheme (km)			
$L_N = 13.6$	$L_M = 24.5$	$L_P = 1.2$	
Section length of rearrangement transmission line and constraints (km)			
$L_N = 13.6$	$L_M = 1.2$	$L_{P1} = 5$	
$L_{P2} = 2.95$	$L_{P3} = 2.95$	$L_{P4} = 1.3$	
$L_{P5} = 1.7$	$L_{P6} = 2$	$L_{P7} = 2.3$	
$L_{P8} = 3.3$	$L_{P9} = 3$	$V.C = 2$	
Transmission line parameters (Ω/km)			
$R_0 = 0.3328$	$X_0 = 1.3795$	$R_1 = 0.1759$	$X_1 = 0.4092$
(Ω/km)		(Ω/km)	
$X_{TOTAL-OLD-SCHEME} = 11.0672 (\Omega)$		$X_{TOTAL-REARRANGEMENT-SCHEME} = 16.067 (\Omega)$	

A Fars 66KV, transposed with TUP line was simulated using the distributed parameter model shown in Fig. 8. Various system operations and fault conditions are investigated during the simulations process and the results of new arrangement are compared with the conventional one. The fault conditions and results are summarized in Fig. 9.

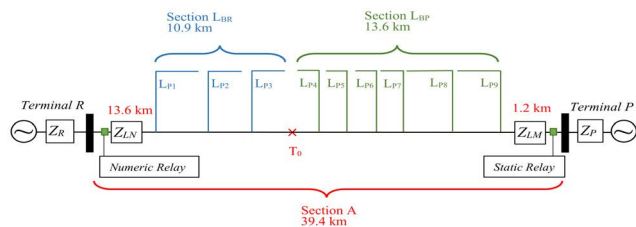


FIGURE 8. A single line diagram of the rearrangement TUP line in Fars network.

In Fig. 9 the error-distance for SLG faults is compared with the result of relay P and R in the conventional scheme. The error of rearrangement method is calculated for the faults occurring at the sections L_{BR} and L_{BP} . However, for the faults occurring at the section A, regardless of the fault type and with $R_F = 0$, the rearrangements method has no error-distance.

Although for 3PH faults at sections L_{BR} and L_{BP} the rearrangement results violate the Visual Constraint, they still yield better results compared with that of the conventional schemes. Since the relays are experiencing an overreach, the worse-case is when the R_F is equal to zero.

The results of rearrangement method on sections L_{BR} and L_{BP} for SLG faults with different R_F are compared with each other and indicated that they do not violate Visual Constraints and its results are illustrated in Fig. 10.

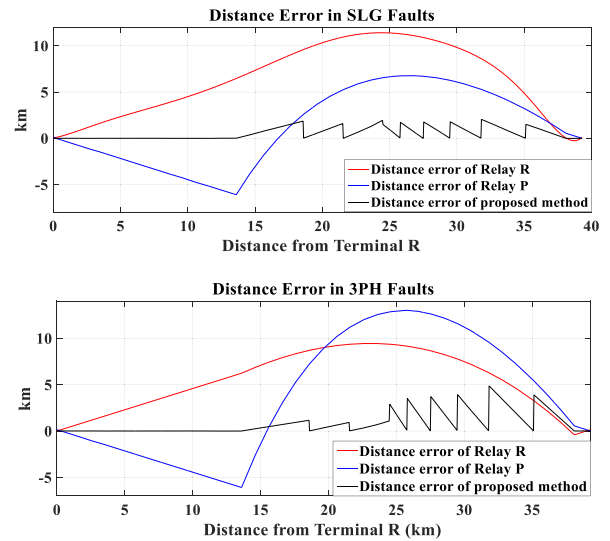


FIGURE 9. The results of comparison between conventional and proposed scheme.

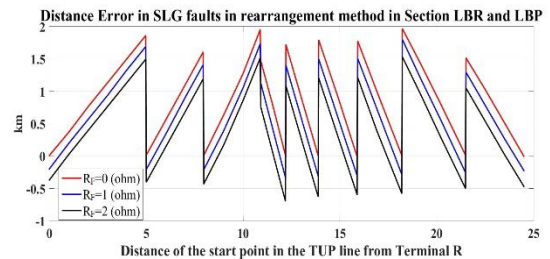


FIGURE 10. The results of SLG fault in the proposed with diverse R_F .

The results shown in Fig. 9 and 10, indicates that in all sections of the new rearrangement scheme, the protection constraints are satisfied for both relays. Although in section LBP and merely for 3PH and 2PH faults our proposed technique might violate visual constraint, for all the other types of errors in the entire sections at least one relay can estimate an acceptable fault location and can significantly reduce the error-distance.

V. FIELD FAULT EVENTS EVALUATION

There are several TUP lines in Fars transmission network and for two of them, the proposed technique has been implemented since 2018. One of the installed relays having used our rearrangement technique, can only indicate the fault type and the location of the fault without recording the fault event, as it is a static relay. Moreover, this transmission line has been installed in mountains and without having the data of the faults, finding the exact location of a fault might take up to more than 48 hours. However, after using the rearrangement technique, the shut down time of this line has not exceeded more than two hours.

Six faults occurred in this line since 2018 are reported in table (4) indicate that the $Z_{Error-Distance}$ never exceed 0.81 kilometers, which yield a considerable reduction in

TABLE 4. Field results.

Fault Location Section	Real Fault Location from terminal <i>R</i> (km)	Fault type	Error Distance in conventional scheme (km)		Error Distance in the proposed method (km)
			Relay <i>R</i>	Relay <i>P</i>	
<i>LP1</i>	14.59	SLG	6.8	-3.6	0.369
<i>Section A</i>	5.6	SLG	2.28	-2.45	0.21
<i>LP5</i>	26.8	SLG	6.76	11.14	0.708
<i>LP8</i>	33.8	SLG	4.09	6.47	0.81
<i>LP2</i>	19.6	LL	8.84	8.91	0.33
<i>Section A</i>	30.5	SLG	5.91	9.52	0.27

the repairing process time. Nevertheless, had the proposed technique not been used, the simulation results show that the aforementioned errors could be greater than 11 kilometers and the shut down time would greatly be increased.

For instance, although it was essential to determine the faults data to locate the fault in the discussed transmission line, the static relay is not replaced with a numeric one, and yet the location is reliably estimated for majority of the faults.

VI. COMPARATIVE STUDY

In this section our proposed method via other methods are compared in diverse categories namely, accuracy, calculation and cost.

In this comparison, the other methods can be categorized into two main sections, Single ended fault detection and Synchronized phasor measurements. The results of the comparison are summarized in the table 5. Moreover, to clarify, this comparison is imposed upon the case study in section V. For single-ended group, the Eriksson method is used as it is the most accurate one among the other single-ended methods. [6] The results are illustrated in table 6.

TABLE 5. Comparison table.

Fault Location techniques	Accuracy	Calculation	Cost
Single-ended	unreliable	Not applicable	affordable
Synchronized phasor measurements	accurate	Complex	Highly expensive
Proposed method	Error is Less than V.C in SLG faults ¹	Simple	affordable

¹ According to section III.A.2

According to the table 5, not only Single ended fault detection techniques are unable to estimate the fault location correctly, but they might also lead to miscoordination, meaning that these techniques are unreliable for TUP line cases. This result can be proved according to table 6; on the other hand;

TABLE 6. Comparison table of the simulated case.

Fault Location techniques	Maximum Error in Km	Real Fault Location from terminal <i>R</i> (km)	Fault type	Line length (km)	Maximum Error	Finding the fault location by linemen team (hour)
Single-ended (Eriksson method)	11.36	24.5	SLG	39.3	28.9%	Up to 72 hours
Synchronized phasor measurements	0.143	25.3	SLG	39.3	0.36%	Up to 3 hours
Proposed method	1.965	31.8	SLG	39.3	4.98%	Up to 3 hours

although the error of proposed method is 5%, it is less than the visual constraint. This means that the result is reliable for the linemen team and finding the location of the fault by the repairing team is almost the same as using Synchronized phasor measurements method. It should be noted that the maximum errors described in table 6 can be varied according to the arrangement of TUP lines and the type of the fault.

Moreover, Synchronized phasor measurements methods can accurately locate the fault location, yet according to the proposed method, the accuracy of the fault locating is based on the topology of the network, and hence one can rearrange the network according to the needed accuracy.

From calculation standpoint, the Single ended fault detection based techniques are not supposed to have high complex calculation, since they have no access to the other end's current and voltage, and hence unable to find the location of the fault. However, Synchronized phasor measurements methods are in dire need of complex calculation, resulting offline method in some cases. However, the proposed method is much simpler in regards to the calculation complexity and the location of the fault can be determined by using table 2. This means that in the proposed method even old distance relays are functional.

Although, according to table 6, synchronized phasor measurements methods have the best results in finding the fault locations, they impose high financial burden to the project for two main reason. The first one roots from this point that a considerable number of TUP lines are temporarily and they can correctly be protected by using single-ended based techniques after the installation period of the whole project. The second one is, however, using high technological devises such as PMUs or GPS system, making them highly expensive.

Yet, despite the fact that, single-ended based techniques are the most affordable ones, they cannot fulfill the desired accuracy for fault locating. On the other hand, in spite of being slightly more costly than single-ended based techniques, the proposed method can have a significant impact on the accuracy of fault locating.

Comparing the final results with those of similar works, one can simply conclude that the novel proposed

rearrangement technique not only can reduce the outage time, but also might discard the need of installing high technologic devices such as PMUs, GPS and even numeric relays for finding the exact location of the faults.

VII. CONCLUSION

Single-ended fault location methods could be accurate if the transmission line is uniform, while in uncompleted tied transmission line reveal unreliable fault location. Connecting parallel section of the uncompleted transmission lines make the line non-uniformed.

On the other hand, Multi-ended fault location algorithms can greatly improve the fault location accuracy, yet a majority of these algorithms require the transfer of large amounts of data, alignment of the data sets, and complicated solutions to calculate the distance to the fault point. These algorithms are prone to the risk of time-consuming fault location determination in online applications, while imposing considerable costs. Moreover, financial investigation to implement such techniques are supposed to be unnecessary in temporary transmission line schemes.

The proposed novel and economic rearrangement technique has many advantages over existing methods in that it can calculate the location of the fault much faster, maintain the protection coordination constraint compared with conventional techniques. Furthermore, it does not require advanced digital relays, let alone data transfer. In the case of multi-section or hybrid lines, our proposed method can still yield acceptable answers with some considerations. In fact, the relay's fault location has to be modified by considering the impedance of different sections.

In the conventional arrangement of these types of transmission lines, in cases, the relays could not locate the fault location. However, implementing the proposed technique, most of the time, relays can calculate the actual fault location and present the data to operations personnel in real-time. It is noteworthy to mention that the proposed technique is applied to the Fars-Iran power system in 2018 and yield excellent performance in practice since then.

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HOOMAN TORKAMAN received the B.S. and M.Sc. degrees in power engineering from Shiraz University, Iran, in 2010 and 2013, respectively. His research interests include hydro power plants, renewable energy, protection coordination, power electronics, and data science. Recently, he is focused on smart grids and renewable energy.



EHSAN ZERAATKAR received the B.S. and M.Sc. degrees in control engineering from Shiraz University, Iran, in 2008 and 2012, respectively. His research interests include optimizing convergence in numerical methods, such as neural networks. Recently, he is focused on machine learning and deep learning and its application in signal and image processing.



NASIM DEYHIMI received the B.S. degree in electrical engineering from the Shiraz University of Technology, Iran, in 2010, and the M.Sc. degree in power engineering from Shiraz University, in 2013. His research interests include smart grids, renewable energy, power system stability, power electronics, and data science. Recently, he is focused on power distribution planning and renewable energy.



HASSAN HAES ALHELOU (Senior Member, IEEE) received the B.Sc. degree (Hons.) from Tishreen University, in 2011, and the M.Sc. and Ph.D. degrees (Hons.) from the Isfahan University of Technology, Iran. He is currently with the Department of Electrical and Computer Systems Engineering, Monash University, Clayton, VIC, Australia. At the same time, he is a Professor and a Faculty Member with Tishreen University, Syria, and a Consultant with Sultan Qaboos University (SQU), Oman. Previously, he was with the School of Electrical and Electronic Engineering, University College Dublin (UCD), Dublin, Ireland, from 2020 to 2021, and with the Isfahan University of Technology (IUT). He has published more than 200 research papers in high-quality peer-reviewed journals and international conferences. His research papers received 2550 citations with H-index of 26 and I-index of 56. He has authored/edited 15 books published in reputed publishers, such as Springer, IET, Wiley, Elsevier, and Taylor and Francis. He serves as an Editor for a number of prestigious journals, such as *IEEE SYSTEMS JOURNAL*, *Computers and Electrical Engineering* (Elsevier), *IET Journal of Engineering*, and

Smart Cities. He has also performed more than 800 reviews for high prestigious journals, including *IEEE TRANSACTIONS ON POWER SYSTEMS*, *IEEE TRANSACTIONS ON SMART GRID*, *IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS*, *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, *Energy Conversion and Management*, *Applied Energy*, and *International Journal of Electrical Power and Energy Systems*. He has participated in more than 15 international industrial projects over the globe. His research interests include renewable energy systems, power systems, power system security, power system dynamics, power system cybersecurity, power system operation, control, dynamic state estimation, frequency control, smart grids, micro-grids, demand response, and load shedding. He was included in the 2018 and 2019 Publons and Web of Science (WoS) list of the top 1% best reviewer and researchers in the field of engineering and cross-fields over the world. He was a recipient of the Outstanding Reviewer Award from many journals, such as *Energy Conversion and Management*, *ISA Transactions*, and *Applied Energy*. He was a recipient of the Best Young Researcher in the Arab Student Forum Creative among 61 researchers from 16 countries at Alexandria University, Egypt, in 2011. He also received the Excellent Paper Award 2021/2022 from *IEEE CSEE JOURNAL OF POWER AND ENERGY SYSTEMS* (SCI IF: 3.938; Q1).



PIERLUIGI SIANO (Senior Member, IEEE) received the M.Sc. degree in electronic engineering and the Ph.D. degree in information and electrical engineering from the University of Salerno, Salerno, Italy, in 2001 and 2006, respectively. Since 2021, he has been a Distinguished Visiting Professor with the Department of Electrical and Electronic Engineering Science, University of Johannesburg. He is currently a Professor and the Scientific Director of the Smart Grids and Smart Cities Laboratory, Department of Management and Innovation Systems, University of Salerno. His research interests include centered on demand response, energy management, the integration of distributed energy resources in smart grids, electricity markets, and planning and management of power systems. In these research fields, he has coauthored more than 660 articles, including more than 390 international journal articles that received in Scopus more than 13600 citations with an H-index equal to 57. In 2019, 2020, and 2021, he has been awarded as a Highly-Cited Researcher in engineering by Web of Science Group. He has been the Chair of the IES TC on Smart Grids. He is an Editor of the Power & Energy Society Section of *IEEE ACCESS*, *IEEE TRANSACTIONS ON POWER SYSTEMS*, *IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS*, *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, and *IEEE SYSTEMS JOURNAL*.

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