A simplified approach to calculate the earth fault current division factor passing through the substation grounding system

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Abstract. The main aim of designing a safe grounding system is to provide a low impedance path to the flow of the earth fault currents without exceeding the operational constraints and equipment limits that will ensure electrical continuity. One of the most significant and well-known parameters to design a safe grounding system in power systems is the exact determination of the maximum earth fault current division factor. This paper presents a simplified and accurate method to calculate the earth fault current division factor in different states of the earth fault occurrence within and the vicinity of the substation under study. In the proposed method, a hybrid overhead-cable line, the impact of the frozen soil, mutual coupling between phase conductors and guard wires, grounding system resistance of adjacent substations, different tower footing resistances, the impact of the phase conductor impedance, and different spans in transmission lines can be considered. In addition, a closed-form formulation is also developed for the occurrence of the earth fault on the transmission line. Finally, details of the analysis results of this study have been compared with other methods in the literature. The validity and accuracy of the proposed approach also have been assayed and confirmed in details.

1. Introduction

Designing a safe grounding system is one of the most important issues in substation design which minimize the touch and step voltages elevation within permissible limits and provides low impedance path to pass the earth fault currents with considering the operation and protection constraints and therefore the continuity of electricity. To design a safe substation grounding

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grid, we need to determine correctly the earth fault current passing through the grounding system and also its distribution in several alternate paths. The earth fault currents in a power system flow along phase conductors, overhead ground wires, towers and substation grounding systems [1]. Therefore, it is necessary to model overhead lines and adjacent substation grounding systems to calculate, correctly the earth fault current distribution in possible paths.

In the past three decades, a number of researchers have investigated several approaches to determine the earth fault current division and distribution which have

been reported [2–18]. A number of methods have made some different approximations and simplifications for evaluation of this issue such as considering identical spans of incoming/outgoing overhead lines, uniform tower footing resistances, an overhead ground wire connected to the earth at various towers through the tower footing resistance which is substituted by an infinite ladder network and etc. [2–7,12] while the other approaches have been reported as analytical methods [1,8–18]. In addition, the problem of earth fault current division factor was discussed in [19–22] which does not provide an approach for this issue with considering the different length of spans, non-uniform tower footing resistance and adjacent the substation grounding system. The proximity effects among the grounding system of substation under study and other grounding systems have been considered by Nahman [5], Ramezani and Shahrtash [15]. The study presented in [17] is one of the first investigations to assess the impact of the frozen soil on the grounding resistance of the substation grounding grids and the tower footing resistances. The proposed approach in [10] is based on the tableau analysis for an unbalanced and multi-wire a transmission line. This method suffers from complexity in implementation of a large and complicated power system and also for Hybrid overhead-cable Transmission Lines (HTL). In [12], a 5×5 primitive matrix model is applied to determine earth fault current distribution through returning paths in electric distribution systems without considering HTL, tower footing resistances and non-uniform spans. The earth fault split factor is defined by an experimental equation in [13]. The frozen soil can lead to an increase in grounding resistances, and consequently, the earth fault current division factor will change. As well as one of the most significant parameters affected by the earth fault current division factor is cable connected to the overhead line to feed a substation which has been reported in [6,23]. In these cases, a remarkable part of the earth fault current passing through the cable sheath is injected into the soil. Refs. [24–26] present an analytical formulation to compute the reduction factor in Global Earthing Systems (GESs). A method based on EMTP-ATP program has been presented in [27] to determine the value of currents flowing into substations grounding. The application of the multi-conductor method has been described in [28] to compute fault current distribution on transmission lines. This procedure is based on the Carson-Clem equations which usage to the power frequency calculations is enough accurate although suffers from complexity in simulation. A phase domain based circuit model of the faulted MV network has been presented to evaluate Cross-Country Fault (CCF) currents on hybrid (cable-overhead) medium voltage distribution systems [29,30]. In this approach, the earth fault currents flowing in the cable screens are calculated with CCF occurring in different cable lines. According to this method, the overhead HV network is presented by Thevenin circuit model which is not possible to calculate the earth fault current distribution in the ground wire and tower footing resistances.

Basically, the ability of methods to consider the contribution of the effective parameters in a simple and comprehensive way can be proposed as appropriate criteria to evaluate their performances. A literature review in this issue shows that none of the presented approaches can include all of the mentioned parameters. In this paper a simplified and accurate method with a closed-form formula is developed for the computation of earth fault current passing through a grounding system of substation under study which can be included the following features:

- Non-uniform spans of overhead transmission lines;
- Towers with non-uniform footing resistance;
- Mutual impedance between phase conductors and ground wire;
- Grounding system resistance of adjacent substations;
- Faulted point in inside and outside the substation;
- Including the impedance of phase conductor in calculations;
- Considering substation fed by a hybrid overhead-cable line.

The proposed method in [1] takes into account all the mentioned parameters except one of them. In [8], the authors assumed that the short-circuit current passing through the phase conductor is known, while in the proposed method in this paper, the currents passing through the phase conductors are taken unknown that include in the final proposed formula. As can be seen in the obtained results of this paper, considering this problem in the proposed approach can lead to an accurate and safe calculation of the earth fault current division factor. It can be stated that a major limitation and weakness of the proposed method in this study and some of other references is that some of them cannot investigate the proximity effects among the grounding system of substation under study and other grounding grids. Finally, the results of the proposed method have been compared and validated with those obtained by some previous methods in [1,4] and the accuracy of the presented approach is shown.

2. Problem description

The main aim of designing a grounding system is to provide a return path for generated currents by load imbalances, inductive transfers and earth faults. Earth
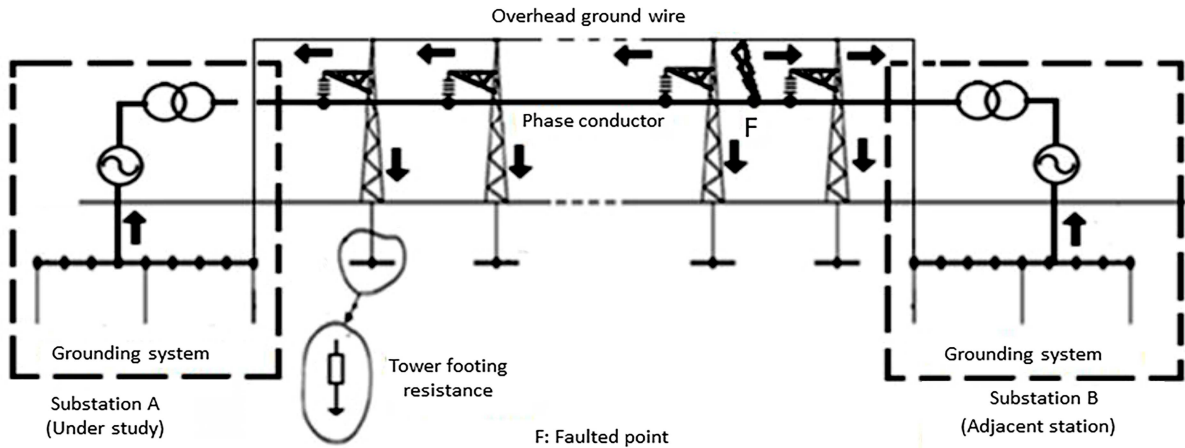
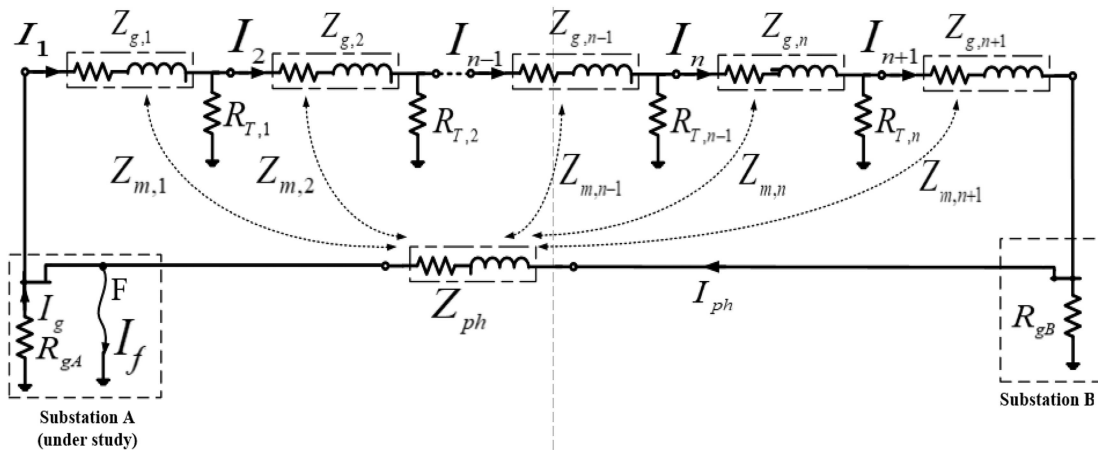**Figure 1.** Typical power system configuration.

Figure 2. Circuit model of the faulted phase for a power network.

faults usually lead to the most hazardous conditions for a grounding system, where touch and step voltages are produced between conductive objects connected to the substation grounding system, the circumambient soil and other conductive objects not directly connected to the grounding system under fault. Determining these maximum hazardous voltages is an important issue for designing a substation grounding system. The magnitude of the earth fault current passing through the grounding grids is an important component in designing a grounding system and their performance, and also plays a key role in computing the Ground Potential Rise (GPR) and then desirable maximum touch and step voltages. From a grounding perspective, only the portion of earth fault current that returns to the grounding grid of substation under study via the buried ground components and the soil rather than the total earth fault current. Figure 1 shows the distribution of the earth fault current in various paths of the power system such as grounding system of adjacent substations, tower footing resistances, phase conductors, guard wires and etc. which can contribute

to a better understanding of the performance of a grounding system. In the sequel, the closed-form formulation of the problem; first for earth faults inside the substation and then it's outside will be developed.

2.1. Earth fault current-division factor calculation

The problem is how to compute the portion of the earth fault current passing through the grounding grid of substation A due to different possible paths in parallel which can be defined as "the earth fault current division factor". Figure 2 shows the circuit model of the faulted phase for the network connected to the faulted point inside substation A. In this figure, the earth fault current division factor (S_f) is defined based on IEEE standard [19] as follows:

$$S_f = \frac{I_g}{I_f}, \tag{1}$$

where I_g and I_f are respectively represented to the magnitude of the earth fault current flowing via the grounding system of the substation A and the magni-

tude of the earth fault current which is calculated by short circuit study.

To solve this problem, the presented procedure by Ramezani and Shahrtash [1] can be used to the solutions of non-uniform ladder circuits. According to this method, the mutual impedance ($Z_{m,j}$) between the overhead ground wires and phase conductors are waived off in the first stage and then the equivalent circuit of overhead ground wires with their self-impedances ($Z_{g,j}$) tower footing resistances ($R_{T,j}$) and grounding system resistance of adjacent substation (R_{gB}) for total number of spans ($n + 1$) will be specified. Finally, by containing the impact of the mutual impedances, the earth fault current distribution among the substation grounding system under study and other parallel paths of the power system is calculated.

In [1], the authors assumed that short-circuit current passing through the conductor phase (I_{ph}) from the adjacent substation side is calculated using short-circuit studies and therefore its value in the presented model presented is known. But, in this paper, however, the injected earth fault current to the faulted point from adjacent substations is one of the unknowns that will be calculated using the proposed method.

2.2. The proposed method to compute S_f due to a fault inside substation A

Based on the presented procedure in [1], Figure 3 depicts a new equivalent circuit with one adjacent substation (for Figure 2) considering the earth fault current sent from the adjacent substation (I_{ph}) to the short circuit place as the unknown parameter. Previous studies of S_f calculation by authors have suffered from some of conceptual and theoretical weaknesses. But in the proposed method as shown in Figure 2, some of the most important parameters affecting the determination of the earth fault current division factor the such as grounding resistance of adjacent substation, the source dependent on the ground wire current and phase conductor impedance (Z_{ph}) have been modeled in the phase branch. Therefore, the general closed-
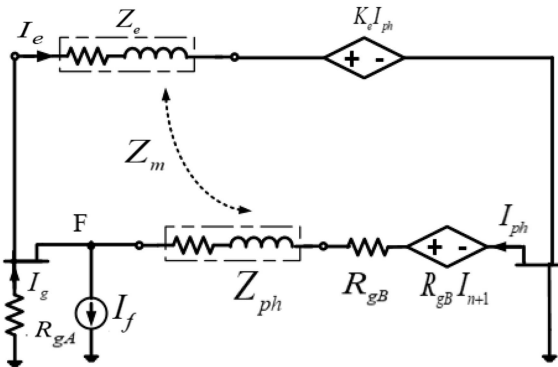
form formula presented in this paper is able to calculate not only earth fault current distribution but also phase current sent from the adjacent substation to the short circuit place. In addition, a portion of the fault current flowing through the overhead ground wire of the incoming/outgoing transmission line is introduced as I_e as shown in Figure 3.

$$Z_e = \frac{T_{11}\left(Z_{g,n+1} + R_{gA}\right) + T_{12}}{\psi_1},$$

$$K_e = \frac{-R_{gA}}{\psi_1},$$

$$\psi_1 = T_{21}\left(Z_{g,n+1} + R_{gA}\right) + T_{22}. \tag{2}$$

Also in Figure 2, I_{n+1} can be found as following:

$$I_{n+1} = \frac{I_e}{\psi_1} + R_{gA}\frac{T_{21}}{\psi_1}I_{ph}, \tag{3}$$

where T_{11}, T_{12}, T_{21}, and T_{22} are transmission matrix elements of non-uniform ladder circuits containing the overhead ground wires and towers which is detailed in Appendix B [1]. With the same procedure, the generalized equivalent circuit for a substation under study with N outgoing transmission lines and adjacent substations can be arranged as shown in Figure 4. By using the equivalent circuit presented in Figure 4 and with substituting I_{n+1} by Eq. (3) for each outgoing transmission lines, the loop equations can be written in matrix form as Eq. (4) in order to calculate earth fault current distribution.

$$\begin{bmatrix} A_{N \times N} & B_{N \times N} \\ C_{N \times N} & D_{N \times N} \end{bmatrix} \begin{bmatrix} I_E \\ I_R \end{bmatrix} = \begin{bmatrix} 0_{N \times 1} \\ R_{N \times 1} \end{bmatrix}.I_f \tag{4}$$

where,

$$A_{N \times N} = \begin{bmatrix} a_{11} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & a_{NN} \end{bmatrix}$$

Figure 3. The equivalent circuit with one adjacent substation for Figure 2.
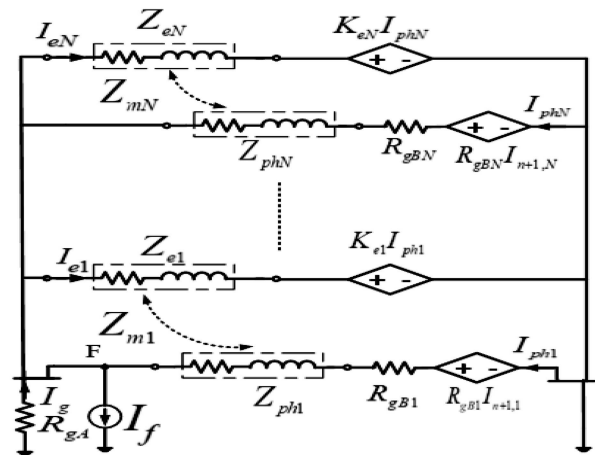
Figure 4. Generalized equivalent circuit with N outgoing transmission line.

$$a_{ij} = \begin{cases} Z_{ei} - \dfrac{R_{gBi}}{\psi_{1i}} - Z_{mi} \\ \qquad \text{if} \quad i = j, \quad i = 1, ..., N \\ 0 \qquad \text{else} \end{cases}$$

and,

$$B_{N \times N} = \begin{bmatrix} b_{11} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & b_{NN} \end{bmatrix}$$

$$b_{ij} = \begin{cases} K_{ei} + R_{gBi} - \dfrac{R_{gBi}^2 . T_{12i}}{\psi_{1i}} - Z_{mi} + Z_{phi} \\ \qquad \text{if} \quad i = j, \quad i = 1, ..., N \\ 0 \qquad \text{else} \end{cases}$$

and

$$C_{N \times N} = \begin{bmatrix} c_{11} & \cdots & -R_{gA} \\ \vdots & \ddots & \vdots \\ -R_{gA} & \cdots & c_{NN} \end{bmatrix}$$

$$c_{ij} = \begin{cases} -\left(\dfrac{R_{gBi}}{\psi_{1i}} + Z_{mi} + R_{gA} \right) \\ \qquad \text{if} \quad i = j \qquad i = 1, ..., N \\ -R_{gA} \qquad \text{else} \end{cases}$$

and

$$D_{N \times N} = \begin{bmatrix} d_{11} & \cdots & R_{gA} \\ \vdots & \ddots & \vdots \\ R_{gA} & \cdots & d_{NN} \end{bmatrix}$$

$$d_{ij} = \begin{cases} R_{gBi} + R_{gA} + Z_{phi} - \dfrac{R_{gBi}^2 . T_{12i}}{\psi_{1i}} \\ \qquad \text{if} \quad i = j \quad i = 1, ..., N \\ R_{gA} \qquad \text{else} \end{cases}$$

and

$$I_E = [I_{e1} I_{e2} \cdots I_{eN}]^T,$$

$$I_R = [I_{ph1} I_{ph2} \cdots I_{phN}]^T,$$

$$R_{N \times 1} = [00 \cdots 0 R_{gA}]^T,$$

where R_{gA} is grounding system resistance of substation A (under study), R_{gBi} is grounding system resistance of i-th adjacent substation and I_{ei} is the earth fault passing through i-th outgoing transmission line from substation A.

2.3. The proposed method to compute S_f due to an earth fault on the transmission line
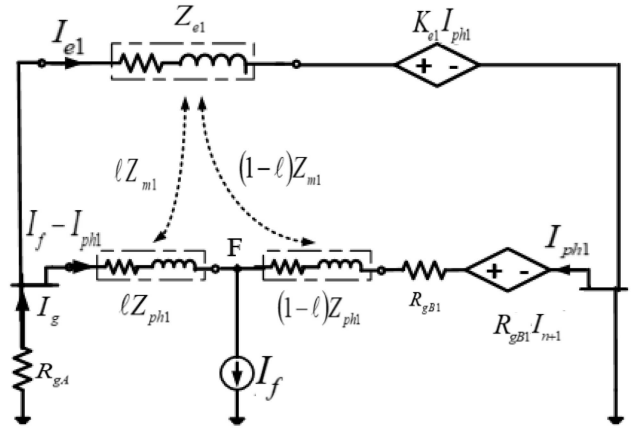As shown in Figure 5, if an earth fault occurs on the

Figure 5. The final equivalent circuit for an earth fault at a distance ℓ.

percentage of transmission line length (in a distance ℓ), Eq. (4) is changed to Eq. (5) for a generalized equivalent circuit with N outgoing transmission line with considering I_{n+1} with Eq. (3) for each outgoing transmission lines.

$$\begin{bmatrix} A_{N \times N} & B_{N \times N} \\ C_{N \times N} & D_{N \times N} \end{bmatrix} \begin{bmatrix} I_E \\ I_R \end{bmatrix} = \begin{bmatrix} E_{N \times 1} \\ K_{N \times 1} \end{bmatrix} . I_f, \quad (5)$$

where,

$$E_{N \times 1} = [X_1 X_2 \cdots X_N]^T,$$

$$K_{N \times 1} = [Y_1 0 \cdots 0]^T,$$

$$X_i = \ell (Z_{phi} - Z_{mi}),$$

$$Y_i = (\ell Z_{phi} - R_{gA}).$$

2.4. Influence of cable line feeding transmission line on S_f
When an earth fault occurs at a substation that is fed by a hybrid cable-overhead transmission line, a significant portion of the earth fault current passes through the cable sheaths and is discharged into the surrounding soil. Due to the high importance of this issue, different studies have attempted to quantify the impact of a hybrid cable-overhead transmission line feeding the substation under consideration to determine the earth fault division factor. Therefore, in order to take this effect into account, we need a proper cable model. Hence, an equivalent circuit of a cable line during an earth fault has been considered to achieve the final hybrid equivalent circuit based on the proposed method in this paper which has been detailed in [15]. By combining this equivalent circuit of a cable line and the aforementioned Figure 2 for overhead lines including the resistance to ground of grounding systems at the ends of each transmission lines, tower footing resistance and etc., the equivalent circuit depicted in
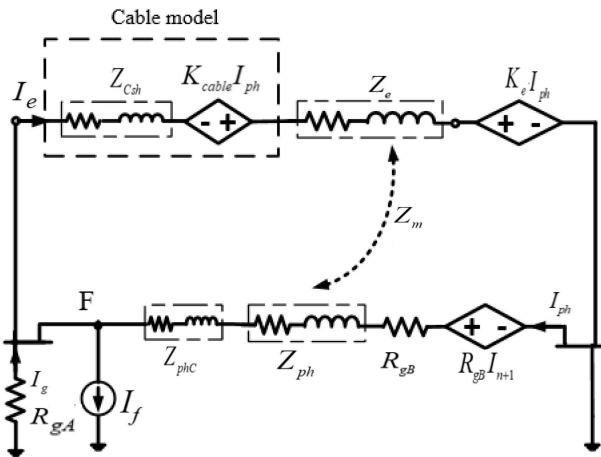
Figure 6. Equivalent circuit of a combined cable-overhead line.

Figure 6 is obtained for a hybrid cable -overhead line during an earth fault at the substation under study. In Figure 6, Z_{Csh} and K_{Cable} are the self-impedance of cable sheaths, the mutual impedance between the cable phase conductors and the cable sheaths, respectively, which can be determined by Carson's theory [16]. Also, Z_{phC} is the phase impedance of cable conductors.

Assuming that a hybrid cable -overhead line has been used to j-th transmission line of a substation with N outgoing transmission line. By applying Kirchhoff's voltage and current laws to the generalized scheme of

Figure 6 for N outgoing transmission line, the earth fault current distribution can be calculated after little changes in Eq. (4) as follows:

- In matrix A, replace Z_{ej} by $Z_{ej} + Z_{Csh\,j}$;
- In matrix B, substitute K_{ej} by $K_{ej} + K_{cable\,j}$ and;
- In matrices C and D, $Z_{ph\,j}$ is changed to $Z_{phC\,j} + Z_{ph\,j}$.

3. The proposed overall procedure

Figure 7 depicts the structure and the steps to be carried out in this paper in order to determine the earth fault current distribution in a power system. Finally, it is clear that this proposed overall procedure can simply calculated the earth fault current split factor (S_f) under following conditions:

- An earth fault occurred to inside or close to the substation under consideration;
- Occurrence of a fault on transmission lines;
- For the occurrence of earth fault on hybrid transmission lines (cable-overhead transmission line).

4. Numerical results

In this section, our main findings and numerical results are presented to validate the proposed procedure and
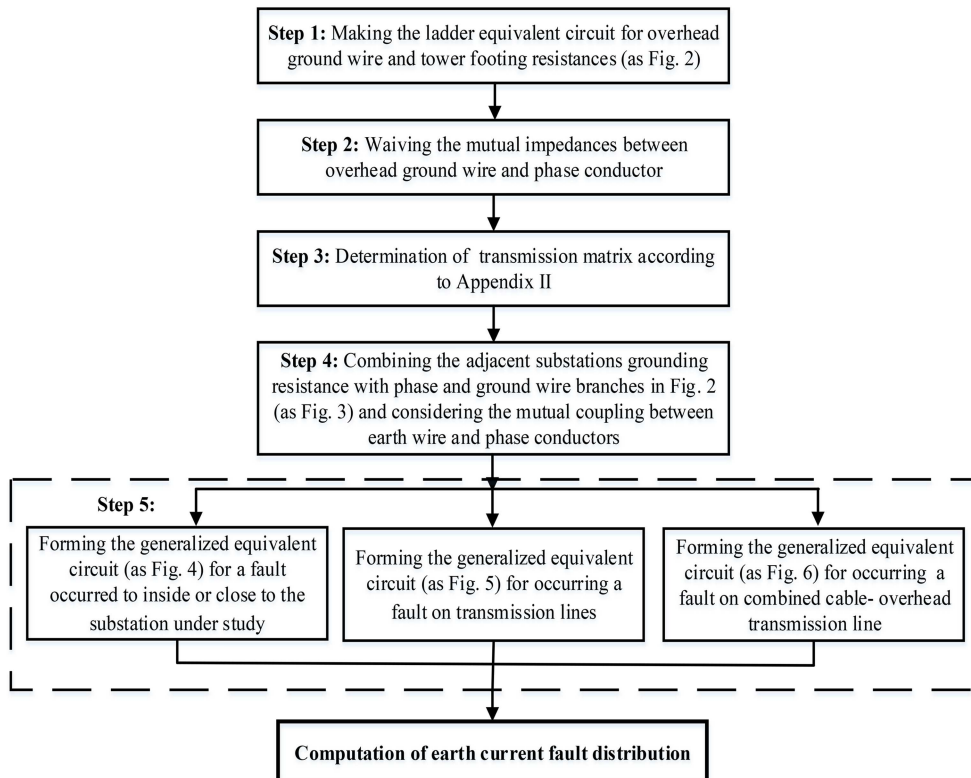

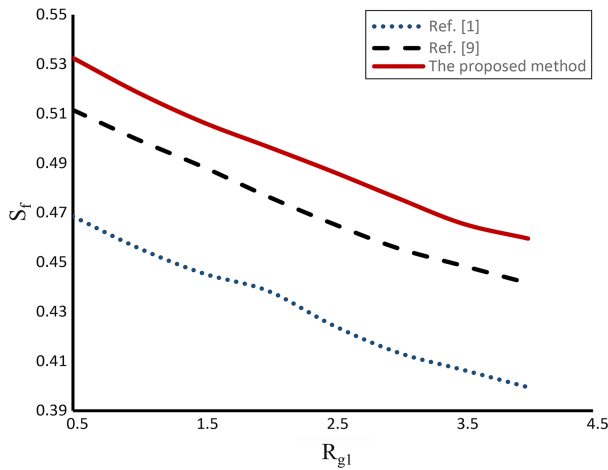**Figure 7.** Flowchart of the proposed procedure.

Figure 8. Comparison of S_f obtained by the proposed method with the results of [8] and [10] for different grounding system resistances of adjacent substation.
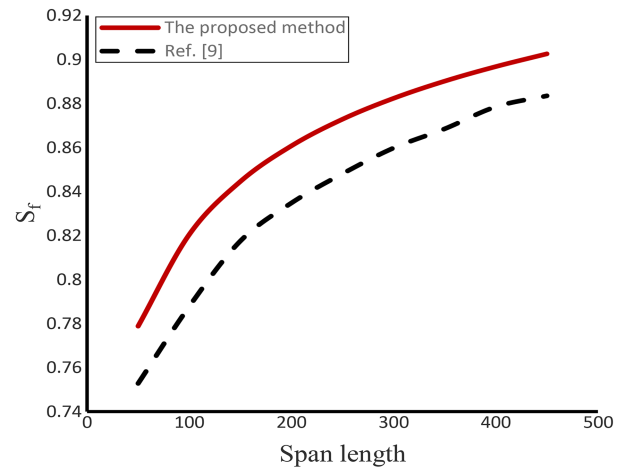

Figure 9. Comparison of S_f obtained by the proposed method with the result of [10] for different span lengths of outgoing transmission line.

to quantify the effects of different parameters on S_f. The analysis and discussion are performed with the aim to predict the efficiency of the proposed method for calculation of the fault current passing through the substation grid in order to design a safe grounding system as the most important constraint.

4.1. Influence of grounding system resistance of adjacent substation on S_f

The results of earth fault current division factor S_f are computed for the substation of the Karkheh power plant with the given diagram and the transmission line data between substations presented in [1]. In order to compare the results of the proposed method with [1,9], a double circuit transmission line is assumed to be applied to the same network (because the presented procedure in [9] is an accurate, analytical and complicated method to determine the magnitude and distribution of the earth fault current which cannot be applied to the non-identical lines). Figure 8 shows the results of the new method, [1] and, [9] for different values of grounding system resistance of adjacent substation. The accuracy of the proposed closed-form formula is demonstrated with the comparison between the obtained results and those obtained from the more accurate, analytical and complicated procedure based on the complete circuit model [9]. As shown in Figure 9, the curve of the earth fault current division factor calculated by the proposed method is above the curve obtained from [19] and this result guarantees a safer grounding system design rather than[1]. It is necessary to mention that [9] and some previously reported procedures cannot analyze S_f for a substation understudy with the non-identical outgoing transmission lines, while the proposed method can carry it out easily.

4.2. Influence of span length on S_f
Figure 9 shows the earth fault current division factor

(S_f) of substation under study as a function of the span length of outgoing transmission line for the substation of the Karkheh power plant with relative data presented in [1]. The presented values were computed using both the proposed method and the presented procedure in [9]. The obtained findings by both methods are in good agreement which shows the high accuracy of the proposed procedure. Also, the obtained results illustrate that the earth current passing through the grounding system of the substation under consideration will increase when the length of span increases. In addition, the positive error of the obtained results by the presented method will lead to the safe design of a grounding system.

4.3. The obtained results of S_f for earth fault on the transmission line
According to the discussions presented in Section 2, consider now the overhead line section for the given network by Ref. [19] with the data in Appendix A and 20 spans. By applying the proposed procedure, based on the circuit compact model of Figure 5, earth fault current distribution factor calculations are made considering identical spans for an outgoing transmission line of substation under study. Figure 10 compare, for different locations of an earth fault on the transmission line, the obtained results of the proposed method with those obtained in [1,9]. Note that these positive errors of the proposed procedure compared to the presented accurate method in [9] will lead to designing a safe grounding system of substations under study.

4.4. Influence of the number of spans on S_f (for earth faults inside and in the vicinity of a substation)
As aforementioned in the literature review, most of the research studies have suffered from considerable limitation to consider the actual equivalent circuits of
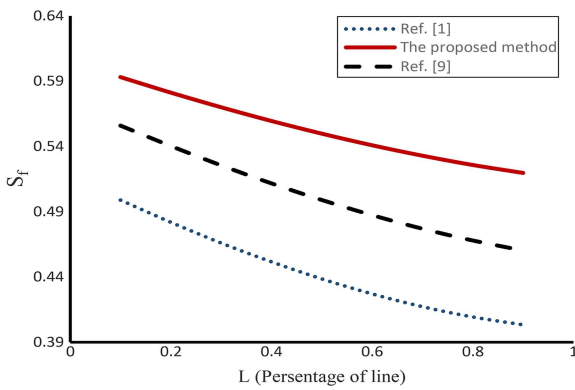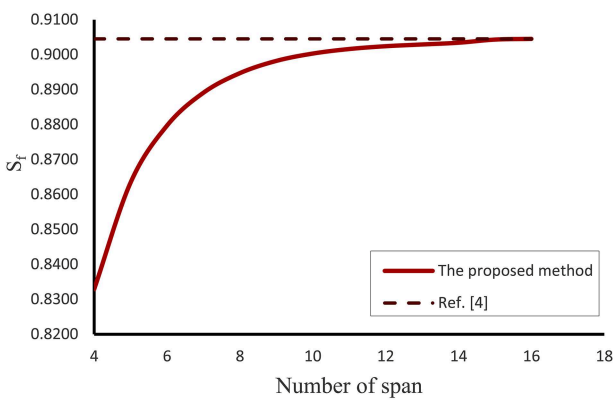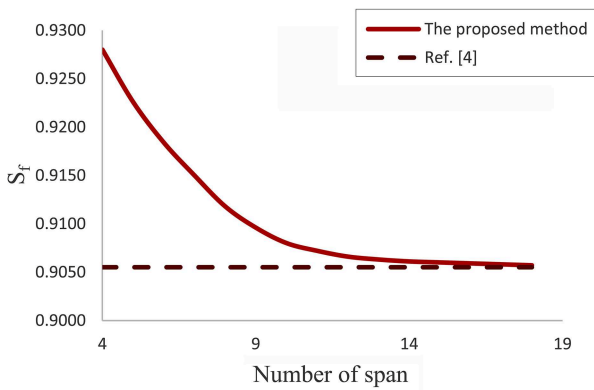
Figure 10. Comparison between the calculated S_f by the proposed method, [8] and [10].

(a)

(b)

Figure 11. Comparison between S_f obtained to the proposed method and [4], (a) earth faults inside a substation (b) earth faults in the vicinity of a substation.

the ladder network containing overhead ground wire and tower footing resistances for short transmission lines. They often use an infinite ladder network instead of overhead ground wire and towers to model a typical power system for all cases. This issue can be led to high approximation order for a short transmission line. The presented model in the proposed method will be able to provide an equivalent circuit of overhead ground wire and tower foot resistances for short transmission lines with non-identical spans. Figure 11 shows the
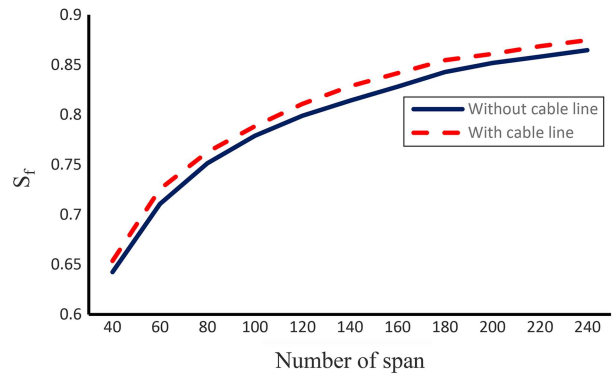

Figure 12. Effects of hybrid transmission line on S_f by the proposed method.

effect of the number of spans on the earth fault current division factor (S_f) by comparing the proposed method with [4] for the given network by Ref. [19] with the presented data in Appendix A. As illustrated in these figures, the obtained results of the proposed method are similar to [4] for more than 16 spans of the outgoing transmission line as a case study. This case study confirms that due to high computation error, the presented model in [4] should not be applied to short transmission lines, however, the proposed method is able to compute the earth fault current division factor for all of the cases through an accurate and simple procedure.

4.5. Effect of hybrid cable-overhead transmission line on S_f

The curves illustrated in Figure 12 yield the earth fault current division factor (S_f) of the substation under consideration as a function of the number of spans for a hybrid cable-overhead and alone overhead transmission line. It can be observed that the magnitude of S_f is considerably affected by the cable line feeding the overhead transmission line section. Based on the obtained results for a case study, considering a hybrid outgoing transmission line in generalized equivalent circuit of Figure 4 will lead to an increase in the earth fault passing through the relative substation with the maximum positive error of about 2.11%. This positive error plays an important role in a safe and cost-efficient grounding system design. Consequently, calculation of the exact S_f with considering the influence of the hybrid line can help us to access a safe grounding system. In the sequel, it should be noted that if calculating S_f are performed for a power system without the cable-overhead transmission line, the obtained grounding system design may not be safe for the same power network with the hybrid lines.

5. Conclusion

In order to calculate the earth fault current division factor, an accurate and simplified method with closed

form formula and its detailed approach are presented. The main achievements of this paper are summarized as the following features:

- Physical coupling as mutual impedance between phase conductors and ground wire and short line with different spans can be modeled;

- Varying parameters including non-uniform spans, tower footing resistances, grounding system resistance of adjacent substations can be easily taken into account;

- Complicated topology of power network can be analyzed due to the universality of the presented procedure;

- The effect of the phase conductor impedance is essentially included in calculations;

- Faulted point can be located inside and outside the substation on transmission line;

- Hybrid cable-overhead transmission line can be considered.

The closed-form formula presented in the proposed method is very efficient due to the fact that the implementation of this procedure is straightforward, which will be very interactive and usable for the engineering society. Further, findings of the presented method in this study have been compared and discussed with [1] and an accurate and analytical procedure [9] which are confirmed. Finally, the obtained results depict the small positive error for the presented method in this paper compared to the accurate procedure that this achievement can guarantee the needed assurance to design a safe grounding system of substation under study.

For the future, it would be very interesting to repeat this analysis by considering the proximity effects among the grounding grid under study and tower footing resistances of incoming/outgoing transmission lines.

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Appendix A

Example network data [19] is shown is Table A.1.

Appendix B

Figure B.1 shows the equivalent circuit of transmission line ground wire(s) and towers without considering mutual impedances between ground wire and phase conductor. In this ladder circuit the spans, their self-impedances and tower footing resistances may be dissimilar.

Equivalent circuit of one span and tower depicts in Figure B.2. The transfer function of this network can be extracted as the following relation:

$$\begin{bmatrix} lV_j \\ I_j \end{bmatrix} = \begin{bmatrix} lT_{j1} & T_{j2} \\ T_{j3} & T_{j4} \end{bmatrix} \begin{bmatrix} V_{j+1} \\ I_{j+1} \end{bmatrix} = T_j \begin{bmatrix} V_{j+1} \\ I_{j+1} \end{bmatrix}, \qquad (B.1)$$

Table A.1. Example network data.

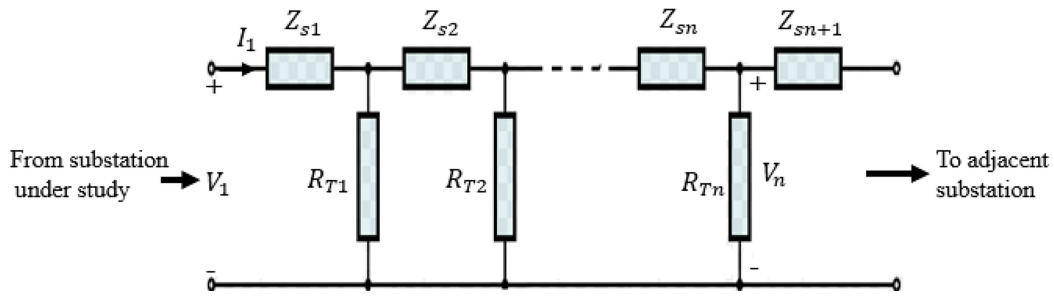|	
f (Hz)	50
Z_g (Ω/km)	$7+j1.3$
Z_{gm} (Ω/km)	$0.05+j0.38$
Span length (m)	100
R_T (Ω)	10
R_{gB} (Ω)	0.5
R_{gA} (Ω)	0.5
Z_{ph} (Ω)	$0.292+j0.08$

Figure B.1. Typical equivalent circuit of transmission line ground wire(s) and towers [8].
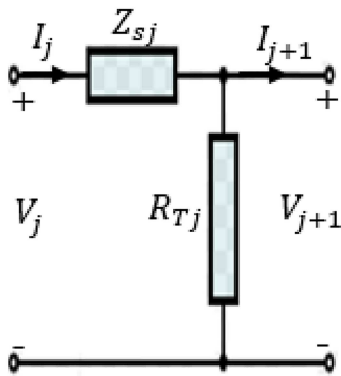

Figure B.2. Two-port module of one span and tower [8].

where,

$$T_{j1} = 1 + \frac{Z_{sj}}{R_{Tj}},$$

$$T_{j2} = Z_{sj},$$

$$T_{j3} = \frac{1}{R_{Tj}},$$

$$T_{j4} = 1.$$

In Figure B.1, transmission matrix elements of non-uniform ladder circuits containing the overhead ground wires and towers can be calculated as follows [1]:

$$\begin{bmatrix} V_1 \\ I1 \end{bmatrix} = \begin{bmatrix} T_1 & T_2 \\ T_3 & T_4 \end{bmatrix} \begin{bmatrix} V_n \\ I_n \end{bmatrix} = \prod_{j=1}^{n} T_j \begin{bmatrix} V_n \\ I_n \end{bmatrix}. \quad \text{(B.2)}$$

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