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Formulation of instantaneous fault-branch currents in case of cross-circuit faults on asymmetrical double-circuit transmission lines

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Abstract:

Cross-circuit faults (CCFs) are atypical short-circuit faults occurring between two dissimilar phases of the different circuits of double-circuit transmission lines with a high occurrence probability. Circuit analysis of the asymmetrical double-circuit lines' model in such fault cases is a sophisticated one, particularly in the time domain, because all the mutually coupled six phases of the line circuits are to be essentially incorporated. From analyzing the circuit model of asymmetrical double-circuit lines with non-identical circuits on a time domain basis, this paper develops clear-cut formulas governing the instantaneous fault-branch currents flowing from the faulty phases at the fault point into the fault branches during CCFs. They are acquired in terms of the line one-end circuits' phase currents and the fault location measured from the same end. The proposed formulas can readily be employed in practical applications such as fault analysis, line relaying/protection, and fault location/classification, particularly, those intended to be developed in the time domain in the case of CCFs. The formulas are validated via the simulation studies in PSCAD/EMTDC with an accurate time-domain model of the asymmetrical lines.

Keywords: Cross-circuit faults (CCFs); Asymmetrical double-circuit lines; Fault analysis; Fault-branch currents (FBCs)

1. Introduction

Power transmission lines are the essential components for a stable operation of integrated power systems. The double-circuit or parallel structure of transmission lines with both of the circuits installed at a common tower is widely applied in power systems, due to its technical, environmental, and economic advantages over the single-circuit structure. Overhead lines comprise exposed phase conductors, leaving them prone to the high incidence of short-circuit faults during their operation [1, 2].

The fault analysis of double-circuit lines is challenging compared to that of single-circuit lines due to the mutual coupling existent between the line circuits [3]. The situation would be more complicated when taking account of atypical faults like cross-circuit ones [4]. Cross-circuit faults (CCFs) are short circuits occurring between non-identical phases of the different circuits of double-circuit lines at the same time and location [5].

Referring to Fig. 1, CCFs take place in two distinct forms; non-earthed cross-circuit fault (NECCF) and earthed cross-circuit fault (ECCF). The NECCF is a flashover between two dissimilar phases of the line circuits (a and c′ in Fig. 1) without the ground being involved. The ECCF is a flashover between two dissimilar phases of the line circuits and the tower body, and hence the ground connection exists.

In fault conditions, the currents flowing from the faulty phases at the fault points into the fault branches are, here, referred to as fault-branch currents (FBCs). They are the key fault parameters resulting from an in-depth fault analysis. If accessible, they would have practical applications and ease dealing with practical subjects such as the line relaying/ protection [5–10] and the fault location/classifica-

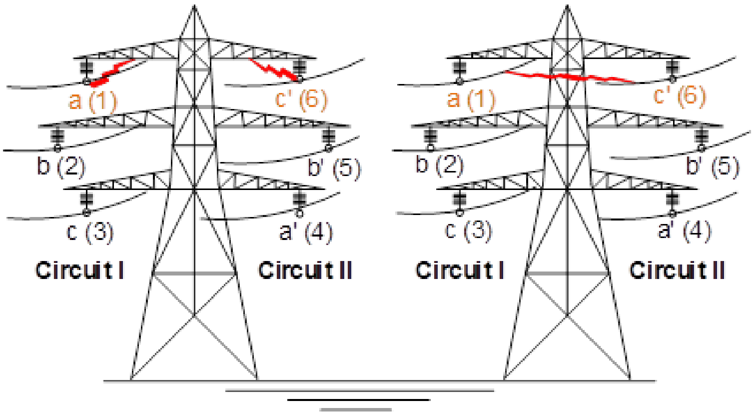

Figure 1. The different types of CCFs; NECCF (right) and ECCF (left) .

tion [11–16]. As for the asymmetrical double-circuit lines in the case of CCFs, the fault analysis, particularly in the time domain, would be a sophisticated one, because all the mutually-coupled six phases of the line circuits are to be essentially incorporated. This might be the reason why the research in the literature and reference books lacks the analysis for obtaining the FBCs in the case of the CCFs on asymmetrical double-circuit lines.

From time domain-based analysis of the circuit model of asymmetrical double-circuit lines comprising, in a general case, non-identical circuits, this paper develops clear-cut formulas governing the instantaneous FBCs during NECCF and ECCF. They are attained in terms of the line one-end circuits' phase currents and the fault location measured from the same end. The proposed formulas can readily be employed in the subjects mentioned above, particularly, those intended to be developed in the time domain in the case of CCFs. The validity of the formulas derived are confirmed through simulation studies in PSCAD/ EMTDC with an accurate time-domain model of the asymmetrical lines.

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2. The study line circuit model

The study double-circuit line is considered, in a more general case, to be comprised of the non-identical circuits of asymmetrical conductors on both circuits with the mutual coupling existing, as in practice, between all its six phases. Further, the line circuits are assumed to be terminated, as in most practical cases, at common buses at the local and remote ends.

For the formulation in the next section to be conducted in a clear-cut manner, the line's phases, parameters, and quantities are represented by its circuits' conductors numbers 1-3 on the circuit I and 4-6 on circuit II, as in Fig. 1. For the study line characterized above, the following phase resistance and inductance matrices are defined on the faulty phases (1 and 6) and their parallel healthy phases (4 and 3).

$$R_{ph} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} & r_{36} \\ r_{41} & r_{42} & r_{43} & r_{44} & r_{45} & r_{46} \\ r_{61} & r_{62} & r_{63} & r_{64} & r_{65} & r_{66} \end{bmatrix} \quad (1)$$

$$L_{ph} = \begin{bmatrix} l_{11} & l_{12} & l_{13} & l_{14} & l_{15} & l_{16} \\ l_{31} & l_{32} & l_{33} & l_{34} & l_{35} & l_{36} \\ l_{41} & l_{42} & l_{43} & l_{44} & l_{45} & l_{46} \\ l_{61} & l_{62} & l_{63} & l_{64} & l_{65} & l_{66} \end{bmatrix} \quad (2)$$

where the entries with the repetitive subscript numbers are the phase series resistances and self-inductances, while the other entries are the mutual resistances and inductances between the circuits' phases. Defining the parameters;

$$\zeta_{1j} = r_{1j} + l_{1j} \times d/dt \quad (3)$$

$$\zeta_{3j} = r_{3j} + l_{3j} \times d/dt \quad (4)$$

$$\zeta_{4j} = r_{4j} + l_{4j} \times d/dt \quad (5)$$

$$\zeta_{6j} = r_{6j} + l_{6j} \times d/dt \quad (6)$$

in terms of the entries in (1) and (2) for j= 1, 2, ... and 6 with *d/dt* being the time derivative operator, Fig. 2 shows the study line circuit model in the time domain during NECCF and ECCF. In the model, the line distributed-parameter effect [1] is safely neglected based on the fact that the asymmetrical lines are mostly short or medium in length. The CCFs are located at the per-unit distance of d_F, as measured from the local end. Hence, the parameters (3) - (6) appear in the line model with the factors d_F and (1–d_F), respectively, on the left and right of the fault, as shown in Fig. 2.

3. Formulation of the fault-branch currents (FBCs)

Regarding both the phase 1-phase 6 and phase 1-phase 6-ground CCFs considered in Fig. 2, the instantaneous FBCs i_{1F} and i_{6F} flowing from the faulty phases 1 and 6 to the

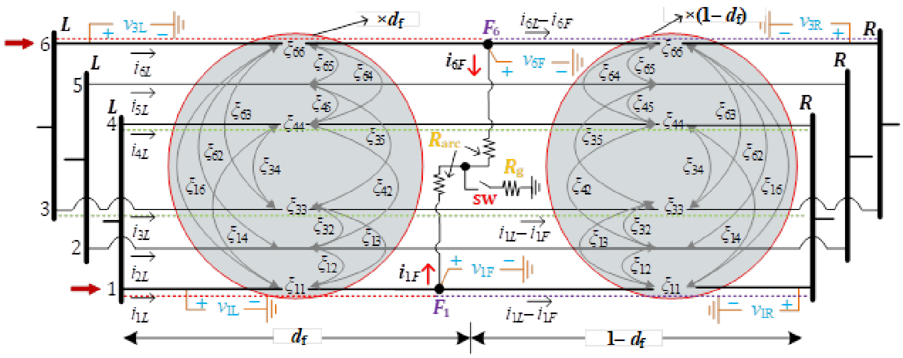


Figure 2. Time-domain circuit model of the study line in case of NECCF (sw=off) and ECCF (sw=on).

fault points F_1 and F_6 can be accessible through an analytical process, which is addressed in the present section. Considering the faulty phases 1 and 6, the fault-point voltages $v_{1F}(t)$ and $v_{6F}(t)$ can be obtained in the time domain in terms of the line circuits' phase currents at the local end by applying the KVL law in the path between the bus L and the fault points F_1 and F_6 marked with the red dashed line in Fig. 2 as follows.

$$v_{1F}(t) = v_{1L}(t) - d_f \times \sum_{j=1}^{6} (\zeta_{1j} \times i_{jL}(t)) \tag{7}$$

$$v_{6F}(t) = v_{3L}(t) - d_f \times \sum_{j=1}^{6} (\zeta_{6j} \times i_{jL}(t)) \tag{8}$$

where $v_{1L}(t)$ and $v_{3L}(t)$ are the voltages of the faulty phases at the local end (bus L) and $i_{jL}(t)$ denotes the local-end line circuits' current on the phase specified by j.

With the line circuits being terminated at common buses at both ends as in Fig. 2, the faulty-phase voltages at the remote bus ($v_{1R}(t)$ and $v_{3R}(t)$) can be obtained through the parallel healthy phases (4 and 3) by applying the KVL law in the path between the buses L and R marked in green in Fig. 2 as follows.

$$v_{1R}(t) = v_{1L}(t) - \sum_{j=1}^{6} (\zeta_{4j} \times i_{jL}(t)) +$$
$$(1-d_f) \times (\zeta_{14} \times i_{1F}(t) + \zeta_{64} \times i_{6F}(t)) \tag{9}$$

$$v_{3R}(t) = v_{3L}(t) - \sum_{j=1}^{6} (\zeta_{3j} \times i_{jL}(t)) +$$
$$(1-d_f) \times (\zeta_{63} \times i_{6F}(t) + \zeta_{13} \times i_{1F}(t)) \tag{10}$$

On the faulty phases 1 and 6, the following equations also hold in the path between the fault points (F_1 and F_6) and bus R, which is marked in purple in Fig. 2.

$$v_{1F}(t) - v_{1R}(t) =$$
$$(1-d_f) \times (-(\zeta_{11} \times i_{1F}(t) + \zeta_{16} \times i_{6F}(t)) + \sum_{j=1}^{6} (\zeta_{1j} \times i_{jL}(t))) \tag{11}$$

$$v_{6F}(t) - v_{3R}(t) =$$
$$(1-d_f) \times (-(\zeta_{66} \times i_{6F}(t) + \zeta_{61} \times i_{1F}(t)) + \sum_{j=1}^{6} (\zeta_{6j} \times i_{jL}(t))) \tag{12}$$

Substituting (7) and (9) into (11) and (8) and (10) into (12), the following equations in terms of the FBCs $i_{1F}(t)$ and $i_{6F}(t)$ result.

$$(\zeta_{11} - \zeta_{14}) \times i_{1F}(t) + (\zeta_{16} - \zeta_{64}) \times i_{6F}(t)$$
$$= (1/(1-d_f)) \times \sum_{j=1}^{6} (\zeta_{1j} - \zeta_{4j}) \times i_{jL}(t) \tag{13}$$

$$(\zeta_{61} - \zeta_{13}) \times i_{1F}(t) + (\zeta_{66} - \zeta_{63}) \times i_{6F}(t)$$
$$= (1/(1-d_f)) \times \sum_{j=1}^{6} (\zeta_{6j} - \zeta_{3j}) \times i_{jL}(t) \tag{14}$$

From the equations above, the FBCs are obtained for the NECCF and ECCF in the following sections.

3.1 Non-earthed cross-circuit fault (NECCF)

As for the NECCF in Fig. 2 with *sw*= off, the FBCs are equal and in opposite directions. Hence, they can be obtained by setting $i_{6F}(t)$ = -$i_{1F}(t)$ in either (13) or (14). Doing this as for (13), the following equation for the FBCs results.

$$i_{1F}(t) = -i_{6F}(t) = (1/(1-d_f)) \times \sum_{j=1}^{6} (\gamma_j \times i_{jL}(t)) \tag{15}$$

where γ_j for the phase number j=1, 2, ... and 6 is defined as follows.

$$\gamma_j = (\zeta_{1j} - \zeta_{4j})/\rho \tag{16}$$

where:

$$\rho = (\zeta_{11} + \zeta_{64}) - (\zeta_{14} + \zeta_{16}) \tag{17}$$

For the FBCs to be calculable via (15), (16) is to be decomposed into the terms with and without the derivative operator d/dt . According to the definitions made in (3) - (6), (17) can be written as follows.

$$\rho = r_\rho + l_\rho \times d/dt$$
$$= (r_{11} + r_{64} - r_{14} - r_{16}) + (l_{11} + l_{64} - l_{14} - l_{16}) d/dt \tag{18}$$

Multiplying both the numerators and denominators of (16) by ρ = r_ρ - l_ρ × d/dt and having d^2/dt^2 = -$\omega_0{}^2$ for the system sinusoidal quantities with the fundamental angular frequency of ω_0 , (16) are obtained as follows.

$$\gamma_j = \alpha_j + \beta_j d/dt \quad (19)$$

where α_j and β_j for the phase number j=1, 2, ... and 6 are defined as follows.

$$\alpha_j = \mu \times ((r_{1j} - r_{4j})r_\rho + \omega_0^2 (l_{1j} - l_{4j})l_\rho) \quad (20)$$

$$\beta_j = \mu \times ((l_{1j} - l_{4j})r_\rho + (r_{1j} - r_{4j})l_\rho) \quad (21)$$

where:

$$\mu = 1/((r_\rho)^2 + (\omega_0 l_\rho)^2) \quad (22)$$

As a result, 15 can be summarized via (20) - (22) as follows.

$$i_{1F}(t) = -i_{6F}(t)$$

$$= (1/(1-d_f)) \times \sum_{j=1}^{6} (\alpha_j \times i_{jL}(t) + \beta_j \times d/dt\, i_{jL}(t)) \quad (23)$$

3.2 Earthed cross-circuit fault (ECCF)

As for the ECCF in Fig. 2 with sw = on, (13) and (14) can be considered mathematically as a set of two equations with two unknowns of the FBCs as in (24).

$$A \times i_{1F}(t) + B \times i_{6F}(t)$$

$$= (1/(1-d_f)) \times \sum_{j=1}^{6} (\zeta_{1j} - \zeta_{4j}) \times i_{jL}(t)$$

$$A' \times i_{1F}(t) + B' \times i_{6F}(t)$$

$$= (1/(1-d_f)) \times \sum_{j=1}^{6} (\zeta_{6j} - \zeta_{3j}) \times i_{jL}(t) \quad (24)$$

where

$$A = (\zeta_{11} - \zeta_{14}) \quad (25)$$

$$B = (\zeta_{16} - \zeta_{64}) \quad (26)$$

$$A' = (\zeta_{61} - \zeta_{13}) \quad (27)$$

$$B' = (\zeta_{66} - \zeta_{63}) \quad (28)$$

As a result, the FBCs $i_{iF}(t)$ and $i_{iF}(t)$ are acquired by solving (24) , as in (29) and (30).

$$i_{1F}(t) = \frac{B'C - BC'}{AB' - A'B}$$

$$= (1/(1-d_f)) \times \sum_{j=1}^{6} (\gamma' \times i_{jL(t)}) \quad (29)$$

$$i_{6F}(t) = \frac{AC' - A'C}{AB' - A'B}$$

$$= (1/(1-d_f)) \times \sum_{j=1}^{6} (\gamma'' \times i_{jL(t)}) \quad (30)$$

where

$$\gamma_j' = (\eta_j - \delta_j)/\sigma \quad (31)$$

$$\gamma_j'' = (\phi_j - \psi_j)/\delta \quad (32)$$

with η_j , δ_j , ϕ_j and being obtained for the phase number j= 1, 2, ... and 6 as follows.

$$\eta_j = (\zeta_{66} - \zeta_{63})(\zeta_{1j} - \zeta_{4j}) \quad (33)$$

$$\delta_j = (\zeta_{16} - \zeta_{64})(\zeta_{6j} - \zeta_{3j}) \quad (34)$$

$$\phi_j = (\zeta_{11} - \zeta_{14})(\zeta_{6j} - \zeta_{3j}) \quad (35)$$

$$\psi_j = (\zeta_{61} - \zeta_{13})(\zeta_{1j} - \zeta_{4j}) \quad (36)$$

where

$$\sigma = (\zeta_{11} - \zeta_{14})(\zeta_{66} - \zeta_{63}) - (\zeta_{61} - \zeta_{13})(\zeta_{16} - \zeta_{64}) \quad (37)$$

For the FBCs in (29) and (30) to be calculable, (33) - (36) and hence (31) and (32) are to be decomposed into the terms with and without the derivative operator *d/dt* . From (3) - (6) and having again d^2/dt^2 = -ω_0^2 , (37) in the denominators of (31) and (32) can be written as follows.

$$\sigma = \sigma' + \sigma'' \times d/dt;$$

$$\sigma' = ((r_{11} - r_{14})(r_{66} - r_{63}) - (r_{61} - r_{13})(r_{16} - r_{64})) -$$

$$(\omega_0^2 \times ((l_{11} - l_{14})(l_{66} - l_{63}) - (l_{61} - l_{13})(l_{16} - l_{64}))) \quad (38)$$

$$\sigma'' = ((r_{11} - r_{14})(l_{66} - l_{63}) - (r_{61} - r_{13})(l_{16} - l_{64})) +$$

$$((r_{66} - r_{63})(l_{11} - l_{14}) - (r_{16} - r_{64})(l_{61} - l_{13}))$$

likewise, (33) - (36) comprising the numerators of (31) and (32) are written as follows.

$$\eta_j = \eta_j' + \eta_j'' d/dt;$$

$$\eta_j' = (r_{66} - r_{63})(r_{1j} - r_{4j}) - \omega_0^2 (l_{66} - l_{63})(l_{1j} - l_{4j}) \quad (39)$$

$$\eta_j'' = (r_{66} - r_{63})(l_{1j} - l_{4j}) + (l_{66} - l_{63})(r_{1j} - r_{4j})$$

$$\delta_j = \delta_j' + \delta_j'' d/dt;$$

$$\delta_j' = (r_{16} - r_{64})(r_{6j} - r_{3j}) - \omega_0^2 (l_{16} - l_{64})(l_{6j} - l_{3j}) \quad (40)$$

$$\delta_j'' = (r_{16} - r_{64})(l_{6j} - l_{3j}) + (l_{16} - l_{64})(r_{6j} - r_{3j})$$

$$\phi_j = \phi_j' + \phi_j'' d/dt;$$

$$\phi_j' = (r_{11} - r_{14})(r_{6j} - r_{3j}) - \omega_0^2 (l_{11} - l_{14})(l_{6j} - l_{3j}) \quad (41)$$

$$\phi_j'' = (r_{11} - r_{14})(l_{6j} - l_{3j}) + (r_{6j} - r_{3j})(l_{11} - l_{14})$$

$$\psi_j = \psi_j' + \psi_j'' d/dt;$$

$$\psi_j' = (r_{61} - r_{13})(r_{1j} - r_{4j}) - \omega_0^2 (l_{61} - l_{13})(l_{1j} - l_{4j}) \quad (42)$$

$$\psi_j'' = (r_{61} - r_{13})(l_{1j} - l_{4j}) + (r_{1j} - r_{4j})(l_{61} - l_{13})$$

Multiplying both the numerators and denominators of (31) and (32) by $\sigma = \sigma' - \sigma'' \times d/dt$, γ_j' and γ_j'' are obtained as follows.

$$\gamma_j' = \alpha_j' + \beta_j' \times d/dt$$

$$\alpha_j' = \lambda \times ((\eta_j' - \delta_j') \times \sigma' + \omega_0^2 \times (\eta_j'' - \delta_j'') \times \sigma'') \quad (43)$$

$$\beta_j' = \lambda \times ((\eta_j'' - \delta_j'') \times \sigma' - (\eta_j' - \delta_j') \times \sigma'')$$

$$\gamma_j'' = \alpha_j'' + \beta_j'' \times d/dt$$

$$\alpha_j'' = \lambda \times ((\varphi_j' - \psi_j') \times \sigma' + \omega_0^2 \times (\varphi_j'' - \psi_j'') \times \sigma'') \quad (44)$$

$$\beta_j'' = \lambda \times ((\varphi_j'' - \psi_j'') \times \sigma' - (\varphi_j' - \psi_j') \times \sigma'')$$

where

$$\lambda = 1/((\sigma')^2 + (\omega_0 \times \sigma'')^2) \quad (45)$$

As a result, (29) and (30) can be summarized as follows.

$$i_{1F}(t) = (1/(1-d_f)) \times \sum_{j=1}^{6} (\alpha'_j \times i_{jL}(t) + \beta'_j \times d/dt i_{jL}(t)) \quad (46)$$

$$i_{6F}(t) = (1/(1-d_f)) \times \sum_{j=1}^{6} (\alpha''_j \times i_{jL}(t) + \beta''_j \times d/dt i_{jL}(t)) \quad (47)$$

Thus, (23), (46) and (47) are the clear-cut formulas governing the FBCs in terms the fault distance and line circuits' currents for the different types of CCFs. The validity of the formulas would be assessed through simulation studies in the following section.

4. Validity assessment

Fig. 3 shows a test system with its specifications, through which the validity assessment of the proposed FBCs formulas is conducted via the simulations in PSCAD/EMTDC. Referring to the double-circuit line's phasing geometry and the conductor types detailed in Fig. 3, the numerical values of the matrices in (1) and (2) are obtained as follows.

$R_{ph}(\Omega/\text{km}) =$

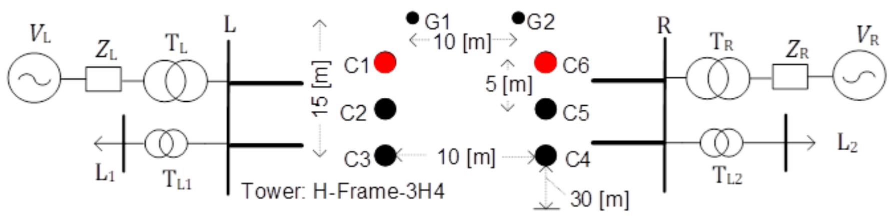
$$\begin{bmatrix} 0.24136 & 0.11403 & 0.10931 & 0.10903 & 0.11349 & 0.11979 \\ 0.10931 & 0.10380 & 0.22037 & 0.99970 & 0.10368 & 0.10903 \\ 0.10903 & 0.10368 & 0.09997 & 0.27043 & 0.10380 & 0.10931 \\ 0.11979 & 0.11349 & 0.10903 & 0.10931 & 0.11403 & 0.29142 \end{bmatrix}$$

$L_{ph}(\text{H/km}) =$

$$\begin{bmatrix} 0.00204 & 0.00092 & 0.00079 & 0.00072 & 0.00076 & 0.00077 \\ 0.00079 & 0.00093 & 0.00208 & 0.00080 & 0.00077 & 0.00072 \\ 0.00072 & 0.00077 & 0.00080 & 0.00224 & 0.00093 & 0.00079 \\ 0.00077 & 0.00076 & 0.00072 & 0.00079 & 0.00092 & 0.00221 \end{bmatrix}$$

The CCFs of both types involve the conductors C_1 and C_6, as shown in Fig. 3. They are assumed to be located at 5, 50, and 95% of the line length (100 km), each with Rarc = 5 Ω and R_g = 50 Ω . Fig. 4 shows the low-pass filtered line circuits' phase currents at the local end (i_{jL}(t)) for the NECCF and ECCF at 50%. The FBCs are calculated by inserting these currents and their time derivatives at each fault location beside the fault location value into (23) , (46) , and (47). The currents' phase derivatives are obtained in a discrete manner via (48) with the sampling interval of Δt = 10 μs, as follows

$$d/dt i_{jL}(t) = (1/\Delta t) \times (i_{jL}(t) - i_{jL}(t-\Delta t)) \quad (48)$$



- Sources– f= 60 Hz, V_L= V_R= 230<0 kV, Z_L= Z_R= 0.2+2.0i Ω.
- Transformers– T_L&T_R: 100 MVA, 230 Δ/132 Y_g kV, T_{L1}&T_{L2}: 50 MVA, 132 Y_g /63 Δ kV.
- Loads L_1&L_3: P_L= 50 MW and Q_L= 30 MVAr.
- Parallel line– length: 100 km, model: frequency dependent, circuit-I conductors type: ACSR (Hawk), circuit-II conductors type: ACSR (Oriole).

Figure 3. The test system and specifications.

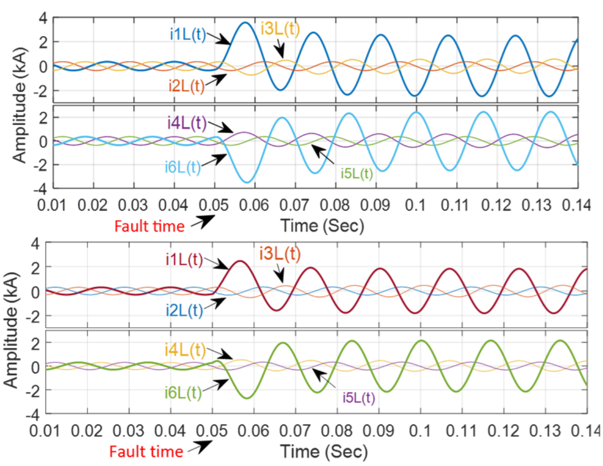


Figure 4. Line circuits' phase currents (i_{jL}(t)) in case of the NECCF (upper) and ECCF (lower) at 50%.

Fig. 5 shows the FBCs obtained via (23) in the case of the NECCFs at the three fault locations Moreover, the FBCs obtained via (46) and (47) are shown in Figs. 6 and 7 in the case of the ECCFs at the three fault locations. All the results are compared with the relevant FBCs measured in the test system. These are regarded as valid reference FBCs since the PSCAD exploits a valid double-circuit line time-domain model in which the line distributed-parameter effect is taken into account [17]. From the results, a very close correlation is found between the measured and calculated FBCs. pointing to the high accuracy of the proposed FBCs formulation. This accuracy can be viewed with respect to the deviation of the magnitude and phase angle of the calculated FBCs from those of the measured (reference) ones. As for the phase angle, the FBCs are obtained with a negligible phase lag equivalent to Δt, originating from the discrete time derivatives in (48). As for the magnitude, with the data given in the magnified portion of the waveforms in Figs. 5 - 7, the error of the calculated FBCs is obtained relative to the measured references, and the results are given in Fig. 8. From the results, (23) , (46) and (47) give the FBCs with an insignificant error, respectively, within 0.032

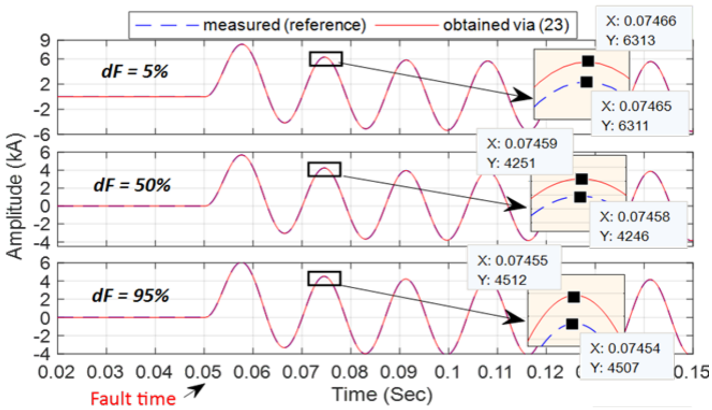


Figure 5. The FBC $i_{1F}(t)$=-$i_{6F}(t)$ in case of NECCFs at the three locations.

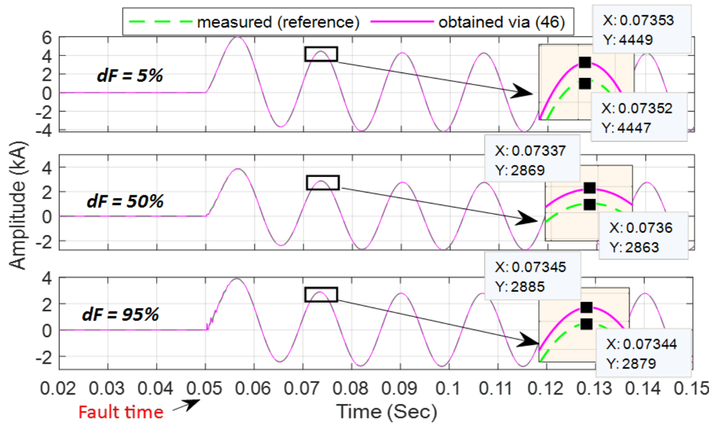


Figure 6. The FBC $i_{1F}(t)$ in case of ECCF at the three locations.

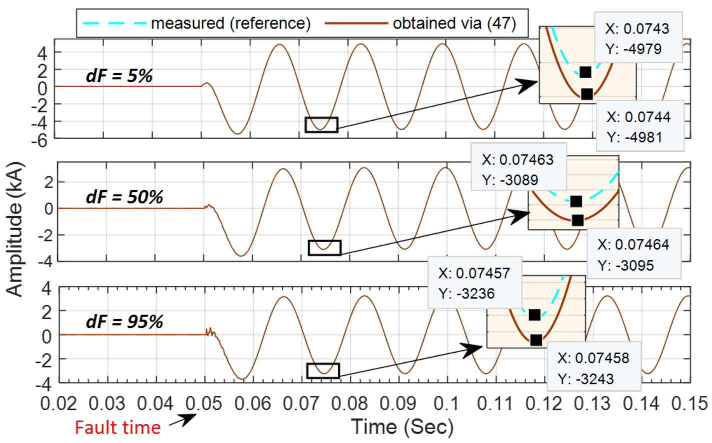


Figure 7. The FBC $i_{6F}(t)$ in case of ECCFs at the three locations.

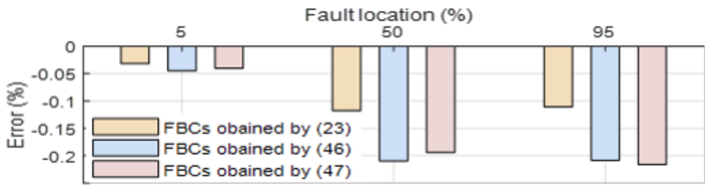


Figure 8. The computation error of the proposed FBCs formulas.

- 0.120%, 0.045 - 0.210%, and 0.040 - 0.220%, which is attributed to the line distributed-parameter effect neglected in developing the FBCs.

5. Conclusion

This paper has addressed the formulation of the instantaneous fault-branch currents in the case of both types of cross-circuit faults on asymmetrical double-circuit transmission lines with non-identical circuits. From analyzing the line circuit model on a time domain basis, valid formulas describing the fault-branch currents in terms of the one-end line circuits' currents and the fault location have been derived. The validity assessment through software simulations has shown that the proposed formulas return the currents with a high accuracy exceeding 99.7% with respect to the measured currents.

Authors contributions
All authors contributed equally to prepare the paper.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] J. D. Glover, M. S. Sarma, T. Overbye, and A. Birchfield. "Power systems analysis and design.". *Cengage Learning*, 2022.

[2] K. Nishant, B. R. Bhalja Bhavesh, V. Pandya, P. Tripathi, and S. Jena. "A phasor-distance based faulty phase detection and fault classification technique for parallel transmission lines.". *Int. J. of Emerg Elect. Power Syst.*, **21**(4):1–16.

[3] K. R. Pillay and B. S. Rigby. "Studying the impact of mutual coupling on distance protection relays using a real-time simulator. ". *IEEE Africon*, **11**:1–6, 2011. DOI: https://doi.org/10.1109/AFRCON.2011.6072015.

[4] D. J. Spoor and J. Zhu. "Intercircuit faults and distance relaying of dual-circuit lines. ". *IEEE Trans. on Power Del.*, **20**(3):1846–1852, 2005. DOI: https://doi.org/10.1109/TPWRD.2004.833899.

[5] V. H. Makwana and B. Bhalja. "New adaptive digital distance relaying scheme for double infeed parallel transmission line during inter-circuit faults. ". *IET Gener. Transm. & Distrib.*, **5**(6):667–673, 2011. DOI: https://doi.org/10.1049/iet-gtd.2010.0707.

[6] M. H. H. Musa, A. Y. M. Abbas, and A. h. I. A. Ahmed. "Cross-country, evolving, and inter-circuit relaying scheme for double-circuit transmission line.". *presented at the Int. Conf. Computer, Control, Electrical, and Electronics Engineering (ICCCEEE), Sudan*, pages 1–5, 2021. DOI: https://doi.org/10.1109/ICCCEEE49695.2021.9429581.

[7] S. Hasheminejad, S. G. Seifossadat, and M. Joorabian. "New travelling-wave-based protection algorithm for parallel transmission lines during inter-circuit faults. ". *IET Gener., Transm. & Distrib*, **11**(16):3984 – 3991, 2017. DOI: https://doi.org/10.1049/iet-gtd.2017.0027.

[8] A. Swetapadmaa and A.Yadav. "Protection of parallel transmission lines including inter-circuit faults using Naı ve Bayes classifier.". *Alex. Eng. J.*, **55**(2):1411–1419, 2016. DOI: https://doi.org/10.1016/j.aej.2016.03.029.

[9] S. V. Unde, P. Gawande, and S. Dambhare. "New algorithm for protection of double circuit transmission lines using modal currents. ". *IEEE Trans. Power Del.*, **34**(5):1967–1977, 2019. DOI: https://doi.org/10.1109/TPWRD.2019.2906939.

[10] A. Swetapadma and A. namikaYadav. “Directional relaying using support vector machine for double circuit transmission lines including cross-country and inter-circuit faults. ”. *Int. J. Electr. Power & Energ. Syst.*, **18**(6):254–264, 10.1016/j.ijepes.2016.02.034. DOI: https://doi.org/2016.

[11] A. N. kumar, M. S. Kumar, M. Ramesha, B. Gururaj4, and A. Srikanth. “Support vector machine based fault section identification and fault classification scheme in six phase transmission line. ”. *IAES Int. J. of Art. Intel.*, **10**(4):1019–1024, 2021. DOI: https://doi.org/10.11591/ ijai.v10.i4. pp. 1019-1024.

[12] N. Kumar, A. Sanjay, Ch., and Chakravarthy. “Fuzzy inference system-based solution to locate the cross-country faults in parallel transmission line. ”. *Int. J. of Elect. Eng. & Edu.*, **58**(1):83–96, 2019. DOI: https://doi.org/10.1177/0020720919830905.

[13] A. Saber. “New fault location algorithm for four-circuit overhead lines using unsynchronized current measurements. ”. *Int. J. of Elect. Power & Ener. Syst.*, **120**(1):1–6, 2020. DOI: https://doi.org/10.1016/j.ijepes.2020. 106037.

[14] H. Mehrjerdi and Amir Ghorbani. “High-speed auxiliary fault location element for distance relays in double-circuit lines. ”. *Elect. Power Syst. Research*, **200**:1–11, 2021. DOI: https://doi.org/10.1016/j.epsr.2021.107470.

[15] A. Ghorbani and H. Mehrjerdi. “Negative-sequence network based fault location scheme for double-circuit multi-terminal transmission lines.”. *IEEE Trans. on Power Del.*, **34**(3):1109–1117, 2019. DOI: https://doi.org/10.1109/ TPWRD.2019.2906056.

[16] V. Ashok, A. Yadav, M. Pazoki, and A. Y. Abdelaziz. “Fault location scheme for cross-country faults in dual-Circuit line using optimized regression t. ”. *Electr. Power Comp. and Syst.*, **14**(14-15):1632–1648, 2021. DOI: https://doi.org/10.1080/15325008.2020.1856232.

[17] M. H. Khazaei and F. A. Haghjoo. “Comprehensive PMU-based fault location algorithm for Double circuit and multi-terminal transmission lines.”. *Journal of Iranian Association of Electrical and Electronics Engineers*, **14**(1):1–10, 2017.