Fault Resistance Influence on Faulted Power Systems with Distributed Generation

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Abstract—Fault resistance (R_F) is a critical component in power systems protection schemes and fault locations algorithms. It introduces an error that if not taken into account for, may cause misoperation of ground distance relays and fault locators. The presence of distributed generation (DG) is becoming common in power systems, and new fault location methods and power system protection schemes are being developed to consider it. This paper proposes an analysis of the R_F influence in power system relaying and fault location algorithms with and without DG, allowing future research for fault resistance compensation.

Keywords: Protective relaying, fault resistance, distributed generation, fault location.

I. Introduction

POWER systems are exposed to different causes of service interruption, like faults and erroneous operation. A fault in a circuit is defined as any failure which interferes with the normal flow of current [1]. Electric power systems are normally subject to these permanent and non-permanent faults. These faults can take out-of-service the faulted component for seconds or even hours depending on the fault type. The fault phenomenon is associated with different causes, like lightning, insulation breakdown, wind, trees falling across lines, animals or any contact with electrical equipments.

Most faults on transmission lines of 115kV and higher voltages are caused by lightning. The high voltage between conductors and ground causes ionization, which provides a path to ground for the charge induced by the lightning stroke. After about 20 cycles with circuit breakers (CB) opened, to allow deionization, the CB may be re-closed to restore the line. If re-closing is not successful, the fault may be permanent [1]. In this case, the maintenance crew has to search the faulted line to remove the fault using a fault location estimative.

Faults may be classified as shunt, an unbalance between phases or between phase and neutral, or series, an unbalance in the line impedance and does not involve the neutral or ground, neither any interconnection between phases [2].

On three-phase power systems, there are 10 distinct possible shunt faults types [3]. Between 70% and 80% of the line faults are phase-to-ground faults, and 5% involves all three-phases [1]. These faults may be initially considered an ideal short-circuit ($R_F = 0$). However, fault resistance may not be negligible in several cases. For multi-phase faults, the fault path may consist of an electrical arc between two high voltages conductors and for faults involving ground, the path may consists of an electrical arc between the conductor and a grounded object, such as the shield wire, the transmission tower or a tree. In both cases there is not negligible R_F in the faults paths.

For faults resulted from isolators flash-over, the arc resistance and the tower footing resistance are series connected. The tower footing resistance ranges 5Ω-50Ω and can be considered constant during the fault. The arc resistance is negligible in the first miliseconds, and increases with the time [3]. For relaying consideration, the arc resistance is assumed constant and given by (1).

$$R_{arc} = \frac{76 \cdot V^2}{S_{sc}} \qquad (1)$$

where V is the system voltage in kV and S_{sc} is the short circuit capacity in kVA at the fault location [3].

II. Fault Resistance Influence In Distance Relaying

Distance relaying is commonly used as the primary protection scheme on transmission lines. Based on the information of the line impedance per length unit, distance relays determines the apparent positive sequence impedance seen from the measuring point and compares it with the pickup setting, which is based on a line percentage to be protected. If the measured impedance is inside the protection zone, an internal fault is diagnosed and a trip command is sent to the circuit breaker [4].

Distance relaying uses several zones to protect a transmission line, called stepped distance protection. The first zone, usually designated as Zone 1, is set to trip with no intentional time delay, the set is usually 80–90% of the transmission line impedance. For faults outside Zone 1, distance relays are used as backup protection, using over-reaching zones of protection with time delay [5].

During a low resistance fault, the measured apparent impedance is close to the effective impedance between the relay and earth. Distance relay equations are developed considering a fault with negligible fault resistance [6]. However, the fault resistance introduces an error in the distance estimation due to the fact that in these cases the apparent impedance measured by the relay is not directly proportional to the distance between the relay and the fault

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location. For a symmetrical fault [3], the apparent positive sequence impedance seen by the relay is given by (2):

$$Z_A = \frac{E}{I} = Z_F + R_F \cdot \left[\frac{I_R}{I_S} + 1 \right] \tag{2}$$

where Z_A is the apparent positive sequence impedance, E and I are the voltage and current phasors calculated at the relay point, Z_F is the line impedance between the relay and the fault point, R_F is the fault resistance and I_R and I_S are respectively the currents flowing from the remote end and the sending end of the line.

Eq. (2) demonstrates clearly the R_F influence in a distance relay, influence that can lead into possible problems as under-reaching phenomenon. The phenomenon is illustrated in Fig. 1. In this example, the distance relay would miss-operate for an internal fault, especially for faults close to zones boundaries or with high R_F.

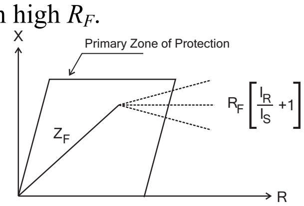

Fig. 1. Distance relaying R-X diagram subject to under-reaching due to R_F

For shunt faults with high R_F, not only the apparent positive sequence impedance depends on the fault resistance, but also on the power system structural and operational conditions, like short circuit levels at both ends of the line. The operational conditions can be expressed by the ratio of voltage magnitudes at the line ends (h) and the load angle (δ) of the line, i.e. $E_R / E_S = he^{-j\delta}$ [7]. For a phase-ground fault with R_F, illustrated in Fig. 2, the apparent impedance measured by the relay at terminal S [8] is given by:

$$Z_A = Z_{1LS} + \frac{3R_F}{\dfrac{(Z_\Sigma + 3R_F)\cdot(1 - h \cdot e^{-j\delta})}{Z_{1S} + h \cdot Z_{1S} \cdot e^{-j\delta}} + 2C_1 + C_0 \cdot (1 + 3K_{0L})} \tag{3}$$

where:

$$Z_\Sigma = \frac{2Z_{1S} \cdot Z_{1R}}{Z_{1S} + Z_{1R}} + \frac{Z_{0S} \cdot Z_{0R}}{Z_{0S} + Z_{0R}} \tag{4}$$

$$C_1 = \frac{Z_{1R}}{Z_{1S} + Z_{1R}} \tag{5}$$

$$C_0 = \frac{Z_{0R}}{Z_{0S} + Z_{0S}} \tag{6}$$

$$K_{0L} = \frac{Z_{0L} - Z_{1L}}{3Z_{1L}} \tag{7}$$

where $Z_p = Z_{pLT} + Z_{pST}$, for p = 0,1, and subscriptions "0" and "1" means zero and positive sequence components and T means the terminal S or R. Z_{pLT} is the line impedance, Z_{pST} is the source impedance, Z_{1L} and Z_{0L} are the positive and zero sequence line impedance.

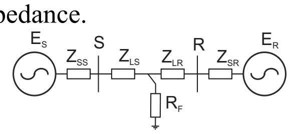

Fig. 2. Phase –A to ground fault model

In (3), as in (2), it is shown that for high R_F the apparent impedance measured is higher than the impedance between the relay and the fault point, resulting in distance relay miss-operation.

A common technique to minimize the R_F influence in distance relaying is the use of the quadrilateral operational characteristic, which provides more fault resistance coverage and arc compensation than circular *mho* [6]. Some works suggest the R_F estimation while using distance relaying [9]-[11]. Those works provide estimative and R_F compensation prior to the trip decision.

III. Fault Resistance Influence in Fault Location

When a line is out-of-service due to a fault, the power system looses reliability. If the fault is non permanent, the line is back in service in seconds, if there is automatic re-closing, or minutes, for manual re-closing. Usually, non permanent faults are caused by lightning. If the fault is permanent, the line is usually out-of-service for a longer time period. In this case maintenance teams must find the permanent fault and remove it before restoring the system.

In both cases, a good estimative of the fault location could reduce the maintenance team search time considerably. This estimative can be provided by the numeric relays or by specialized software. The traditional methods for fault location estimation are based on positive sequence impedance estimative methods and traveling wave methods [12].

Traveling wave techniques uses as input data the line length and the wave velocity. It estimates the fault location energizing the faulted line and measuring the return time of a reflected wave. The comparison between the known line length and the determined length obtained by the return time of the reflected wave results in the fault distance [12].

Positive sequence impedance methods use one-terminal or two-terminal data and apply similar technique used by distance relays. From voltages and currents measured, the apparent impedance from the relay point is determined and compared with the total line impedance, resulting in the fault location estimative.

A. One-terminal data methods

One-terminal data fault locators are the mostly common technique used nowadays. The only information needed is the total line impedance and the local currents and voltages data. Several works [13]-[15] were developed to obtain the fault distance using this technique for transmission and distribution systems.

As distance relays, for zero fault resistance the apparent positive-sequence impedance measured is proportional to the fault distance, which can be estimate for each fault type [12] as shown in table 1.

TABLE I
Single impedance equation for negligible fault resistance

Fault type	Positive-sequence impedance (xZ_{1L})
a-ground	$V_a/(I_a+kI_R)$

b-ground	$V_b/(I_b+kI_R)$
c-ground	$V_c/(I_c+kI_R)$
a-b or a-b-ground	V_{ab}/I_{ab}
b-c or b-c-ground	V_{bc}/I_{bc}
c-a or c-a-ground	V_{ca}/I_{ca}
a-b-c	V_{ab}/I_{ab}, V_{bc}/I_{bc}, V_{ca}/I_{ca}

where:

$$k = \frac{Z_{0L} - Z_{1L}}{3 \cdot Z_{1L}} \tag{8}$$

where Z_{0L} is the zero-sequence line impedance, Z_{1L} is the positive-sequence line impedance, x is the per-unit fault distance and I_R is the residual current ($3I_0$).

However, the fault location estimative is affected by many parameters, including R_F, which may be high for ground faults [12]. The R_F influence, combined with the load effects, results as the main fault location errors source. Fig. 3 illustrates an equivalent circuit for a symmetrical fault between S and R terminals.

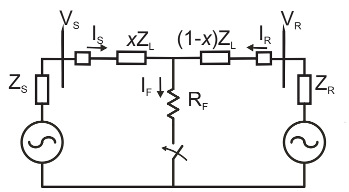

Fig. 3. Symmetrical fault between terminals S and R

The voltage from terminal S is given by:

$$V_S = x \cdot Z_L \cdot I_S + R_F \cdot I_F \tag{9}$$

where:

V_S is the voltage at terminal S
x is the distance to the fault in per-unit
Z_L is the line impedance between the two terminals
I_S is the line current from terminal S
R_F is the fault resistance
I_F is the fault current

The apparent impedance (Z_{FS}) from terminal S is given by:

$$Z_{FS} = \frac{V_S}{I_S} = x \cdot Z_L + R_F \cdot \frac{I_F}{I_S} \tag{10}$$

From (10) it is shown that if the currents I_F and I_S are complex numbers, R_F will have an active and a reactive component. The reactive component will be zero for equal angles between I_F and I_S. Using superposition, supposing I_L as the load current and the difference $\Delta I_G = I_S - I_L$, (10) results in:

$$Z_{FS} = \frac{V_S}{I_S} = x \cdot Z_L + R_F \cdot \frac{1}{d_S \cdot n_S} \tag{11}$$

where d_s is the current distribution factor, given by (12) and n_s is the circuit load factor, given by (13).

$$d_S = \frac{\Delta I_G}{I_F} = \frac{Z_R + (1-x) \cdot Z_L}{Z_L + Z_S + Z_R} = |d_S| \angle \beta \tag{12}$$

$$n_S = \frac{I_S}{\Delta I_G} = |n_S| \angle \gamma \tag{13}$$

From (12) and (13) it is shown that the angle of the ratio I_F/I_S is determined by two factors: the current distribution factor (d_s), which results from the system impedances and n_s, given by the line flow. For homogeneous systems, the angle β is zero, and there are no contributions from d_s to the fault resistance reactive component. Also, for a greater I_S current in relation to the I_L current, the angle γ becomes close to zero. For angles β and γ close to zero, the resulting contributions from factors d_s and n_s to the fault resistance reactive component is zero, once this contribution is given by the sum of both angles (α) [12]. Fig. 4 illustrates the R_F influence, given in R-X diagram.

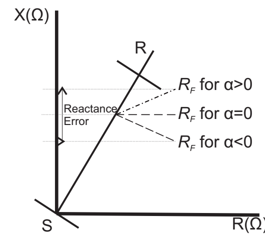

Fig. 4. R_F influence depending on α value

B. Two-terminal data methods

The two-ended impedance-based fault locators are based in the same fundaments of one-ended impedance methods. Looking to eliminate the errors introduced by the one-ended techniques, two-terminal location methods are more accurate than one-terminal methods as they minimize the fault resistance influence, loading and charging current effects [12]. Some works [16]-[18] were developed to estimate the fault location using two-terminal data based on synchronized and unsynchronized data.

Supposing a symmetrical fault, as shown in Fig. 3 the Kirchoff voltage's law from terminals S and R are given by:

$$V_{S\,abc} = V_{F\,abc} + x \cdot Z_{L\,abc} \cdot I_{S\,abc} \tag{14}$$

$$V_{R\,abc} = V_{F\,abc} + (1-x) \cdot Z_{L\,abc} \cdot I_{R\,abc} \tag{15}$$

where

$V_{S\,abc}$ Voltage vector at the sending end
$V_{F\,abc}$ Voltage vector at the fault point
x Fault distance from the sending end
$V_{R\,abc}$ Voltage vector at the remote end
$Z_{L\,abc}$ Line impedance matrix
$I_{S\,abc}$ Current vector from sending end
$I_{R\,abc}$ Current vector from remote end

Subtracting (15) from (14), the unknown voltage vector at the fault point is eliminated, resulting:

$$V_{S\,abc} - V_{R\,abc} + Z_{L\,abc} \cdot I_{R\,abc} = x \cdot Z_{L\,abc} \cdot \left(I_{S\,abc} + I_{R\,abc} \right) \tag{16}$$

From (16), the unknown voltage at the fault point, given by $V_F = R_F \cdot I_F$ is eliminated, as the R_F influence. The distance estimative can be then obtained by manipulating (16):

$$\begin{bmatrix} Y_a & Y_b & Y_c \end{bmatrix}^T = \begin{bmatrix} M_a & M_b & M_c \end{bmatrix}^T \cdot x \Rightarrow Y = M \cdot x \tag{17}$$

where

$$Y_j = V_{S_j} - V_{R_j} + \sum_{i=a,b,c} Z_{L_{ji}} \cdot I_{R_i} \tag{18}$$

$$M_j = \sum_{i=a,b,c} Z_{L_{ji}} \cdot \left(I_{S_i} + I_{R_i}\right) \quad (19)$$

where *j=a b, c*. From (17)-(19), the fault location estimative (x) can be obtained by:

$$x = \left(M^+ \cdot M\right)^{-1} \cdot M^+ \cdot Y \quad (20)$$

where M^+ is the complex conjugate of M. For unsynchronized data from the two-terminals, the fault distance can be solved using techniques provided by [19].

IV. Influence on Distributed Generation

Distributed generation (DG) can be classified as generators located at a customer energy service provider or utility site and may be stand-alone or connected to the power distribution system (PDS). The main DG impact in PDS is the change in the system's power flow, which was characterized by having a radial power flow, and that now may have a loop power flow. This characteristic must be considered in the protection system's design, due to the DG influence in the fault current, in subjects like coordination of protection equipment and selectivity, which must be reevaluated [20]. If not taken account for, DG may affect the protection schemes as: false feeders tripping, protection blinding, increased or decreased fault levels, unwanted islanding, prohibition of automatic reclosing and unsynchronized reclosing [21]. To avoid this, the DG's fault current contribution estimative must be done and considered as an infeed current to the PDS.

Synchronous generators are the main source of electric energy in power systems, and are also commonly used as DG. Its equivalent circuit is considered dynamic, since the impedance seen by currents entering or leaving the terminals are continually changing. Its dynamic behavior is given by a complex set of differential equations [22]. However, for a disturbance as a short circuit, a solution of such set of equations would result in a long processing time.

To overcome the computational time limitation, generators can be replaced by Thevenin equivalents, representing the worst condition after the fault, rotating machine speed can be considered as constant and the fault can be considered to be removed before there is a speed change [2]. The model proposed by [23], illustrated in Fig. 5, represents the synchronous generator in the subtransient period, composed by the machine d-axis sub-transient reactance X_d'', its armature resistance R_a'' and its internal voltage E_g'', which can be considered constant during the fault.

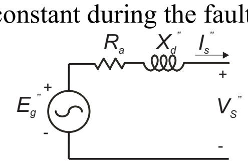

Fig 5. Model of a synchronous generator in the subtransient period

The Thevenin equivalent in Fig. 5 was obtained from a solid ($R_F = 0$) symmetrical short-circuit, which imposes the voltages at the terminals machine equal to zero ($V_a = V_b = V_c = 0$), resulting a zero voltage to d-axis and q-axis ($V_d = V_q = 0$), obtained from Park's transformation. However, when R_F is not negligible, the voltages at the machine terminals are not zero, which introduces an error in the model if R_F is much higher than the synchronous machine armature resistance. This influence may interfer on the estimated fault current contribution from DG, which may cause protection schemes or other tasks based on this information miss-operation.

V. Fault Location with Distributed Generation

Several recent impedance based techniques were developed to estimate the fault location on DG systems [24], [25]. The R_F effect in this kind of methodologies includes those existing effects on fault location techniques, cited on Section III, and on DG, cited on Section IV, since these methodologies are classic fault location techniques, modified for DG systems.

In [24], the DG contribution is not considered known, but it is calculated using the fault state of the system. This could lead to fewer errors due to the fault resistance. However, the fault resistance must be known prior to the location analysis in the DG's fault contribution calculation, which is also unavailable, leading to errors in the same way.

In [25], the DG is modeled directly as a Thevenin equivalent during the fault period, as described on Section IV, using the pre-fault condition of the system. Then, its fault current contribution is estimated, returning higher errors than in the same methodology for systems without DG, since there is now a sum of error contributions: the intrinsic ones from the fault location technique and the ones from the erroneous modeling of the distributed generation.

VI. Case Studies

To emphasize the fault resistance influence on the topics shown on Sections II – V, hypothetical case studies were analyzed using ATP/EMTP and Matlab.

A. Distance Relaying

To analyze the fault resistance influence in distance relaying, several phase-a-to-ground faults were simulated in a hypothetical power system, with a total length of 29.3 *km* with a total line impedance of 8.0799 + j7.9895 Ω per phase, as illustrated in Fig. 6. For apparent positive sequence impedance estimation (Z_{1E}), Table I equations are used, as proposed by [12], and zone 1 is set to 85% of the line length (24,85 *km*) with a *mho* characteristic. Results are shown in Table II.

TABLE II
RESULTS FOR DISTANCE RELAYING SIMULATIONS

Fault distance (km)	Z_{1E} (Ω)	R_F (Ω)	Zone 1
0.418	4.8343 + 0.2207i	5	Internal
0.418	12.8116 + 0.8879i	15	External
12.55	45.8114 +12.3282i	100	External
16.74	30.5870 + 7.8077i	40	External
16.74	5.6035 + 4.5692i	1	Internal
25.1	6.9253 + 6.8469i	0	External
24.69	5.7713 + 5.7057i	0	Internal
24.69	6.7569 + 5.7103i	1	Internal
24.69	8.1883 + 5.7331i	2.5	External

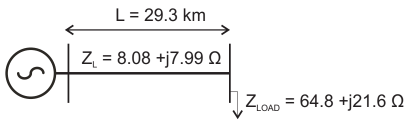

Fig. 6. Case study for distance relaying

Analyzing the results presented in Table II, it can be seen the direct influence of R_F, resulting on underreaching for faults with high R_F, even at the begging of the line, resulting on distance relay miss-operation for faults with high R_F.

B. Fault Location

To show the R_F influence on fault locators, the system shown in Fig. 5 is simulated for phase *a*-to-ground faults. The method applied a one-terminal apparent impedance based, proposed in [15]. The fault location is given by:

$$x = \frac{V_{a(r)} \cdot I_{f(i)} - V_{a(i)} \cdot I_{f(r)}}{A \cdot I_{f(i)} - B \cdot I_{f(r)}} \tag{21}$$

$$\begin{aligned} A = {} & Zl_{aa(r)} \cdot I_{a(r)} - Zl_{aa(i)} \cdot I_{a(i)} + Zl_{ab(r)} \cdot I_{b(r)} \\ & - Zl_{ab(i)} \cdot I_{b(i)} + Zl_{ac(r)} \cdot I_{c(r)} - Zl_{ac(i)} \cdot I_{c(i)} \end{aligned} \tag{22}$$

$$\begin{aligned} B = {} & Zl_{aa(r)} \cdot I_{a(i)} + Zl_{aa(i)} \cdot I_{a(r)} + Zl_{ab(r)} \cdot I_{b(i)} \\ & + Zl_{ab(i)} \cdot I_{b(r)} + Zl_{ac(r)} \cdot I_{c(i)} + Zl_{ac(i)} \cdot I_{c(r)} \end{aligned} \tag{23}$$

where V_a is the voltage at the relay point of phase *a*, I_f is the fault current, Zl_{mn} is the line impedance between phases *m* and *n*, I_m is the current at the relay point, the subscripts (i) and (r) are imaginary and real part and *m*, *n* the phases *a*,*b*,*c*.

TABLE III
RESULTS FOR FAULT LOCATION ESTIMATION

Fault distance (km)	Fault distance estimated (km)	R_F (Ω)	Error (%)
2.0921	2.1875	1k	-0.3255
12.5528	12.6776	1k	-0.4261
16.7371	16.7331	0	0.0136
16.7371	16.7440	40	0.0238
16.7371	16.8318	1k	-0.3235
16.7371	17.2939	5k	-1.9012
25.1056	25.1988	1k	-0.3180

From Table III it can be seen that the method proposed by [15] has no fault resistance effects, once the errors are only near to 2% for $R_F = 5k\Omega$, as illustrated in Fig. 7.

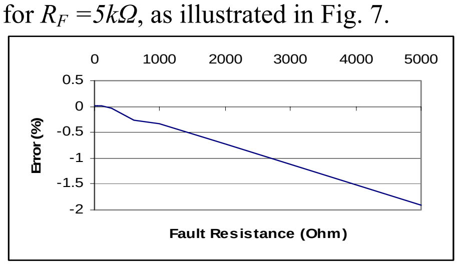

Fig. 7. R_F influence on a fault at 16.7371 km

C. Distributed Generation

To emphasize the fault resistance influence on the synchronous generator model used in short-circuit contingency analysis, as presented on Section IV, several symmetrical faults were simulated at ATP/EMTP on the machine terminals for different fault resistances. The internal voltage (E_g) is obtained by:

$$E_g = V_s + Z_{syn} \cdot I_s \tag{24}$$

where V_s is the machine terminal voltages, Z_{syn} is the machine impedance and I_s is the current flowing out of the synchronous generator.

From (24), the subtransient fault current from the machine may be obtained by:

$$I_a = \left(V_s - E_g\right) \cdot Z_{sub} \tag{25}$$

where Z_{sub} is the machine's subtransient impedance. The estimated fault currents are shown in Table IV, compared with the simulated ones.

TABLE IV
RESULTS FOR SYNCHRONOUS MACHINE FAULT CURRENT

R_F (Ω)	Estimated I_s(kA)	Simulated I_s (kA)	Absolute Error (%)
0	$10.443\angle 126.99^o$	$10.874\angle -50.83^o$	-3.962
1	$3.4928\angle 154.97^o$	$4.8812\angle -32.67^o$	-28.4434
5	$3.0974\angle 149.89^o$	$4.7572\angle -32.45^o$	-34.8906
25	$3.0196\angle 148.67^o$	$4.7321\angle -32.41^o$	-36.1890
40	$3.0123\angle 148.55^o$	$4.7297\angle -32.41^o$	-36.3106
100	$3.0051\angle 148.43^o$	$4.7274\angle -32.41^o$	-36.4322
300	$3.0019\angle 148.37^o$	$4.7263\angle -32.40^o$	-36.4861

The results show a correct current estimation only for solid faults. For other R_F, the current estimation has a considerable error, making this model inadequate for such analysis.

D. Fault Location with Distributed Generation

To emphasize the R_F influence on the techniques described on Section V, 67 three-phase faults were simulated in the system described in [25], with $R_F = 0\ \Omega$ and $10\ \Omega$, which can be considered low resistance values. The results are shown in Fig. 8.

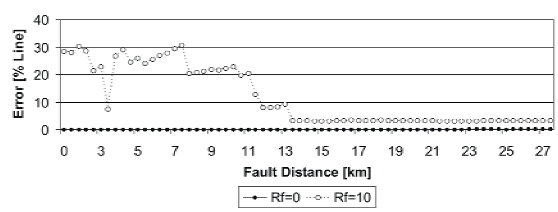

Fig. 8. R_F influence on fault location with DG

Fig. 8 shows that for faults with no resistance, the error obtained in the fault location technique described in [25] is very low, almost insignificant, since its maximum value stays near 0% of the total line length for all the fault location cases simulated (from the beginning of the feeder until its end).

However, as R_F increases, the fault location methodology described in [25] returns higher error values, even for low R_F values. The smallest error obtained was more than 3% for a 10Ω fault, while the highest one was around 30% of the total line length, which represents almost 10km, and is also associated with the R_F influence to the DG model, as shown in

Section IV. The DG model influence is clearly demonstrated in Fig. 8, between 0km and 13km, where the methodology uses the DG model to evaluate the fault location in each iterative step of the algorithm.

VII. Conclusions

In this paper, the fault resistance influence was analyzed in distance relaying, synchronous machines models, fault location algorithms with and without distributed generation.

The theoretical analysis concludes that the existence of non-negligible R_F influences almost all the studied subjects. The first studied case, distance relaying, has shown a great R_F performance dependency, justifying the common use of quadrilateral characteristic to improve the R_F coverage and the development of new techniques to compensate the parameters value. The 2nd case presented and studied, one-terminal fault location algorithms, resulted in a small R_F performance dependency. The 3rd case analyzed however, a synchronous machine exposed to an external fault with significant R_F, resulted also in high R_F dependency. It becomes necessary in this case, the development of new equivalent models of synchronous machines for studies of fault contingency analysis considering significant R_F. The last case studied the R_F influence in fault location methodologies for DG systems. The method studied also showed high R_F performance dependency, indicating the need of development of new fault location algorithms.

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