CONSIDERATION OF SPECIFIC RESISTANCE OF A CONDUCTOR BY THE METHOD OF APPARENT IMPEDANCE

VADA ĪPATNĒJĀS PRETESTĪBAS IEVĒROŠANA, PIELIETOJOT ŠĶIETAMĀS PRETESTĪBAS METODI

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Keywords: apparent impedance, medium voltage networks, single- phase-earth fault, specific resistance, two terminal power line

Introduction

The attention to protecting the two terminal power lines against single-phase-earth fault using single-terminal fault data has been paid for a long time. The various methods based on digital technique have been proposed [1; 2; 3]. The methods of frequency allocation and analysis of initial voltages are applied to locate the fault which requires additional technical means [4]. Even neural artificial network is used to achieve advantageous results [5; 6].
In 2004 the attempt was made [7] to apply distant protection classical algorithm (1):

$$\dot{Z}_a = \frac{\dot{U}_{ph}}{\dot{I}_{ph} + \dot{K}_N \dot{I}_g} \tag{1}$$

- where $\dot{Z}_a$ – apparent impedance to fault place; $\dot{K}_N$ – compensation coefficient; $\dot{U}_{ph}$ – faulty phase voltage; $\dot{I}_{ph}$ – faulty phase current; $\dot{I}_g$ – ground (neutral) current - for determining the direct sequence reactance X_1 to single-phase-earth fault place. Afterwards this way of handling $\dot{Z}_a$ (here it is called the apparent impedance method) was accomplished for single lines [8]. Still later the method was considered for double circuit (parallel) lines [9]. In [10] the method was applied for medium voltage grids with small single-phase-earth currents. The similar methods are considered for two terminal lines by other types of short circuits [11].

The fundamental expressions

The quantities used further for calculation of direct sequence reactance are:

$$R_a = \mathrm{Re}\left(\frac{\dot{U}_{ph}}{\dot{I}_{ph} + \dot{K}_N \dot{I}_g}\right); \tag{2}$$

$$X_a = \mathrm{Im}\left(\frac{\dot{U}_{ph}}{\dot{I}_{ph} + \dot{K}_N \dot{I}_g}\right), \tag{3}$$

where R_a stands for apparent resistance to fault place, X_a – apparent reactance to fault place.
To come to an end formulas, we must rely on expression for phase voltage $\dot{U}_{ph}$:

$$\dot{U}_{ph} = \dot{I}_{1l}\dot{Z}_1 + \dot{I}_{2l}\dot{Z}_2 + \dot{I}_{0l}\dot{Z}_0 + \dot{I}_f R_f = (\dot{I}_{1l} + \dot{I}_{2l})\dot{Z}_1 + \dot{I}_{0l}\dot{Z}_0 + R_f \dot{I}_f \,, \tag{4}$$

where $\dot{I}_{1l}$; $\dot{I}_{2l}$; $\dot{I}_{0l}$ and $\dot{I}_f$ – positive, negative, zero sequence current at monitoring place and fault current through fault place; $\dot{Z}_1$; $\dot{Z}_0$ and R_f – positive; zero sequence impedance of the line to fault place and fault resistance (the resistance through which phase conductor connects to earth as a result of fault occurring).
Putting designations, displayed by cluster of formulas (5):

$$\dot{k} = \frac{\dot{I}_g}{\dot{I}_{ph}} = \frac{3\dot{I}_{0,l}}{\dot{I}_{ph}} = k' + jk''\,;\ k' = \mathrm{Re}(\dot{k})\,;\ k'' = \mathrm{Im}(\dot{k})\,;\ \dot{I}_{0,l} = \frac{\dot{k}}{3}\dot{I}_{ph}\,;$$
$$\dot{I}_{1.l} + \dot{I}_{2,l} = \frac{3-\dot{k}}{3}\dot{I}_{ph}\,;\ \dot{k}_f = \frac{\dot{I}_f}{\dot{I}_{ph}} = k_f' + jk_f''\,;\ k_f' = \mathrm{Re}(\dot{k}_f)\,;\ k_f'' = \mathrm{Im}(\dot{k}_f) \tag{5}$$

and opening the meaning of $\dot{Z}_1$; $\dot{Z}_0$ we receive expression for $\acute{U}_{ph}$, which can be used in basic formula (1):

$$\dot{U}_{ph} = \dot{I}_{ph}\{(R_c + \dot{k}R_g + \dot{k}_f R_f) + j\frac{1}{3}[(3-\dot{k})X_1 + \dot{k}X_0]\}\,, \tag{6}$$

where R_c; R_g; X_1; X_0 are conductor and ground resistance to fault place; positive sequence and zero sequence reactance to fault place; $\acute{k}$ – the ratio of ground current $\dot{I}_g$ against phase current $\dot{I}_{ph}$. In medium voltage grids it is implied that zero sequence resistance R_0 doesn't differ from conductor resistance R_c.
The sought reactance X_1 to fault place as well as (if necessary) fault resistance R_f can be found by rather lengthy calculations with the following end formulas:

$$X_1 = \frac{BX_a - DR_a}{B - aD} = \frac{(f' + f''tg\varphi_f)X_a - (f'tg\varphi_f - f'')R_a}{f'(1 - atg\varphi_f) + f''(tg\varphi_f + a)}\,; \tag{7}$$

$$R_f = \frac{R_a - aX_a}{B - aD} = \frac{h}{k_f'}\frac{R_a - aX_a}{f'(1 - atg\varphi_f) + f''(tg\varphi_f + a)}\,. \tag{8}$$

The distance l to fault place can readily be determined:

$$l = \frac{X_1}{X_{1sp}}\,. \tag{9}$$

The quantities f'; f''; a; h depend on power line specific parameters of which are the following: R_{csp} – phase conductor specific resistance; R_{gsp} – ground specific resistance; X_{1sp} – positive sequence specific reactance; X_0 – zero sequence specific reactance as well as on measured currents: $\dot{I}_{ph}$ – faulty phase current and $\dot{I}_g$ – ground (neutral) current. The coefficient k_f' and tgφ depend on current $\dot{I}_{ph}$ which is measured and current through fault place $\dot{I}_f$ which can not be measured but can be obtained in the iterating process of calculation.

Peculiarities of applying the method to medium voltage networks

There are no difficulties with measuring all necessary currents with desired accuracy. Measuring phase voltage, the difficulties are to be overcome, because in medium voltage grids by single-phase-earth fault the faulty phase voltage is much lesser than in normal conditions (as it already was mentioned in [10]). Let us leave this problem to be solved by technicians.
The question of distributed capacitive currents must be defined more correctly as compared with [10] Besides there are not only capacitive to earth currents but also capacitive interphase currents. On the scheme in Fig.1 the distributed capacitive currents are shown.

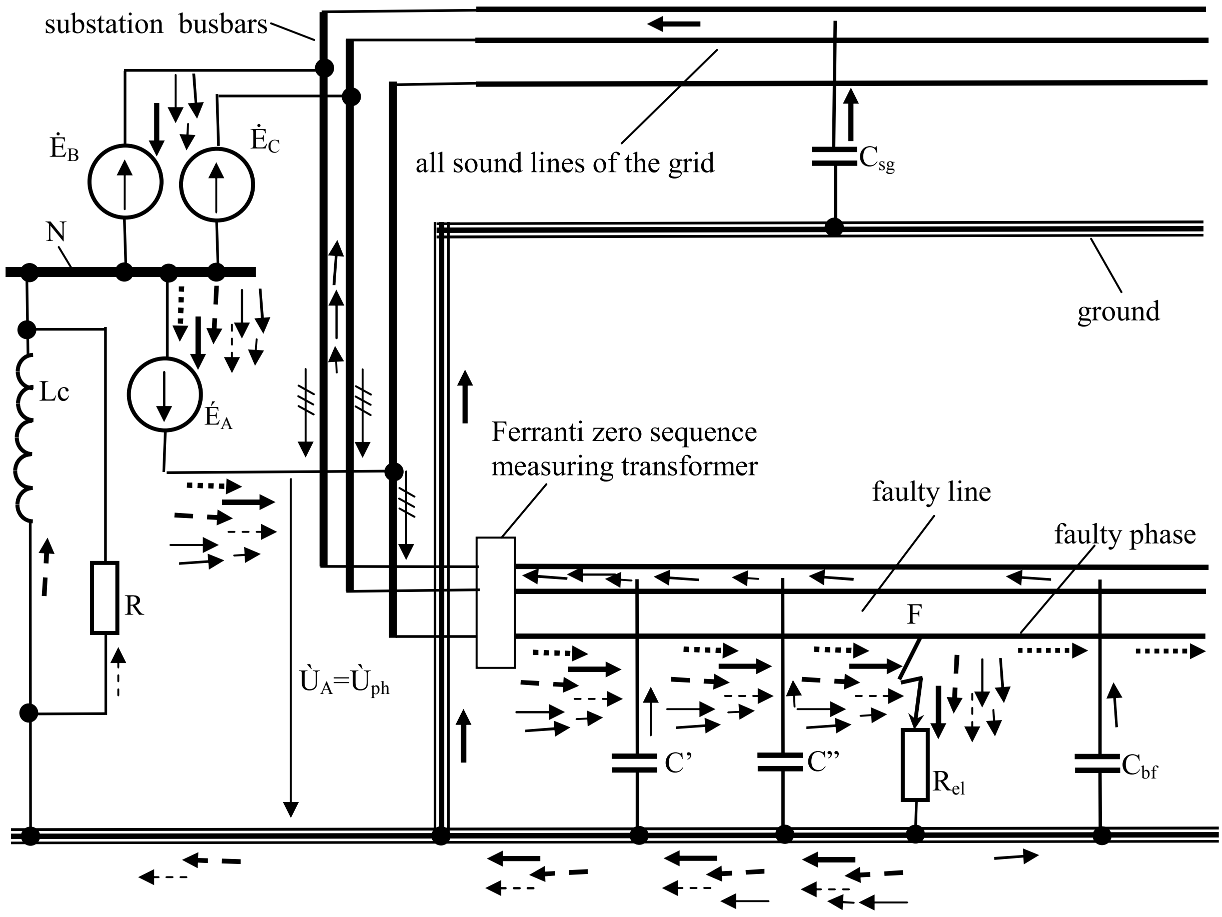

Fig1. Scheme of the grid with small phase-to-earth currents; the outlook of currents with phase-to-earth fault at point F; N – neutral of the grid; $\dot{E}_A$; $\dot{E}_B$; $\dot{E}_C$ – the phase emf, $\dot{E}_{ph}=\dot{E}_A$, U_{ph} – phase voltage of faulted phase; R_{el} – fault transient resistance

$\dot{I}_{lo}$ – load current of faulty phase; $\dot{I}_{csg}$ – capacitive current of sound part of the

$\dot{I}_L$ – current of the compensation coil; $\dot{I}_R$ – active current of the neutral;

$\dot{I}_{c'}$ – the first dissipated capacitive to earth current of the $\dot{I}_{c''}$ – the second ...

$\dot{I}_{cbf}$ – capacive current to earth of faulty line behind fault place

$\dot{I}_{cslin}$ – symmetrical (interphase) capacitive phase current of the whole faulty line

Due to distributed nature of capacitive currents, as considered on the span from Ferranti transformer to fault place F, we can not for phase voltage apply formula (4) without changing it. For $\acute{U}_{ph}$, taking into account that for power line $\dot{Z}_1 = \dot{Z}_2$, we must write:

$$\dot{U}_{ph} = (\dot{I}_{1l} + \Delta I_{1cf})\dot{Z}_1 + \dot{I}_{2l}\dot{Z}_1 + (\dot{I}_{0l} + \Delta\dot{I}_{0cf})\dot{Z}_0 + \dot{I}_f R_f . \qquad (10)$$

The currents $\Delta\dot{I}_{1Cf}$ and $\Delta\dot{I}_{0Cf}$ appear in formula because of distributed character of current $\dot{I}_c$ (see Fig.1) and $\dot{I}_{cs}$. The currents $\dot{I}_{ph}$, $\dot{I}_{1l}$, $\dot{I}_{2l}$, $\dot{I}_{0l}$ can be measured and calculated out of three phase currents or out of their constituent parts. As concerns currents $\Delta\dot{I}_{1cf}$ and $\Delta\dot{I}_{0cf}$, they are implied (can not be measured). Their value may be appreciated by their engagement in the formation of phase voltage (4). Current $\Delta\dot{I}_{1cf}$ consist of two constituents: $\Delta\dot{I}_{1cf}'$ and $\Delta\dot{I}_{1cf}''$, the first being the result (is calculated) of capacitive to earth current and the second – the result of capacitive interphase one. The $\Delta\dot{I}_{0cf}$ is calculated out of capacitive to earth current.
Expression (10) for faulty phase voltage $\dot{U}_{ph}$ is not fit for apparent impedance method which is based on expression (4). Let us decompose the $\dot{U}_{ph}$ according to (10) in two parts:

$$\dot{U}_{ph} = \dot{U}_{ph}' + \Delta\dot{U}_{ph} \tag{11}$$

The first part:

$$\dot{U}_{ph}' = (\dot{I}_{1,l} + \dot{I}_{2,l})\dot{Z}_1 + \dot{I}_{0,l}\dot{Z}_0 + \dot{k}_f \dot{I}_{ph} R_f; \tag{12}$$

and the second one:

$$\Delta\dot{U}_{ph} = \Delta\dot{I}_{1cf}\dot{Z}_1 + \Delta\dot{I}_{0cf}\dot{Z}_0. \tag{13}$$

After we find the first part $\dot{U}_{ph}'$ of the phase voltage $\dot{U}_{ph}$, to determine X_1 and R_f is the routine procedure (see (7) and (8)).
The question is, how to determine voltage $\dot{U}_{ph}'$, provided we know voltage $\dot{U}_{ph}$ which is measured during fault occurrence. This difficulty can be overcome with the help of iteration process. Let us assume that we know the distance to fault place; let it be $l^{(0)}=l_{lin}/2$, l_{lin} – faulty line length. Then the $\dot{I}_c^{(1)}$ and $\dot{I}_{cs}^{(1)}$ are found and $\Delta\dot{I}_{1cf}^{(1)}$ and $\Delta\dot{I}_{0cf}^{(1)}$ are calculated. For $l^{(0)}$, must be calculated $\dot{Z}_1^{(1)}$ and $\dot{Z}_0^{(1)}$. Now $\dot{U}_{ph}^{(1)}$ and $\dot{U}_{ph}'^{(1)}$ are calculated by (13) and (12). Now formula (1) can be let in use, where $\dot{U}_{ph}'$ stands for $\dot{U}_{ph}$, to acquire apparent quantities $X_a^{(1)}$ and $R_a^{(1)}$. At the end through all necessary calculations we come to expression (7) and by formula (9) receive first approximation $l^{(1)}$ of distance to fault place; after that we begin the next turn of iteration, finding $\dot{Z}_1^{(2)}$, $\dot{Z}_0^{(2)}$, $X_a^{(2)}$, $R_a^{(2)}$ ... $l^{(2)}$, continuing iterative process up to acceptable degree of coincidence of the results. Calculating in Excel it requires 3 – 4 iterations for the results to converge.
The trustworthiness of the results by expressions (7) and (8) depends on the precision of all the quantities entering expressions. Putting aside measurement accuracy, the attention must be paid to mentioned specific quantities. They all may deviate from those written in protection device memory; the reason of deviation hides in power line build up or temperature change. Their influence on output quantities X_1 and R_f roughly can be estimated as differential of said output quantities after deviation of each four mentioned specific values.
As can be seen from shown above complicated expressions, mathematical procedure to evaluate influence of said specific parameter deviations can be considered as hopeless. The result can be received more quickly by calculations by means of modern techniques. The peculiar interest arises about phase conductor specific resistance R_{csp}. Preliminary considerations allow to assert that only phase conductor specific active resistance R_{csp} is of greater concern because of phase conductor temperature change. The change is a result of ambient temperature fluctuations and phase wire current loading. Indeed, for copper wire, temperature change 50 ºC causes 20 % resistance change. The calculations show that such an extreme input data can be found, for which deviation of specific resistance to ±5 % can cause direct sequence reactance X_1 change within the limits of more

than ±100 %. In such an outcome, the usefulness of apparent impedance method can be questioned. At the same time remaining three specific quantities do not feel or feel in minimum extent said temperature instability; hereto, digressions of said specific parameters as a result of power line build up can be taken into account by measuring or recalculations; which can't be applied to conductor specific resistance R_{csp} because of volatile wire temperature.
This looks out in the following way. The value R_{csp} is written in the memory of protection device. At the moment of fault occurring, actual conductor resistance is not that one which is written in the memory but some other, changed, say R_{csp}'. Naturally, the protection device gives out some X_l' value deviating from its right value X_l. If the protection device would know actual conductor resistance R_{csp}^a it would give out inerrable positive sequence reactance to fault place X_l. But how can protection device know the actual value R_{csp}^a of conductor resistance?
The calculations showed the following. If there are no loading of the power line, the deviation of R_{csp} practically does not influence the results. The results for loaded line strongly depend on the ratio ground current / load current. The figures are acquired for R_{csp} = 0,306 Ω/km: for the ratio 0,12 the distance error 50 % by ΔR_{csp} = 20 % and for the ratio 0,03 the distance error is 200 %. Such an outcome is not acceptable. Therefore resort can be sought in the appreciation of line phase wire temperature, taking into account outdoor ambient temperature and the figures of power line loading. Naturally, such an approach is not convenient one. An attempt was made to recalculate conductor resistance R_{csp} but it was unsuccessful because it was made on the basis of only expression (1). This expression breaks down into two parts: the real and imaginary ones. Therefore on this basis can be found only two unknowns: R_f and X_1. To find the third unknown R_{csp} one must try to find third equation.
For such an equation can be tried to apply the expression of zero sequence voltage at device input which can be acquired out of three phase voltages:

$$\dot{U}_0 = \dot{I}_{0l}\dot{Z}_0 + \dot{I}_f R_f . \qquad (14)$$

Now we have three equations (2), (3) and (14) and three unknowns R_f, X_1 and R_c. Of course such a set of equations is not possible to solve simultaneously. It is necessary to resort to iteration method. Whether it will converge can be seen proceeding with concrete calculations.

Conclusions

1. The inconsistency of phase conductor specific resistance can cause unacceptable errors by determining the reactance to single-phase-earth fault place applying apparent impedance method to medium voltage grids.
2. This drawback can be diminished if the capacitive current is not compensated as well as by appreciating actual wire temperature. By unloaded power lines the influence of R_{csp} is small.
3. Theoretically the possibility exists to appreciate the phase conductor specific resistance but further research must be made and this possibility must be thoroughly verified with concrete calculations.

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Survilo J. Vada īpatnējās pretestības ievērošana, pielietojot šķietamās pretestības metodi.

Lai izrēķinātu tiešās secības induktīvo pretestību X_1 no ierīces uzstādīšanas vietas līdz vienfāzes īsslēguma ar zemi vietai (un, ja nepieciešams, bojājuma pretestību) vidējā sprieguma tīklos, var pielietot šķietamās pretestības metodi, kurā jāņem vērā šādi līnijas īpatnējie lielumi: fāzes vada aktīvā pretestība R_{csp}, zemes pretestība R_{gsp}, tiešās secības induktīvā pretestība X_{1sp}, nullsecības induktīvā pretestībaX_{0sp}. No minētajiem četriem lielumiem tikai fāzes vada pretestībai R_{csp} ir nestabils raksturs fāzes vada temperatūras izmaiņas dēļ, kas noved pie kļūdainiem rezultātiem, aprēķinot X_1. Pie mazām slodzes strāvām vai kad zemes kapacitatīvā strāva nav kompensēta, R_{csp} ietekme ievērojami mazinās. Praktiski katram īsslēguma ar zemi gadījumam ir nepieciešams izvērtēt vada temperatūru, ņemot vērā apkārtējo temperatūru un EPL noslogotību. Nav iespējams koriģēt ierīcē ierakstīto R_{csp}, izmantojot tikai klasiskā distantaizsardzības algoritma izteiksmi. Lai atrastu īsto aktuālo vada pretestību, ir nepieciešams izskatīt vēl vienu

vienādojumu. Domājams, ka par tādu vienādojumu var kalpot izteiksme nullsecības spriegumam ierīces ieejā, jo nullsecības spriegumu var izkalkulēt no trim fāzes spriegumiem. Šī izteiksme kopā ar klasiskā algoritma izteiksmi, kas sadalīta reālajā un imaginārajā daļā, veidos vienādojumu sistēmu, kas nepieciešama, lai atrastu R_{csp} papildus diviem iepriekšējiem nezināmajiem.

Survilo J., Consideration of specific resistance of a conductor by the method of apparent impedance.
To determine the reactance of positive sequence X_1 from the monitoring place to a single-phase-earth fault (and, if necessary, the fault resistance) in medium-voltage networks, the apparent impedance method can be applied, which takes into account such power line specific quantities as: phase conductor resistance R_{csp}, ground resistance R_{gsp}, positive sequence reactance X_{1sp}, zero sequence reactance X_{0sp}. Of the mentioned four quantities, only the conductor specific resistance has unstable character due to variations in its phase temperature leading to erroneous results at calculation of reactance X_1. At small load currents or in the cases of non- compensated capacitive earth current the influence of R_{csp} considerably diminishes. In practice it is necessary for each single-phase-earth fault case to estimate the wire temperature with due account for ambient temperature and power line loading. Since it is impossible to correct the set R_{csp} value of the protection device using only the equation of distance protection classical algorithm, to find the true actual conductor resistance it is necessary to introduce into the consideration one more equation – e.g. an expression for zero sequence voltage at the device input that can presumably be determined by three phase voltages. Such an expression, together with that for classical algorithm broken down into a real and an imaginary part, will constitute a set of three equations required for finding - additionally to two initial unknowns - the third one, which is R_{csp}.

Сурвило И., Учет удельного активного сопротивления провода фазы при использовании метода кажущегося сопротивления.
При определении индуктивного сопротивления прямой последовательности X_1 от места установки защиты до однофазного замыкания на землю (и, при необходимости, сопротивления повреждения) в сетях среднего напряжения, может быть применен метод кажущегося сопротивления, при котором должны приниматься в расчет следующие удельные параметры линии: активное сопротивление провода фазы R_{csp}, сопротивление земли R_{gsp}, реактивное сопротивление прямой последовательности X_{1sp}, реактивное сопротивление нулевой последовательности X_{0sp}. Из упомянутых четырех величин только сопротивлению фазы провода R_{csp} присущ нестабильный характер из-за изменения температуры провода, что приводит к ошибочным результатам при расчете X_1. При малых токах нагрузки или когда емкостной на землю ток не скомпенсирован, влияние R_{csp} сильно уменьшается. Практически же необходимо для каждого случая однофазного замыкания на землю оценить температуру провода, принимая во внимание окружающую температуру и нагрузку линии. Невозможно скорректировать записанное в защиту R_{csp}, используя только уравнение классического алгоритма дистанционной защиты. Чтобы определить правильное актуальное значение, необходимо ввести в рассмотрение еще одно уравнение. Таким уравнением предположительно может служить выражение для напряжения нулевой последовательности на входе защиты, поскольку оно может быть определено по напряжениям трех фаз. Это уравнение вместе с выражением классического алгоритма, разбитого на реальную и мнимую части, составит систему трех уравнений, необходимых для определения третьего неизвестного R_{csp} дополнительно к двум изначальным неизвестным.