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Directional Overcurrent Relays Coordination Problems in Distributed Generation Systems

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Abstract: This paper proposes a new approach to the distributed generation system protection coordination based on directional overcurrent protections with inverse-time characteristics. The key question of protection coordination is the determination of correct values of all inverse-time characteristics coefficients. The coefficients must be correctly chosen considering the sufficiently short tripping times and the sufficiently long selectivity times. In the paper a new approach to protection coordination is designed, in which not only some, but all the required types of short-circuit contributions are taken into account. In radial systems, if the pickup currents are correctly chosen, protection coordination for maximum contributions is enough to ensure selectivity times for all the required short-circuit types. In distributed generation systems, due to different contributions flowing through the primary and selective protections, coordination for maximum contributions is not enough, but all the short-circuit types must be taken into account, and the protection coordination becomes a complex problem. A possible solution to the problem, based on an appropriately designed optimization, has been proposed in the paper. By repeating a simple optimization considering only one short-circuit type, the protection coordination considering all the required short-circuit types has been achieved. To show the importance of considering all the types of short-circuit contributions, setting optimizations with one (the highest) and all the types of short-circuit contributions have been performed. Finally, selectivity time values are explored throughout the entire protected section, and both the settings are compared.

Keywords: distributed generation; selectivity; overcurrent protection; inverse-time characteristic; protection setting optimization

1. Introduction

Currently, the protection of distributed generation systems (DGS) is increasingly a discussed topic. By the connection of the source to the distributed system, not only the nominal, but also the fault conditions are affected. Therefore, the topical concept of distributed system protection has gradually been becoming inapplicable, and concepts taken from the transmission system protection, such as differential [1–5], distance [6–14], or directional overcurrent [15–30], have increasingly been used.

In a classical radial concept depicted in Figure 1, the major electrical sources are connected to the transmission system and, in contrast, the electrical loads to the distribution system. In view of the network protection, a big advantage of the classical network concept is unidirectional power flow from the transmission to the distribution system. Unidirectional current allows us to use simple protection principles, for example, based on non-directional overcurrent protections.

If the short-circuit occurs in Section 3 (section numbers are green colored in Figure 1), the protection O_3 trip is required first and, after a certain time (selectively), the protection O_2 trip next.

There are two reasons: The first one is a backup of O_3 by O_2 in case of O_3 failure, and the other one is a minimum security margin (usually set at 200 ms), called the selectivity time, between the trips of both protections. In the following text, the first tripping protection (O_3) will be labelled as a primary protection, and the other tripping protection (O_2) will be labelled as a selective protection. As we can see below, the short-circuit contributions flowing through the primary O_3 and selective O_2 protections are the same (if the short-circuit contribution of load 2 is neglected).

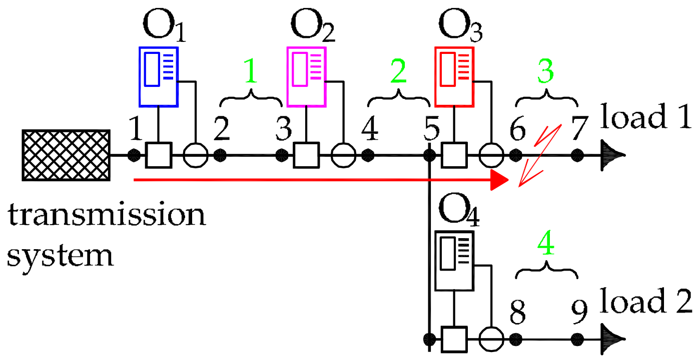

Figure 1. Radial system without distributed generation.

As will be described in detail in the next sections, the aforementioned facts make protection coordination very easy. For the correctly chosen pickup currents, only the types of short-circuit with maximum short-circuit contributions can be taken into account in protection coordination. If the selectivity is met for maximum contributions, it is automatically met for all the others.

In the part of DGS depicted in Figure 2, power sources can also be connected to the distribution system. Short-circuit contributions flow to the short-circuit from both the sides, and non-directional protections are no more applicable. If the overcurrent protections are used, each section must be equipped with two directional protections (the tripping directions are indicated by the green arrows), and the voltage transformer must be added for direction recognition. Let us assume a short-circuit in Section 2, from the left side; O_4 is a primary protection and O_2 is a selective protection. As we can see, the short-circuit contribution flowing through O_4 is increased by generator contribution and it is different from the contribution flowing through O_2 [31–33]. As will be described in detail in the next sections, if short-circuit contributions flowing through primary and selective protections are different, not only the type with maximum short-circuit contributions, but all the required short-circuit types must be taken into account. However, similarly to a classical radial system, only one type of short-circuit can be assumed for protection coordination. The key issue of protection coordination is finding this type.

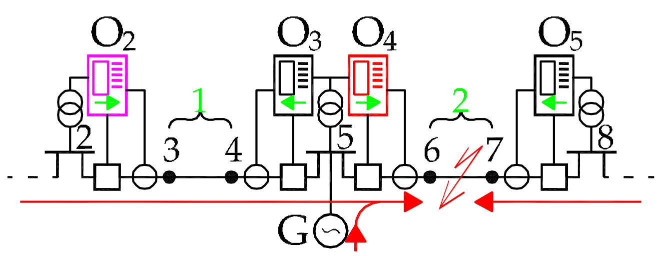

Figure 2. Part of distributed generation system (DGS).

The inverse-time characteristics, by their shape, simulate the function of a fuse or a circuit breaker, and they allow for a faster tripping in case of an high overcurrent and, to the contrary, a slower tripping in case of a low overcurrent. For example, under the IEC standard [34], the tripping time of protection O_i can, according to [35], be written as:

$$t_{tripOi} = \frac{M_{Oi} \cdot K_{Oi}}{\left(I_{pOi}/I_{pcOi}\right)^{E_{Oi}} - 1} \quad (1)$$

where I_{pOi} is short-circuit contribution flowing through protection, M_{Oi} is time multiplier, I_{pcOi} is pickup current, and K_{Oi} and E_{Oi} are slope constants.

The coordination process of directional overcurrent protections with inverse-time characteristics in DGS has already been dealt with by many authors. In most of these works, an appropriately designed optimization is shown as a suitable tool for this purpose. For example, in [15–23], the values of time multipliers M_{Oi} are determined for predetermined values of I_{pcOi} and slopes (E_{Oi} and K_{Oi}). For each protection, only one coefficient is looked for, and the linear programming can be used. Other publications [24–30] have dealt with the determination of time multipliers M_{Oi} and pickup currents I_{pcOi} with predetermined slope. In the latter, the optimization is nonlinear and a more sophisticated optimization method must be used. However, all the aforementioned works [15–30] have mainly focused on the optimization process itself, but not much attention has been paid to choosing the proper short-circuit contributions types; additionally, only the maximum and minimum short-circuit contributions have been taken into account (and/or the current contributions values, without a calculation process description, have only been mentioned). As will be described in the article, the maximum and minimum short-circuit contributions can only be used if the short-circuit contributions flowing through primary and selective protections are the same. Since those works deal with protection of DGS, in which such an assumption cannot be generally held, the selectivity of protections can be disturbed.

2. Tripping Time of Protection

According to (1), the protection tripping time can be determined assuming the short-circuit contribution flowing through the protection $I_{pOi} > I_{pcOi}$ constant during the disconnection process. In case of variable I_{pOi}, tripping time can be calculated from the definition relation [36]:

$$\int_0^{t_{tripOi}} \frac{1}{M_{Oi} \cdot K_{Oi}} \left(\left(\frac{I_{pOi}}{I_{pcOi}} \right)^{E_{Oi}} - 1 \right) dt = 1 \quad (2)$$

Let us consider a simplified case, where the short-circuit contribution $I'_{pOi} > I_{pcOi}$ flows through protection only for time t'_{Oi}. If I'_{pOi} flowed through protection for sufficiently long time t'_{tripOi}, the protection would trip. However, we are assuming $t'_{Oi} < t'_{tripOi}$ and, hence, the trip does not occur. After the aforementioned time t'_{Oi}, a different value of $I_{pOi} > I_{pcOi}$ starts flowing through the protection. To obtain a total tripping time, using (2) it can be written:

$$\begin{gathered} \frac{1}{M_{Oi} K_{Oi}} \int_0^{t'_{Oi}} \left[\left(\frac{I'_{pOi}}{I_{pcOi}} \right)^{E_{Oi}} - 1 \right] dt + \\ \frac{1}{M_{Oi} K_{Oi}} \int_{t'_{Oi}}^{t_{tripOi}} \left[\left(\frac{I_{pOi}}{I_{pcOi}} \right)^{E_{Oi}} - 1 \right] dt = 1 \end{gathered} \quad (3)$$

The result total tripping time can, using (3), be expressed as:

$$t_{tripOi} = \frac{K_{Oi} \cdot M_{Oi} + \left[\left(\frac{I'_{pOi}}{I_{pcOi}} \right)^{E_{Oi}} - \left(\frac{I_{pOi}}{I_{pcOi}} \right)^{E_{Oi}} \right] \cdot t'_{Oi}}{\left(\frac{I_{pOi}}{I_{pcOi}} \right)^{E_{Oi}} - 1} \quad (4)$$

To obtain a more precise value of the total tripping time, the evaluation principle of specific protection must be used.

3. Protection Coordination of Radial System without Distributed Generation

As mentioned in the introduction, if the short-circuit contributions of the loads are neglected, the contributions flowing through the primary and selective protections can be considered the same. If the short-circuit current is very close to, or lower than, the nominal current (e.g., for resistance loads), the short-circuit contribution can be neglected. If the short circuit cannot be neglected (e.g., for loads with rotating machines), the principles described in this chapter cannot be used, and the principles for DGS, described in the following chapter, must be used instead. In Figure 3 there are two possible cases of protection setting coordination between primary and selective protections for the same current I_p flowing through them. In case a), the pickup current of selective (j) protection is higher than the primary (i) protection $I_{pcOi} < I_{pcOj}$. It is obvious the selectivity time between i-th and j-th protections $\Delta t_{i,j}$ is always higher for a lower current I_p. That means that if the selectivity is met for the maximum contribution, it is automatically met for all others. The short-circuit type producing maximum contribution can in this case be labelled as the most sensitive one. A similar case occurs in case of equal pickup currents of both the protections $I_{pcOp} = I_{pcOd}$ (in Figure 2, not drawn).

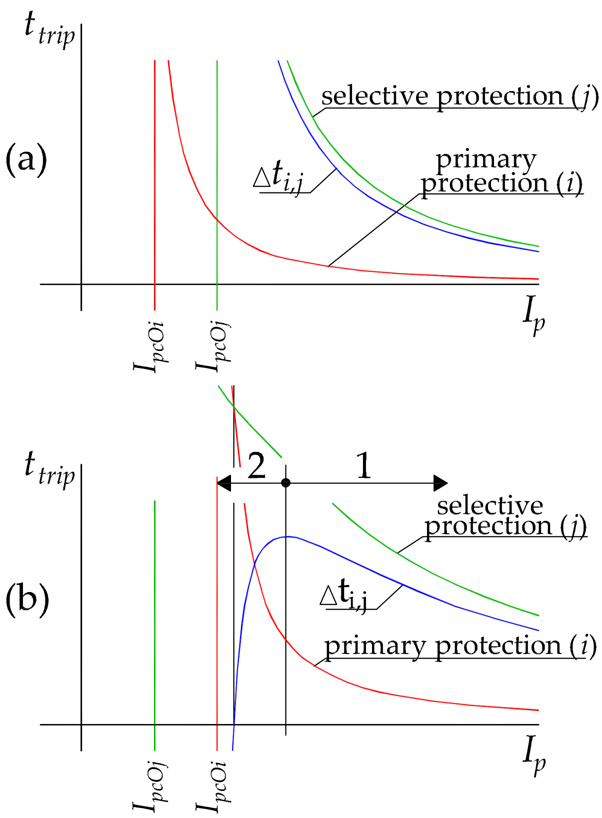

Figure 3. Possible pickup current choices in radial system without distributed generation. (**a**) Pickup current of selective protection is higher than the primary; (**b**) Pickup current of primary protection is higher than the selective.

Another case is depicted in Figure 3b. The pickup current of primary (i) protection is higher than the selective (j) one $I_{pcOi} > I_{pcOj}$. The dependence of the selective time $\Delta t_{i,j}$ on the current I_p can be divided into two parts. In the first part labelled 1, selectivity time is always higher for a lower current I_p, similarly to the previous case. In the second part labelled 2, selectivity time is always lower for a lower I_p, and for some very low values of I_p (near the primary protection pickup current) the selectivity time is negative and selective protection reacts before the primary one. Since the selectivity must be met for all the required short-circuit types, the maximum contribution is not enough, most sensitive short-circuit type cannot be generally determined, and the minimum contribution must also be taken into account. To make coordination as easy as possible, the pickup currents choice had better be made as in Figure 3a:

$$I_{pcOi} \leq I_{pcOj} \tag{5}$$

A simple setting of the k-th protection pickup current can, for example, be done as:

$$I_{pcOk} = k_{pc} \cdot I_{nOk} \tag{6}$$

where I_{nOk} is the nominal current flowing through the protection in a pre-fault state, and k_{pc} is an appropriately determined constant (it always must be higher than 1). For the determination of k_{pc}, two basic facts must be taken into account. For low values of k_{pc}, I_{pcOk} is very close to the nominal current I_{nOk}, hence, there is a risk of a mal-trip. On the other hand, with high values of k_{pc}, the sensitivity of the protection gets decreased.

Due to a radial system topology, condition (5) is always met for the pickup current chosen according to (6).

4. Most Sensitive Short-Circuit Types Finding Process in Distributed Generation Systems

As mentioned in the introduction, in DGS, the short-circuit contributions flowing through primary and selective protections cannot generally be considered the same. In Figure 4 fault path is depicted. Each fault path consists of primary O_i and selective O_j protections, primary n_i and secondary m_i nodes, and the minimum required selectivity time $\Delta t^{\bullet}_{i,j}$.

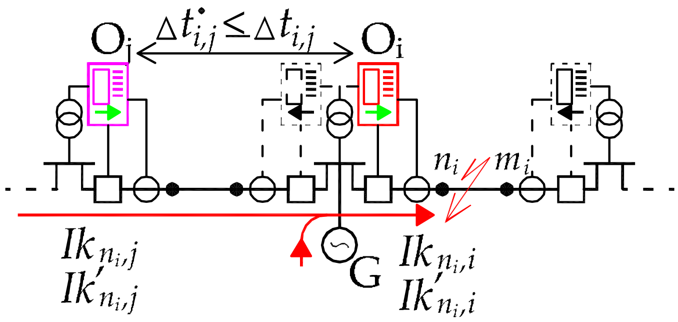

Figure 4. Fault path definition.

Let us assume a generator connected to the bus between the primary and selective protections, and a short-circuit in primary node n_i. Short-circuit contribution flowing through a primary protection $Ik_{n_i,i}$ is increased by the generator contribution and, hence, the contribution flowing through a selective protection $Ik_{n_i,j}$ must be lower $Ik_{n_i,i} > Ik_{n_i,j}$. In Figure 5, there are depicted short-circuit contributions $Ik_{n_i,i}$, $Ik_{n_i,j}$ and $Ik'_{n_i,i}$, $Ik'_{n_i,j}$, each for a different short-circuit type. In case depicted in Figure 5a, a higher sensitivity is obvious for contributions $Ik_{n_i,i}$, $Ik_{n_i,j}$. If slope of the characteristic for a selective protection gets changed, change to sensitivity may occur as in Figure 5b, where a higher sensitivity is obvious for contributions $Ik'_{n_i,i}$, $Ik'_{n_i,j}$. Since the shapes of characteristics are not known before the protection coordination (obtaining their shapes is goal of coordination), the most sensitive short-circuit types are not known either. A possible way of getting the most sensitive short-circuit types is depicted in the diagram in Figure 6.

To identify the most sensitive short-circuit types, all short-circuit contributions flowing through the primary and the selective protection in the primary and secondary nodes of each fault path must be calculated for all the short-circuit types. Another operation necessary is an initial estimation of the topical short-circuit types. Initial topical types can be chosen randomly, but the final setting can be obtained faster if three-phase short-circuits are chosen. After protection coordination for these estimates, minimum required selectivity time $\Delta t^{\bullet}_{i,j}$ is met for three-phase short-circuits, but for other types, the selectivity may not be met. For this reason, selectivity can be calculated for all short-circuit types, and the deviations from, as well as the minimum required selectivity times, can be found:

$$\begin{aligned} \delta tn_{i,j}(kn_{i,j}) &= \Delta tn_{i,j}(kn_{i,j}) - \Delta t^{\bullet}_{i,j}(kn_{i,j}) \\ \delta tm_{i,j}(km_{i,j}) &= \Delta tm_{i,j}(km_{i,j}) - \Delta t^{\bullet}_{i,j}(km_{i,j}) \end{aligned} \tag{7}$$

where, for example, $kn_{i,j}$ is short-circuit type for primary node, $\Delta tn_{i,j}(kn_{i,j})$ is selectivity time between the primary and selective protections for short-circuit type $kn_{i,j}$ in primary node, and $\Delta t^{\bullet}_{i,j}(kn_{i,j})$ is an appropriate minimum required selectivity time. If all deviations are positive, all the required selectivities are met, and topical short-circuit types are the most sensitive ones. If in any node, for any short-circuit type, the deviation is negative, the type of deviation with a minimum value is found and marked as topical. New topical short-circuit types are used for new protection coordination, and the process is repeated until all deviations are positive. The coefficients of the characteristics obtained in the last iteration of the aforementioned process ensure correct selectivity times for all short-circuit types, and the obtained topical types are the most sensitive ones. As it will be shown in the next sections, the protection coordination of DGS considering only some types (in most cases only the maximum ones) of short-circuit contributions, as used in other published works on a similar topic, can effect too-short selectivity in the remaining types.

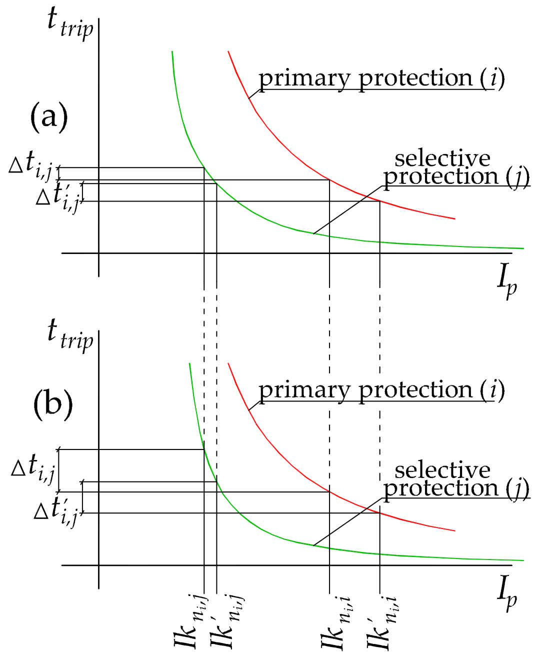

Figure 5. Sensitivity of selectivity for different short-circuit contributions flowing through primary and selective protections. (**a**) higher sensitivity occur for $Ik_{n_i,i}$, $Ik_{n_i,j}$; (**b**) higher sensitivity occur for $Ik'_{n_i,i}$, $Ik'_{n_i,j}$.

A similar result, that is, the coefficients of inverse-time characteristics guaranteeing the selectivity is met for all the required short-circuit types, can be obtained by only one coordination involving the conditions for meeting all the required selectivity times. The total number of these conditions can be obtained as:

$$con\_num = type\_num \cdot 2 \cdot path\_num \tag{8}$$

where *type_num* is number of types that are taken into account, and *path_num* is number of paths. For example, if five short-circuit types and 25 paths are assumed, 5$\cdot\times$ 2$\cdot\times$ 25 = 250 conditions must be taken into account. If the aforementioned process is used, the whole coordination consists of several sub-coordinations with 1$\cdot\times$ 2$\cdot\times$ 25 = 50 conditions. The number of these sub-coordinations is maximally equal to the number of assumed short-circuit types, but in most systems, the number is two or three. In larger systems, where the number of fault paths and short-circuit types is high, the coordination can be greatly accelerated.

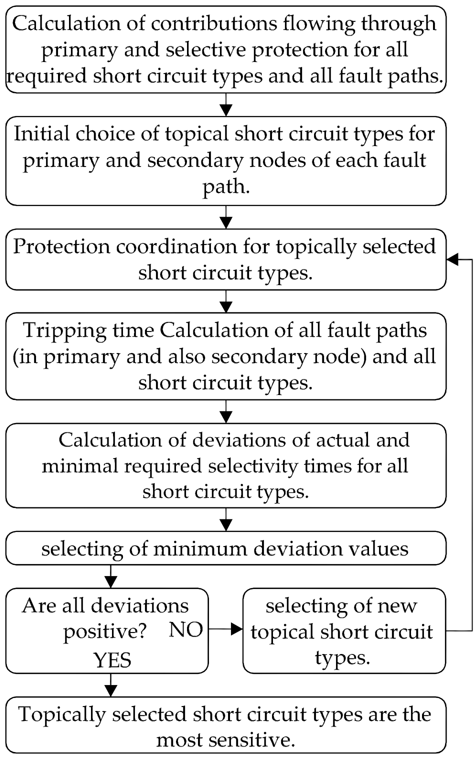

Figure 6. Finding process of the most sensitive short-circuit types.

5. Protection Coordination of Distributed Generation Systems

As mentioned in the introduction, protection coordination in DGS is a complex problem. Since manual coordination is rather complicated, and sometimes almost impossible, an automatic algorithm had better be used. One of the most often used ways is optimization based on the minimization of an appropriately designed objective function:

$$\begin{gathered}\boldsymbol{\psi}^{*} = arg\left(\min_{\boldsymbol{\psi}\in D}\Phi(\boldsymbol{\psi})\right)\\ D = \{\boldsymbol{\psi} \in \mathbb{R}^{n} : \boldsymbol{g}(\boldsymbol{\psi}) \geq \mathbf{0}\}\end{gathered} \tag{9}$$

where $\boldsymbol{\psi}$ is a vector of searched inverse-time characteristic coefficients, $\Phi(\boldsymbol{\psi})$ is an objective function, $\boldsymbol{D}$ is a set of possible $\boldsymbol{\psi}$ values, and $\boldsymbol{g}(\boldsymbol{\psi})$ is a vector of constraints. The goal of optimization is finding the vector $\boldsymbol{\psi}^{*}$ for which the value of $\Phi(\boldsymbol{\psi})$ is minimum. For clarity, part of objective function and constraints only for one primary protection O_1 will be shown on the part of DGS depicted in Figure 7, first.

In our part of DGS protections O_2 and O_3 must be selective to protection O_1 and, hence, fault paths O_1–O_2 and O_1–O_3 must be constructed. Both paths have the same primary and secondary nodes 1 and 2, and minimum required selectivity times $\Delta t^{\bullet}_{1,2}$ and $\Delta t^{\bullet}_{1,3}$. Objective functions can be defined as the sum of all primary protection tripping times in the primary and secondary nodes:

$$\begin{aligned}\Phi(\boldsymbol{\psi}) = & \frac{M_{O_1} \cdot K_{O_1}}{\left(\frac{\boldsymbol{Ik}_{1,1}\left(kn_{1,2}^T\right)}{I_{pcO_1}}\right)^{E_{O_1}} - 1} + \frac{M_{O_1} \cdot K_{O_1}}{\left(\frac{\boldsymbol{Ik}_{2,1}\left(kn_{1,2}^T\right)}{I_{pcO_1}}\right)^{E_{O_1}} - 1} \\ & + \frac{M_{O_1} \cdot K_{O_1}}{\left(\frac{\boldsymbol{Ik}_{1,1}\left(kn_{1,3}^T\right)}{I_{pcO_1}}\right)^{E_{O_1}} - 1} + \frac{M_{O_1} \cdot K_{O_1}}{\left(\frac{\boldsymbol{Ik}_{2,1}\left(kn_{1,3}^T\right)}{I_{pcO_1}}\right)^{E_{O_1}} - 1}\end{aligned} \quad (10)$$

where example $\boldsymbol{Ik}_{2,1}$ is a vector of all types of short-circuit contributions flowing through protection 1 for short-circuit in node 2, and $kn_{1,2}^T$ is a topical short-circuit type for short-circuit in primary node 1. In addition to minimizing the objective function (10), minimum required selectivity times $\Delta \boldsymbol{t}_{1,2}^{\bullet}$ and $\Delta \boldsymbol{t}_{1,3}^{\bullet}$ must also be met:

$$\begin{aligned}\Delta \boldsymbol{tn}_{1,2}\left(kn_{1,2}^T\right) &= \boldsymbol{t}_{1,2}\left(kn_{1,2}^T\right) - \boldsymbol{t}_{1,1}\left(kn_{1,2}^T\right) \geq \Delta \boldsymbol{t}_{1,2}^{\bullet}\left(kn_{1,2}^T\right) \\ \Delta \boldsymbol{tm}_{1,2}\left(km_{1,2}^T\right) &= \boldsymbol{t}_{2,2}\left(km_{1,2}^T\right) - \boldsymbol{t}_{2,1}\left(km_{1,2}^T\right) \geq \Delta \boldsymbol{t}_{1,2}^{\bullet}\left(km_{1,2}^T\right) \\ \Delta \boldsymbol{tn}_{1,3}\left(kn_{1,3}^T\right) &= \boldsymbol{t}_{1,3}\left(kn_{1,3}^T\right) - \boldsymbol{t}_{1,1}\left(kn_{1,3}^T\right) \geq \Delta \boldsymbol{t}_{1,3}^{\bullet}\left(kn_{1,3}^T\right) \\ \Delta \boldsymbol{tm}_{1,3}\left(km_{1,3}^T\right) &= \boldsymbol{t}_{2,3}\left(km_{1,3}^T\right) - \boldsymbol{t}_{2,1}\left(km_{1,3}^T\right) \geq \Delta \boldsymbol{t}_{1,3}^{\bullet}\left(km_{1,3}^T\right)\end{aligned} \quad (11)$$

where example $\boldsymbol{t}_{1,2}$ is a vector of tripping times of protection O_2 for short-circuit in node 1 and all types of short-circuit. Required short-circuit types may not only contain the basic short-circuit types such as three-phase-to-earth, single-phase-to-earth, two-phase-to-earth, or phase-to-phase, but different system configurations can also be taken into account. For example, another short-circuit type can be achieved by disconnection of the auxiliary line section related to protection O_X or O_1. If there is a short-circuit in the section between protection O_X and O_1, one of these protections must trip first and disconnect the relevant auxiliary line section. If there is a connection between the left side of the network (through node 2) and its right side (through nodes related to O_2 and O_3), and the first reaction of O_X is assumed, disconnection of the line causes an increase in the contributions from the right side (flowing through O_1, O_2, and O_3). In order to properly disconnect the affected section, the minimum required selectivity $\Delta \boldsymbol{t}_{1,2}^{\bullet}$ and $\Delta \boldsymbol{t}_{1,3}^{\bullet}$ times must also be guaranteed. Since there had been some short-circuit contributions flowing through O_1, O_2, and O_3 before the O_X tripped, a certain part of the selective times between O_1–O_2 and O_1–O_3 have already been met, and shorter selectivity times for these short-circuit types can be used. For this reason, minimum required selectivity times may be different for each type of short circuit and, in (11), required selectivities $\Delta \boldsymbol{t}_{1,2}^{\bullet}$ and $\Delta \boldsymbol{t}_{1,3}^{\bullet}$ are written as vectors. Final tripping times and selectivities of protections on the right side can be calculated according to (4). In the radial part of the system, the aforementioned increases of short-circuit contributions are not possible and, hence, this type may not be considered.

A general form of objective function (10) can be written as:

$$\Phi(\boldsymbol{\psi}) = \sum_{j \in \boldsymbol{J}} \sum_{i \in \boldsymbol{I}} \frac{M_{O_i} \cdot K_{O_i}}{\left(\frac{\boldsymbol{Ik}_{m_i,i}\left(km_{i,j}^T\right)}{I_{pcO_i}}\right)^{E_{O_i}} - 1} + \frac{M_{O_i} \cdot K_{O_i}}{\left(\frac{\boldsymbol{Ik}_{n_i,i}\left(kn_{i,j}^T\right)}{I_{pcO_i}}\right)^{E_{O_i}} - 1} \quad (12)$$

Similarly, general constraints can be written as:

$$\begin{aligned}\Delta \boldsymbol{tn}_{i,j}\left(kn_{i,j}^T\right) &= \boldsymbol{t}_{n_i,j}\left(kn_{i,j}^T\right) - \boldsymbol{t}_{n_i,i}\left(kn_{i,j}^T\right) \geq \Delta \boldsymbol{t}_{i,j}^{\bullet}\left(kn_{i,j}^T\right) \\ \Delta \boldsymbol{tm}_{i,j}\left(km_{i,j}^T\right) &= \boldsymbol{t}_{m_i,j}\left(km_{i,j}^T\right) - \boldsymbol{t}_{m_i,i}\left(km_{i,j}^T\right) \geq \Delta \boldsymbol{t}_{i,j}^{\bullet}\left(km_{i,j}^T\right)\end{aligned} \quad (13)$$

If all the pickup currents I_{pcOi} and the slope constants E_{Oi} are appropriately chosen, only the multipliers M_{Oi} are looked for, and minimization of (12) with constraints (13) can be fairly easy, mediated by linear programming (e.g., Simplex Method).

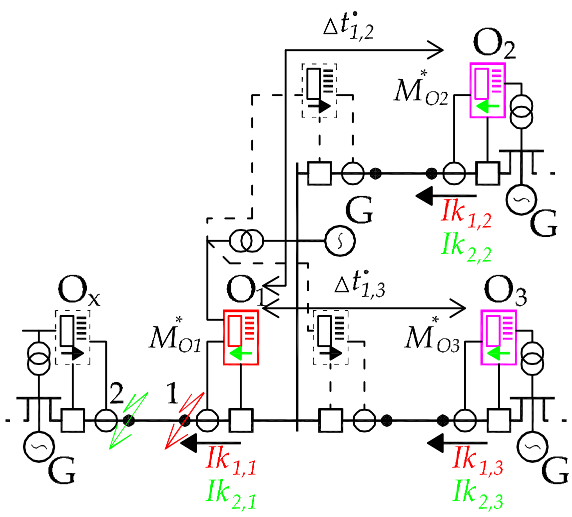

Figure 7. Part of DGS.

6. Pickup Current Choice

Correct pickup currents choice is an important part of the coordination process. As described in Section 3, in the radial systems without distributed generation, pickup currents of the primary protections lower than the secondary ones (5) had better be chosen to allow considering the short-circuit currents producing maximum short-circuit contributions only. In DGS, the pickup current choice does not affect the number of considered short-circuit types and, hence, it can be optional. However, in both the cases, the basic constraint must be met:

$$k_{bn} \cdot I_{nOi} < I_{pcOi} < k_{bk} \cdot Min\{\boldsymbol{Ik}_{m_i,i}\} \tag{14}$$

where I_{nOi} is a nominal current flowing through the protection in a pre-fault state, and k_{bn} and k_{bk} are appropriately chosen safety coefficients. As obvious in Figure 8, if the short-circuit occurs in Section 2, protection $\mathrm{O_X}$ fails, and the pickup current of protection $\mathrm{O_i}$ is chosen according to (14), selective disconnection of Section 2 by $\mathrm{O_i}$ may not occur. Therefore, constraint (14) can only be used if failure of protections is not considered. If failure of protections is to be considered, a tighter constraint must be used:

$$k_{bn} \cdot I_{nOi} < I_{pcOi} < k_{bk} \cdot Min\{\boldsymbol{Ik}_{l_i,i}\} \tag{15}$$

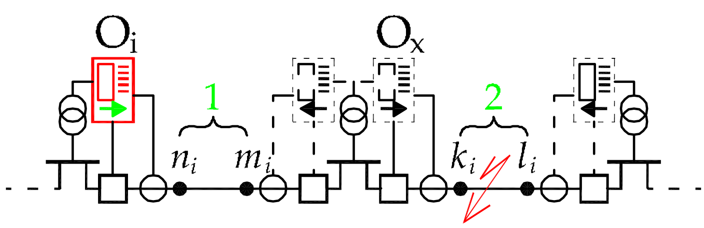

Figure 8. Pickup current choice.

If, for a short-circuit type and a node, trip of the selective protection is not possible with the chosen pickup current, some constraints in (13) can be irrelevant.

7. Protection Coordination Example

To show the importance of considering all the required short-circuit types in different system topologies, protection coordination examples of an IEEE 6-bus [24] and a radial power system without distributed generation depicted in Figures 9 and 10, respectively, have been examined. The lines data used for calculations are entered in Tables 1 and 2. For simplicity, all generators in the IEEE 6-bus power system have the same parameters of subtransient, negative, and zero reactance 15, 20, and 12%, and the loads in a radial power system do not produce any short-circuit contributions. For coordination, five required types of short-circuits have been used (three-phase-to-earth Ik_3, single-phase-to-earth Ik_1, two-phase-to-earth Ik_{2n}, phase-to-phase Ik_2, and three-phase-to-earth with disconnected auxiliary section Ik_{32}). For the first four basic types, minimum selectivity time 200 ms has been required, and for Ik_{32} only a reduced value of 50 ms has been required. The corresponding fault paths are entered in Tables 3 and 4. In both the systems, all pickup currents have been determined according to (6) with the value of constant $k_{pc} = 1.5$, which has been selected to meet the condition (14) for $k_{bn} = 1.1$ and $k_{bk} = 0.8$. All the nominal and pickup currents with the appropriate constraints are entered in Tables 5 and 6. In a real system, even if the connection of DGS does not change, the short-circuit contributions can be variable due to variable system conditions. From this point of view, the maximum and minimum short-circuit contributions of each short-circuit type according to [37] must be calculated and taken into account. Because the presentation of such a number of short-circuits can be slightly confusing, the maximum short-circuit contributions have been presented only (but in the algorithm all the maximum and minimum short-circuit contributions have been considered). All the maximum short-circuit contributions considered in n_i and m_i nodes for all fault paths are entered in Tables 7 and 8.

Table 1. IEEE 6-bus power system line parameters.

Section between Nodes	Positive and Negative Impedance (Ω)	Zero Impedance (Ω)	Susceptance (μS)
1–2	0.1875 + 0.6105i	0.5625 + 1.8315i	4.2254
4–5	0.0625 + 0.2035i	0.1875 + 0.6105i	1.4085
7–8	0.1250 + 0.4070i	0.3750 + 1.2210i	2.8169
10–11	0.1875 + 0.6105i	0.5625 + 1.8315i	4.2254
12–13	0.3750 + 1.2210i	1.1250 + 3.6630i	8.4507
14–15	0.2500 + 0.8140i	0.7500 + 2.4420i	5.6338
17–18	0.1250 + 0.4070i	0.3750 + 1.2210i	2.8169

Table 2. Radial power system line parameters.

Section between Nodes	Positive and Negative Impedance (Ω)	Zero Impedance (Ω)	Susceptance (μS)
2–3	0.1250 + 0.4070i	0.3750 + 1.2210i	2.8169
4–5	0.0938 + 0.3053i	0.2813 + 0.9158i	2.1127
6–7	0.0625 + 0.2035i	0.1875 + 0.6105i	1.4085
8–9	0.0250 + 0.0814i	0.0750 + 0.2442i	0.5634
10–11	0.3750 + 1.2210i	1.1250 + 3.6630i	8.4507
12–13	0.2500 + 0.8140i	0.7500 + 2.4420i	5.6338
14–15	0.1250 + 0.4070i	0.3750 + 1.2210i	2.8169

Table 3. IEEE 6-bus power system fault paths.

Number of Fault Path	Primary Nodes n_i	Secondary Nodes m_i	Primary Protections i	Secondary Protections j
0	1	2	1	9
1	1	2	1	7
2	2	1	2	4
3	2	1	2	14
4	4	5	3	1
5	4	5	3	14
6	5	4	4	10
7	5	4	4	6

Table 3. *Cont.*

Number of Fault Path	Primary Nodes n_i	Secondary Nodes m_i	Primary Protections i	Secondary Protections j
8	10	11	5	3
9	10	11	5	10
10	11	10	6	8
11	11	10	6	12
12	13	12	7	5
13	13	12	7	12
14	12	13	8	2
15	12	13	8	9
16	8	7	9	3
17	8	7	9	6
18	7	8	10	2
19	7	8	10	7
20	17	18	11	5
21	17	18	11	8
22	18	17	12	
23	14	15	13	1
24	14	15	13	4
25	15	14	14	

Table 4. Radial power system fault paths.

Number of Fault Path	Primary Nodes n_i	Secondary Nodes m_i	Primary Protections i	Secondary Protections j
0	2	3	1	
1	4	5	2	1
2	6	7	3	2
3	8	9	4	3
4	10	11	5	2
5	12	13	6	5
6	14	15	7	5

Table 5. IEEE 6-bus power system pickup currents and constraints (all values in A).

Protection O_i	Lower Constraint $1.1 \cdot I_{nOi}$	Pickup Current I_{pcOi}	Upper Constraint $0.8 \cdot Min\{Ik_{m_i,i}\}$
1	147.02	220.53	343.46
2	146.99	220.48	228.00
3	40.45	60.67	344.60
4	40.45	60.68	1111.00
5	64.08	96.11	1486.47
6	64.05	96.07	667.84
7	99.24	148.86	291.98
8	99.30	148.94	499.57
9	198.43	297.65	313.64
10	198.45	297.68	568.88
11	139.87	209.81	1745.48
12	139.85	209.78	731.92
13	70.13	105. 19	1531.34
14	70.09	105.13	365.40

Table 6. Radial power system pickup currents and constraints (all values in A).

Protection O_i	Lower Constraint $1.1 \cdot I_{nOi}$	Pickup Current I_{pcOi}	Upper Constraint $0.8 \cdot Min\{Ik_{m_i,i}\}$
1	487.65	664.98	4105.42
2	487.66	664.99	3753.83
3	161.19	219.80	3455.04
4	161.20	219.82	3127.07
5	326.49	445.22	3456.79
6	121.07	165.10	3114.87
7	201.98	275.42	3114.86

Table 7. IEEE 6-bus power system maximum short-circuit contributions (all values in kA).

Num. of Fault Path	n_i										m_i									
	Ik_3		Ik_1		Ik_{2n}		Ik_2		Ik_{32}		Ik_3		Ik_1		Ik_{2n}		Ik_2		Ik_{32}	
	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j
0	15.1	1.6	15.0	1.6	15.1	1.6	15.1	1.6	16.3	2.6	5.1	4.1	4.5	3.6	4.9	3.9	4.3	3.5	9.4	1.6
1	15.1	0.8	15.0	0.8	15.1	0.8	15.1	0.8	16.3	1.0	5.1	0.5	4.5	0.4	4.9	0.5	4.3	0.4	9.4	0.6
2	8.3	6.6	7.7	5.9	8.0	6.3	8.0	6.3	11.5	9.8	1.3	0.3	1.3	0.3	1.3	0.3	1.1	0.3	7.6	6.4
3	8.3	0.6	7.7	0.6	8.0	0.6	8.0	0.6	11.5	0.6	1.3	0.6	1.3	0.6	1.3	0.6	1.1	0.5	7.6	0.4
4	6.7	5.0	6.2	4.4	6.5	4.8	6.5	4.8	10.5	8.8	4.4	2.8	4.1	2.5	4.3	2.7	3.7	2.4	9.0	7.6
5	6.7	0.6	6.2	0.6	6.5	0.6	6.5	0.6	10.5	0.6	4.4	0.6	4.1	0.6	4.3	0.6	3.7	0.5	9.0	0.5
6	9.5	6.3	8.7	5.7	9.2	6.1	9.2	6.1	12.5	8.8	6.7	4.2	6.0	3.6	6.4	4.0	5.6	3.6	10.5	7.4
7	9.5	2.3	8.7	2.1	9.2	2.2	9.2	2.2	12.5	2.8	6.7	1.7	6.0	1.6	6.4	1.7	5.6	1.5	10.5	2.4
8	11.5	4.3	10.6	4.0	11.2	4.2	11.2	4.2	13.1	4.9	5.9	2.4	4.9	2.0	5.6	2.2	5.0	2.0	8.2	3.1
9	11.5	6.4	10.6	5.7	11.2	6.1	11.2	6.1	13.1	7.4	5.9	2.9	4.9	2.3	5.6	2.7	5.0	2.5	8.2	4.6
10	5.4	3.9	4.8	3.2	5.1	3.7	5.1	3.7	7.8	6.3	2.3	1.0	2.1	0.9	2.3	1.0	2.0	0.9	5.8	4.6
11	5.4	1.2	4.8	1.3	5.1	1.3	5.1	1.3	7.8	1.2	2.3	1.1	2.1	1.1	2.3	1.1	2.0	0.9	5.8	0.9
12	7.3	5.9	6.4	4.9	7.0	5.5	7.0	5.5	9.3	7.9	0.9	0.5	0.8	0.5	0.9	0.5	0.7	0.4	5.1	4.2
13	7.3	1.2	6.4	1.3	7.0	1.3	7.0	1.3	9.3	1.2	0.9	1.1	0.8	1.1	0.9	1.1	0.7	0.9	5.1	0.7
14	15.6	1.2	15.5	1.2	15.6	1.2	15.6	1.2	16.3	1.5	4.0	1.1	3.3	0.9	3.7	1.1	3.4	1.0	6.6	0.7
15	15.6	1.6	15.5	1.6	15.6	1.7	15.6	1.7	16.3	2.2	4.0	2.9	3.3	2.3	3.7	2.7	3.4	2.5	6.6	1.0
16	7.5	4.3	7.0	4.0	7.3	4.2	7.3	4.2	11.5	7.1	1.7	0.4	1.7	0.4	1.7	0.4	1.4	0.4	8.5	5.3
17	7.5	2.3	7.0	2.1	7.3	2.2	7.3	2.2	11.5	3.5	1.7	0.5	1.7	0.5	1.7	0.5	1.4	0.4	8.5	2.6
18	14.7	1.2	14.6	1.2	14.7	1.2	14.7	1.2	16.2	2.3	6.5	2.8	5.8	2.4	6.2	2.6	5.5	2.3	10.9	1.6
19	14.7	0.8	14.6	0.8	14.7	0.8	14.7	0.8	16.2	1.3	6.5	1.0	5.8	0.8	6.2	0.9	5.5	0.8	10.9	0.9
20	10.1	5.9	8.4	4.9	9.4	5.5	9.4	5.5	10.1	5.9	7.7	4.5	6.0	3.5	7.1	4.2	6.5	3.8	7.7	4.5
21	10.1	4.0	8.4	3.2	9.4	3.7	9.4	3.7	10.1	4.0	7.7	3.0	6.0	2.3	7.1	2.8	6.5	2.6	7.7	3.0
22	1.3		1.4		1.3		1.3		1.3		1.2		1.3		1.3		1.0		1.2	
23	12.7	5.0	11.5	4.4	12.2	4.8	12.2	4.8	12.7	5.0	7.2	2.8	5.4	2.0	6.6	2.5	6.1	2.4	7.2	2.8
24	12.7	6.6	11.5	5.9	12.2	6.4	12.2	6.4	12.7	6.6	7.2	3.7	5.4	2.8	6.6	3.4	6.1	3.2	7.2	3.7
25	0.6		0.7		0.7		0.7		0.6		0.6		0.6		0.6		0.5		0.6	

Table 8. Radial power system maximum short-circuit contributions (all values in kA).

Num. of Fault Path	n_i								m_i							
	Ik_3		Ik_1		Ik_{2n}		Ik_2		Ik_3		Ik_1		Ik_{2n}		Ik_2	
	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j	O_i	O_j
0	6.5	0.0	6.5		6.5		6.5		6.0		5.6		5.8		5.1	
1	5.9	5.9	5.6	5.6	5.8	5.8	5.8	5.8	5.5	5.5	4.9	4.9	5.3	5.3	4.7	4.7
2	5.4	5.4	4.9	4.9	5.3	5.3	5.3	5.3	5.0	5.0	4.4	4.3	4.8	4.8	4.4	4.3
3	5.0	5.0	4.3	4.3	4.8	4.8	4.8	4.8	4.7	4.7	3.9	3.9	4.4	4.4	4.0	4.0
4	5.4	5.4	4.9	4.9	5.3	5.3	5.3	5.3	5.0	5.0	4.3	4.3	4.8	4.8	4.3	4.3
5	5.0	5.0	4.3	4.3	4.8	4.8	4.8	4.8	4.7	4.7	3.9	3.9	4.4	4.4	4.0	4.0
6	5.0	5.0	4.3	4.3	4.8	4.8	4.8	4.8	4.7	4.7	3.9	3.9	4.4	4.4	4.0	4.0

In the objective function design in Section 5 and in many publications, too [15–30], the selectivities met only in the primary and secondary nodes have been assumed. To verify the selectivity is met, not only in these nodes but in the entire protected section (between the primary and secondary nodes), different short-circuits placements have been explored in the protected section. Short-circuits have been shifted from the primary n_i to secondary m_i nodes, as depicted in Figure 11.

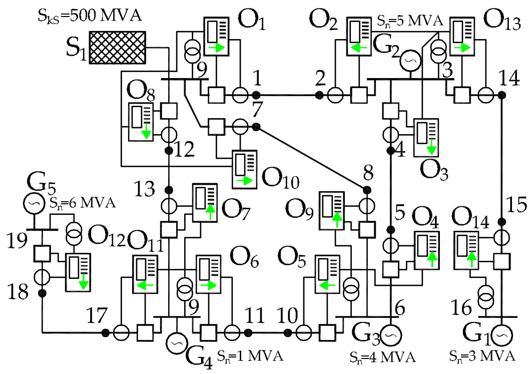

Figure 9. Coordinated IEEE 6-bus power system.

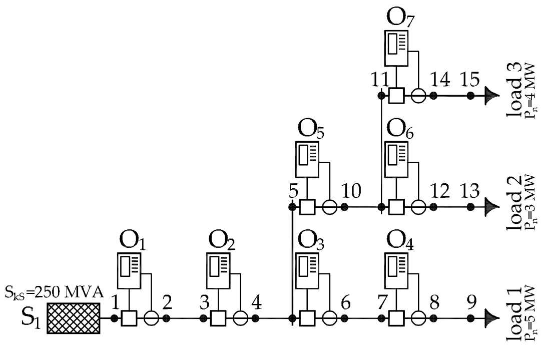

Figure 10. Coordinated IEEE 6-bus power system.

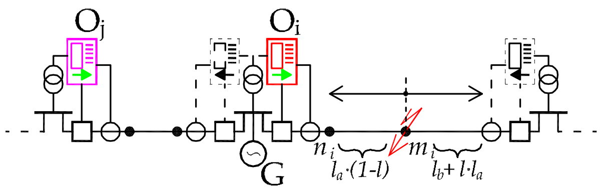

Figure 11. Short-circuit shifting along the protected section.

Short-circuit shifting (change to original lengths l_a and l_b) is facilitated by changing the relative distance l from 0 to 1 with a step 0.01. For $l = 0$, the short-circuit is placed in the original secondary node m_i, and for $l = 1$, the short circuit is placed in primary node n_i. For each l value and each short-circuit type, selectivity times between the primary and selective protections of all fault paths have been calculated and their lowest value $Min\{\Delta tm_{i,j}\}$ has been selected.

Protection coordination has been performed using the algorithms described in Chapters 4 and 5 for two cases. In the first case, coordinations considering only the highest short-circuit types (three-phase-to-earth in all paths) have been performed. In the other case, all five short-circuit types have been considered by the algorithm described in Chapter 4. Dependence of the minimum of selectivity times $Min\{\Delta tm_{i,j}\}$ on relative distance l for both cases is depicted in Figures 12–15. As it can be seen, in the radial system without distributed generation, selectivity time for all short circuit types is always the shortest for the value of $l = 1$, and for lower values of l it is increasing. That means considering only the primary nodes and the types of short-circuits with the highest short-circuit contributions is enough to guarantee the selectivity for all required types. A different case is obvious in the IEEE 6-bus power system, where considering only the highest short-circuits can lead to too-short selectivity times (shorter than the minimum required value of 200 ms) in the remaining types considered.

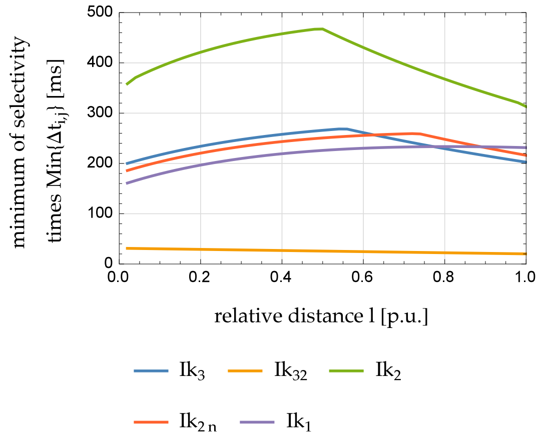

Figure 12. Dependence of the minimum selectivity times $Min\{\Delta tm_{i,j}\}$ on relative distance l for IEEE 6-bus power system where only three-phase-to-earth short-circuits are respected.

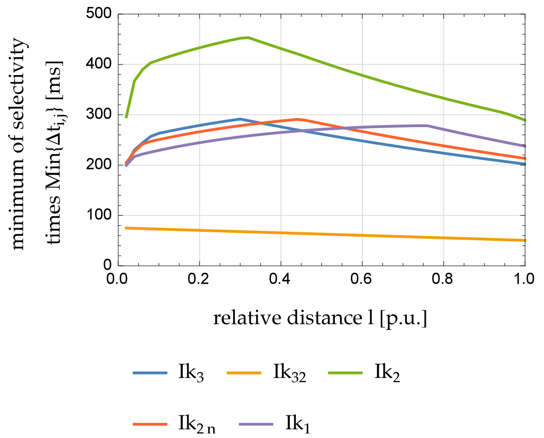

Figure 13. Dependence of the minimum selectivity times $Min\{\Delta tm_{i,j}\}$ on relative distance l for IEEE 6-bus power system where all required short-circuit types are considered.

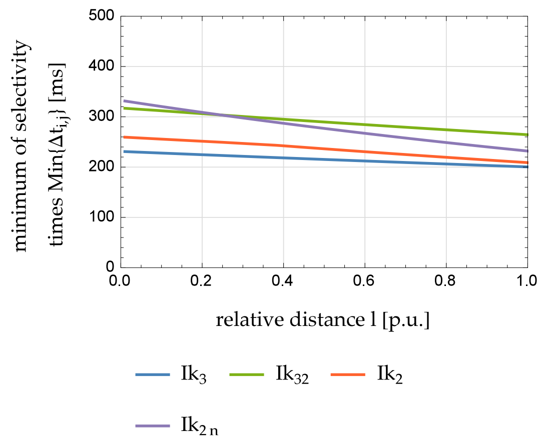

Figure 14. Dependence of the minimum selectivity times $Min\{\Delta tm_{i,j}\}$ on relative distance l for radial power system where only three-phase-to-earth short-circuits are considered.

Next, it can be seen, for both systems, that selectivity times are always the shortest for $l = 0$ (in m_i node) and $l = 1$ (in n_i node). Thus, coordination only in the primary and secondary nodes is enough to guarantee selectivity through the entire protected section, and the algorithm described in Section 5 can be used for system protection coordination.

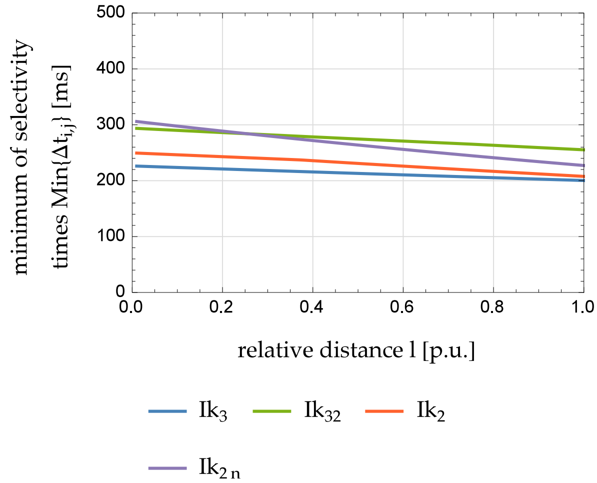

Figure 15. Dependence of the minimum selectivity times $Min\{\Delta tm_{i,j}\}$ on relative distance l for radial power system where all required short-circuit types are considered.

8. Conclusions

In this paper, a new approach to coordination of the directional overcurrent protections with inverse-time characteristics in radial and distributed generation systems has been presented. Unlike other published articles on a similar topic, not just some, but all the required types of short-circuits have been taken into account. Since the coordination of taking into account a greater number of required short-circuit types can be a complex problem, a new algorithm based on the search for the most sensitive short-circuit type has been designed. To speed up the entire process, an automatic coordination algorithm based on the appropriately designed optimization has been used. By the combination of both the aforementioned algorithms, an example of protection coordination in a distributed generation system (IEEE 6-bus power system) and a radial system without distributed generation, has been examined. To point out the necessity of considering all the required short-circuit types, the coordinations have been performed for two cases. In the first case, the coordinations considering only three-phase-to-earth short-circuits and, in the second, the coordinations considering all the required short-circuit types have been performed. To verify the correctness of proposed algorithms, selectivity values have been checked along the entire protected section for all the required short-circuit types. Considering all of the required short-circuit types has been found to be very important in DGS, and if only some of the short-circuit types are considered, selectivity need not be met in the remaining types. Considering only one short-circuit type has been proved usable only in radial systems without distributed generation.

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Conflicts of Interest: The authors declare no conflict of interest.

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