Summary of Useful Concepts About the Coordination of Directional Overcurrent Protections

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***Abstract*—This paper summarizes some useful concepts about the coordination of directional overcurrent protections. The following key topics are described: the analysis of systems in a ring configuration and only one source of short-circuit currents; the impossibility of obtaining selectivity for all the possible system configurations with multiple sources; the need for inverse functions in order to obtain selectivity in systems with multiple sources; the coordination with protections for radial loads; the coordination between instantaneous and delayed functions; the considerations to select the pickup values; the influence of contributions from motors to short circuit currents; the transient configurations due to sequential trips at both line ends; the influence of dynamic behavior of overcurrent functions; the influence of stability constraints; other specific considerations for ground functions; some specific considerations for systems with distributed generation. A summary of these points and their effect on the coordination of directional overcurrent protections is not available in the current literature. This novel description should facilitate the inclusion of these key points in research and coordination studies related to these protective functions.**

***Index Terms*—Coordination of protective relays, directional overcurrent protection, directional overcurrent relays, directional overcurrent functions, power system protection.**

I. INTRODUCTION

DIRECTIONAL overcurrent protection (DOCP) has been utilized for many years. The main concepts about DOCP were developed when the available technology was electromechanical, and the correspondent protective relay only had the directional overcurrent function (DOCF). Nowadays, protective relays usually have multiple protective functions, and the DOCF is only an option in the relay. Classical books and guides [1]–[7] about protective relaying describe the DOCF as well as some of the main conditions for their coordination. Coordination of DOCP has been a challenge for protection engineers for many years, and there were attempts to program the conditions for their coordination since the first years of the use of computers for engineering studies [8], [9].

In 1988, a pioneer article about the use of mathematical optimization to coordinate DOCP was published in a journal [10], and it is the best known original publication about this subject although the main concepts about optimal coordination of DOCF were previously published in a local conference paper [11]. Since the end of the 1980s until now, many articles about this subject have been published. References [12]–[16] are only some recent samples of papers addressing optimal coordination of DOCP. Many articles about optimal coordination of DOCF are primarily related to different ways to perform the optimization, and sometimes the proper application of some basic concepts about coordination of DOCF is not evident. The comparison among different optimization techniques is obviously essential, and the simulation of different power systems taken as examples is also important to understand some coordination problems. However, it is worth emphasizing that a detailed understanding of the main concepts for the coordination of DOCP is necessary in order to properly formulate these engineering problems.

Coincidentally, in 1988 the term "adaptive relaying" was proposed by different researchers [17]–[19], in order to consider that relay settings can be automatically changed depending on conditions of the power system (the option for on-line changes of setting groups has been available in microprocessor-based protective relays for many years). As the connectivity of the power system has a very important effect on the conditions for the coordination of DOCP, the adaptive protection is an attractive option to deal with this problem [19]–[25]. On the other hand, as communication facilities between electrical substations are becoming more frequent and powerful, the possible application of adaptive relaying in order to change the setting groups of the relays is being more easily accepted. Nowadays this fact is being considered as a field of study within the smart grid paradigm [12], [14], [20]–[23].

The main concepts about coordination of DOCP have been traditionally applied to transmission systems (interconnected power systems), where the existence of multiple power sources usually justifies the need for directional supervision of the protective functions. However, the relatively recent application of distributed generation and microgrids has stimulated the study of this subject for meshed networks in distribution systems [19]–[25]. Therefore, the importance of this subject is nowadays related to traditional interconnected power systems as well as distribution systems with distributed generation. Integration of renewable energy is an important trend throughout the world, and the application of optimization techniques and adaptive relaying can provide solutions for the challenges related to optimal coordination of DOCP in these systems. Again, a detailed understanding of the coordination concepts

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is necessary to properly formulate these problems.

This paper explains the following concepts, which are useful for the proper coordination of DOCP: a) the analysis of ring configurations with only one source; b) the impossibility of obtaining selectivity for all the possible system configurations in systems with multiple sources; c) the need for an inverse function in order to obtain selectivity in systems with multiple sources; d) the coordination with protections for radial loads; e) the coordination between instantaneous and delayed overcurrent functions; f) considerations to select the pickup values; g) the influence of contributions from motors to short circuit currents; h) the influence of transient configurations due to sequential trips at both line ends; i) the influence of dynamic behavior of overcurrent functions; j) the influence of stability constraints; k) other specific considerations for ground functions; l) some specific considerations for systems with distributed generation. Detailed coverage of these key points (and their effect on the coordination of DOCP) is not currently available in the current literature.

II. BASIC DEDUCTIONS FOR SYSTEMS IN RING CONFIGURATION WITH ONLY ONE SOURCE FOR SHORT-CIRCUIT CURRENTS

A. System Taken as an Example

For the sake of simplicity, the system taken as an example has only 3 buses (Fig. 1). These concepts can be applied to systems in ring configuration with any number of buses and only one source for short-circuit currents. In this section, contributions from motors (load buses) are neglected since they decay very fast in time. DOCF are required at locations $2, 3, 4$ and 5 in order to obtain selectivity for faults in transmission lines. For example, for a fault at point P, there are two contributions (I_1, I_2) to the short-circuit current, and relays at locations 2 and 5 are blocked by their directional functions.

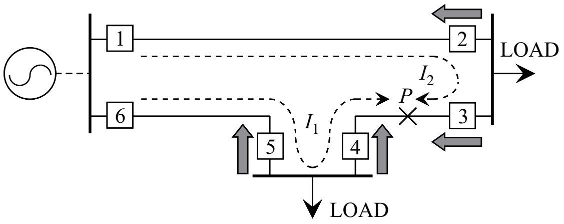


Fig. 1. Example of system with only one source for short-circuit currents.

B. First Deduction

The first point to be deduced is: for systems in ring configuration with only one source for short-circuit currents, the contribution through a branch is larger if the fault point is nearer to the source through the path related to this branch.

A system in ring configuration with only one source for short-circuit currents can be simplified as shown in Fig. 2(a). The short-circuit contribution through branch 1 ($I_{1,1}$) can be computed as:

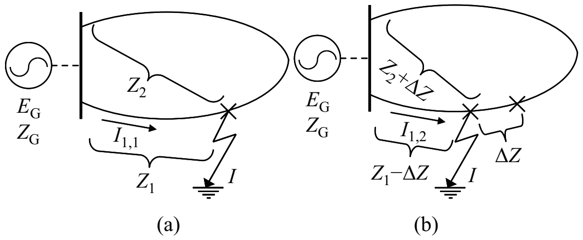
$$I_{1,1} = E_{\mathrm{G}}/[Z_{\mathrm{G}}(Z_1 + Z_2)/Z_2 + Z_1] \tag{1}$$

E_{G} and Z_{G} are Thevenin voltage and Thevenin impedance of the source, respectively. Z_1 and Z_2 are impedances of branch 1 and branch 2, respectively.

If the fault point is nearer to the source through branch 1 by an impedance ΔZ, as shown in Fig. 2(b), then the short-circuit contribution through branch 1 ($I_{1,2}$) is:

$$I_{1,2} = E_{\mathrm{G}}/[Z_{\mathrm{G}}(Z_1 + Z_2)/(Z_2 + \Delta Z) + (Z_1 - \Delta Z)] \tag{2}$$

Both terms of the denominator of (2) are smaller than the correspondent terms of the denominator of (1). Therefore, $I_{1,2}$ is larger than $I_{1,1}$ (it is assumed that angles of these impedances are similar, for the sake of simplicity).



(a) (b)

Fig. 2. Simplified systems for the first deduction.

C. Second Deduction

The second point to be deduced is: for systems in ring configuration with only a source of short-circuit currents, the contribution through a branch is larger if the other branch is open-circuited.

In comparison with Fig. 2(a), Fig. 3 shows the simplified system when branch 2 is open-circuited; the short-circuit contribution through branch 1 ($I_{1,3}$) is:

$$I_{1,3} = E_{\mathrm{G}}/[Z_{\mathrm{G}} + Z_1] \tag{3}$$

The denominator of (3) is smaller than the correspondent denominator of (1). Therefore, $I_{1,3}$ is larger than $I_{1,1}$. This conclusion is shown in [3].

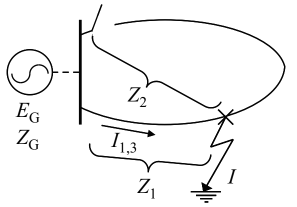


Fig. 3. Simplified system for the second deduction.

D. Practical Consequences of These Deductions

In Fig. 1, the overcurrent function at location 6 must be slower than the DOCF at location 4. The first deduction indicates that the worst current I_1 to be considered is for a fault near location 4. On the other hand, the second deduction indicates that the case with the path for I_2 in open-circuit is even worse. Thus, the system in Fig. 1 can be solved by assuming that circuit breaker 1 is open-circuited, in order to coordinate circuit breakers 2, 4 and 6. Similarly, circuit breakers 5, 3 and 1 should be coordinated by assuming that circuit breaker 6 is open-circuited. Thus, these cases can be easily analyzed using simple time-current graphs. This procedure is well-known by some protection engineers, but the deductions which justify this procedure are rarely known by protection engineers (the second deduction was available in the literature [3], but not the first one).

In some cases, a system in ring configuration with only a source is a part of a larger system which has DOCP. That is, the rest of the power system is located at the "source side" of the ring system (i.e., upstream of 1 and 6, in the system taken as an example). In these cases, the DOCP of the ring system can be coordinated by using the afore-mentioned rules, and the results of locations 1 and 6 can be input data to coordinate the rest of the power system (similarly to the case described in Section V, because locations 1 and 6 can be seen as outgoing feeders from the perspective of the upstream power system).

III. IMPOSSIBILITY OF OBTAINING SELECTIVITY FOR ALL CONFIGURATIONS OF SYSTEMS WITH MULTIPLE SOURCES

For the sake of simplicity, the simple system in Fig. 4(a) is considered. This system has similar equivalent sources at both buses and the DOCP at locations 1, 2, 3 and 4. Configurations with only a source are shown in Figs. 4(b) and 4(c). For the fault shown in Fig. 4(b), 4 should be slower than 2, but 2 should be slower than 4 for the fault shown in Fig. 4(c). The currents seen by the relays can be very similar in both cases; thus, it is impossible to obtain selectivity simultaneously for configurations of Figs. 4(b) and 4(c).

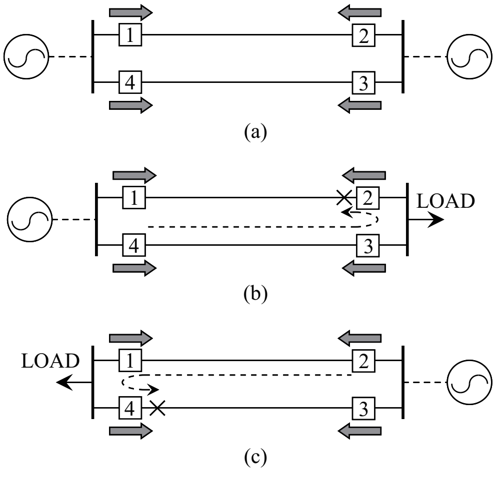


Fig. 4. Simplified systems to show the impossibility of obtaining selectivity for all the configurations of systems with multiple sources.

Different setting groups could be applied for each configuration (if this procedure is automatic, it is adaptive protection). However, this possible solution is not simple, and simplicity is a desired feature of the protective system. A different solution is to accept the possible lack of selectivity for some configurations, in order to guarantee selectivity for the base case. This solution is justified by the fact that the base case (Fig. 4(a)) typically is the preferred configuration, and the power system is rarely operating outside of such a condition (thus, probability of lack of selectivity is not very high). Selectivity for the base case can be obtained because currents at both line ends of a faulted line are greater than currents in the relays which should not operate, and this point is specifically discussed in the following section.

IV. NEED OF INVERSE CURVES TO OBTAIN SELECTIVITY IN SYSTEMS WITH MULTIPLE SOURCES

The previous section does not show the way to obtain selectivity when multiple sources are considered (Fig. 4(a)). In order to analyze a more general case, the system shown in Fig. 5 is considered. For the fault point shown in Fig. 5, the currents at locations 1 and 2 are in the trip direction of the correspondent DOCF. Direction of currents in other lines can or cannot be as shown in Fig. 5, depending on the equivalent sources. Tripping time of the overcurrent function at location i is called t_i here.

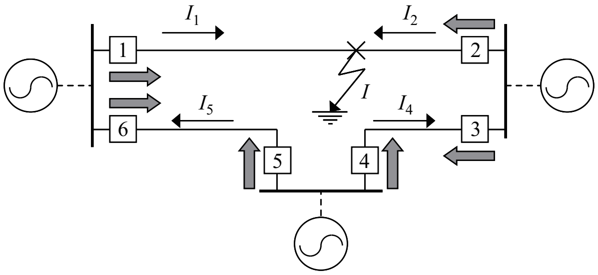


Fig. 5. Simplified system to explain the need of inverse curves in order to obtain selectivity in systems with multiple sources.

Assuming the direction of currents in Fig. 5, t_4 should be greater than t_2 ($t_4 > t_2$). For a fault in line 3–4, a selectivity condition could be $t_6 > t_4$, and for a fault in line 5–6, a selectivity condition could be $t_2 > t_6$. These conditions would seem to be incongruent ($t_4 > t_2$; $t_6 > t_4$; $t_2 > t_6$), and actually there is no solution if the fact that the currents are different is not considered. That is, these conditions cannot be congruent if overcurrent functions with constant time are considered. Only inverse curves, whose operating time is dependent on the current seen by the relay, can offer selectivity for this problem.

The current at each line end of a faulted line is the sum of contributions from sound circuits to the faulted line. Thus, the currents in those sound circuits are smaller than currents in the line ends. That is, I_5 is smaller than I_1, and I_4 is smaller than I_2, for the fault shown in Fig. 5. The tripping time of the overcurrent function at location i is a function of the current seen at that location for a specific fault case. For example, for a specific fault case m in the line j–k, the tripping time t_i at location i actually is $t_i(I_{i,\text{ fault m in line } j\text{–}k})$. This notation emphasizes that the current can be different for each relay location.

Thus, the previous selectivity problem must be formulated as: a) for a given fault case m in line 1–2, $t_4(I_{4,\text{ fault m in 1–2}})$ should be greater than $t_2(I_{2,\text{ fault m in 1–2}})$; b) for a given fault case in line 3–4, $t_6(I_{6,\text{ fault n in 3–4}})$ should be greater than $t_4(I_{4,\text{ fault n in 3–4}})$; c) for a given fault case p in line 5–6, $t_2(I_{2,\text{ fault p in 5–6}})$ should be greater than $t_6(I_{6,\text{ fault p in 5–6}})$. These selectivity conditions are dependent on the ratio between the currents seen by the relays of the faulted line and the currents seen in the remote locations. Therefore, the proper selection of the shape (inversion) of the inverse curves is a key point for the coordination of the DOCP. This point can be analyzed using conventional time-current characteristics [26] or non-traditional curves [27].

In general, the ratio between the currents seen by the relays depends on the fault location and depends on the presence or absence of fault resistances. Therefore, in order to compare a relay pair in a proper way, different cases of fault locations and fault resistances should be analyzed. Actually, fault resistance has an effect on the ratio of positive-sequence currents, but not on the ratio of negative-sequence and zero-sequence currents. Consequently, fault resistance usually has no effect on the ratio of currents for the analysis of the ground-fault DOCP.

V. Coordination with Protective Functions of Feeders for Radial Loads

For the sake of simplicity, the system in Fig. 6 is considered. For the shown fault location, the DOCF of locations 3 and 6 must be coordinated with the protective functions of the radial feeder. The current at location 7 is different with the currents at locations 3 and 6 if all the elements are in service. If the $n-1$ criterion is considered, a transmission line can be out-of-service, and the current at location 7 could be the same as at location 6 (line 3–4 out of service) or at location 3 (line 5–6 out of service).

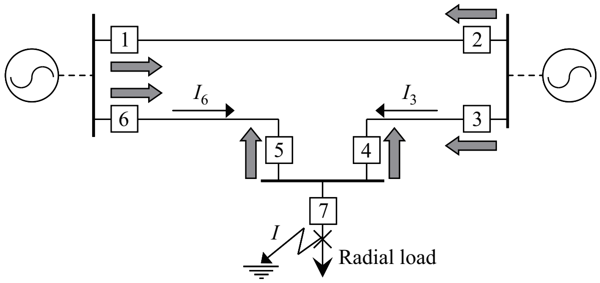


Fig. 6. Simplified system to explain the conditions for the coordination with protective functions of feeders for radial loads.

The protection at location 7 can be an instantaneous function (e.g., differential protection), or an inverse-time overcurrent function, or a combination of both cases (e.g., 50/51). An inverse-time overcurrent function at location 7 can be easily compared with overcurrent functions at locations 3 or 6, using time-current graphs, when the other line is out-of-service (because current is the same at locations to be compared). On the other hand, if all the elements are in service, the comparison should be performed for different fault currents and for the worst cases of the ratios between currents at the analyzed locations. Thus, the inversion of the overcurrent function at location 7 has a strong influence on the coordination of the upstream DOCF. Furthermore, the overcurrent function at location 7 must also be coordinated with the downstream overcurrent devices.

Inclusion of different configurations in the analysis (e.g., considering the simple $n-1$ criterion) could lead to excessive delays in the upstream DOCF or to unfeasibility for reaching solutions. As mentioned in Section III, the use of setting groups according to system configuration could be theoretically useful to obtain improved solutions for these cases, but its price is a lack of simplicity.

VI. Coordination Between Delayed and Instantaneous Functions

The coordination time interval (CTI) between inverse-time functions should consider a margin of error for each inverse-time curve, the clearing time of the circuit breaker which should operate, and a safety margin (and also an over-travel equivalent time if the backup overcurrent relay is electromechanical). The CTI between inverse-time and instantaneous functions does not need to be as high as in the case of two inverse-time functions, because the operative time of the instantaneous functions usually is the maximum expected value whereas the operative time of the inverse-time functions is an average time. On the other hand, the expected maximum operative time of the instantaneous DOCF is slightly higher than in the case of non-directional instantaneous functions (because the instantaneous DOCF needs a waiting time to avoid erratic operations due to transient reversal of currents), but this difference can be neglected for coordination purposes.

The calculation of settings for instantaneous functions of locations with inverse-time and instantaneous functions should be performed before the coordination of delayed functions. The main reason behind this advice is that the setting of the instantaneous function has an influence on the constraints for the coordination of inverse-time functions whereas the settings of the inverse-time functions do not affect the calculation of the instantaneous settings.

Furthermore, coordination of the inverse-time DOCF with constant-time backup protection (e.g., second zone of distance functions) should be considered in the overall coordination problem. References [28] and [29] show that these problems could be included in the formulation of the optimal coordination of the DOCF.

VII. Factors Considered to Select Pickup Values of These Overcurrent Functions

A. Inverse-time Directional Overcurrent Functions

1) Phase-functions

The pickup currents of the inverse-time DOCF are traditionally selected to be greater than the maximum expected load current of the transmission line. This criterion should be complemented with the direction of the load currents, as they are seen by the protective function. That is, maximum load currents are seen in the trip direction in some locations; consequently, their pickups should be set to avoid operation during normal load conditions. However, maximum load currents are not in the trip direction in other locations; consequently, they require a different criterion.

For example, the relay at location 2 in Fig. 1 never sees the load current in its trip direction. This fact can lead to the simplistic conclusion of adjusting the pickup of the DOCF to an extremely low value in this case. However, polarization of the DOCF must be carefully analyzed before the application of this criterion. The directional comparator of a phase DOCF could be quadrature-polarized, and the load current could be related to the polarizing voltage as shown in Fig. 7. Current in phase A (I_{A}) is compared with voltage BC (V_{BC}). Relays perform similar comparisons for currents in phases B and C. In the shown limit case, active power is toward the busbar but reactive power is toward the protected line. Thus, load current could be in the trip direction for some cases of capacitive loads (power factor lower than 0.7 if the angle of the directional characteristic is 45°). Capacitive loads are not the usual cases, but industrial loads could have capacitive compensation and the net industrial load could be capacitive under some circumstances (e.g., in the case of loss of large inductive loads). In such cases, it is necessary to estimate the maximum capacitive load (whose capacitive power factor is lower than 0.7) in order to set the pickup of the DOCF above this value. This value should typically be lower than the maximum expected load of the line.

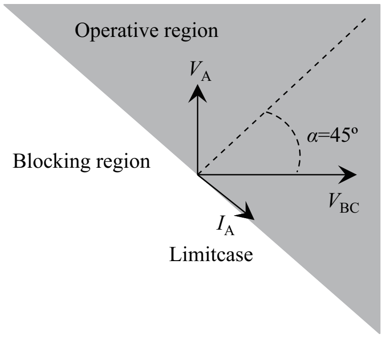


Fig. 7. Example of a quadrature-polarized DOCF.

On the other hand, analysis of systems with multiple sources is not so easy. For example, the relay at location 2 in Fig. 5 could see a low value of load current in the trip direction (considering the direction of active power for all the feasible load flow conditions), but this relay could also see reactive power in the trip direction when the active power is not in the trip direction. Therefore, many load flow conditions should be considered in order to find the worst case for setting the pickup of the phase DOCF.

For the sake of simplicity, some protection engineers set the pickup currents of the phase inverse-time DOCF considering only the power line thermal limit. Analysis of all the possible load flow conditions could lead to recommending lower settings, in order to improve the protection sensitivity, but its price is a lack of simplicity; especially if a detailed analysis of the polarization is required because the sign of the reactive power can be different than the sign of the active power.

2) Ground-functions

The pickup currents of the ground DOCF are not limited by load conditions since zero-sequence currents (ZSC) are almost null during normal conditions. These pickup currents are traditionally selected as a small percentage (e.g., 10%) of the rated current of the current transformer (CT). However, a potential problem can exist because the ground DOCF of the faulted line could be less sensitive than the back-up protection. In order to illustrate this point, Fig. 8 shows a small part of a system. For the sake of simplicity, the radial load is considered to have no influence on the ZSC (e.g., load is fed through transformers with the primary connected in delta). If the pickup currents of the ground DOCF are selected as 10% of the rated currents of the CT, then the relay at location 6 would be more sensitive than the relay at location 4 for ground-faults in the line 3–4, and this fact implies lack of selectivity. For this simple case, a solution is the selection of the same pickup currents for the ground DOCF of locations 3, 4, 5 and 6.

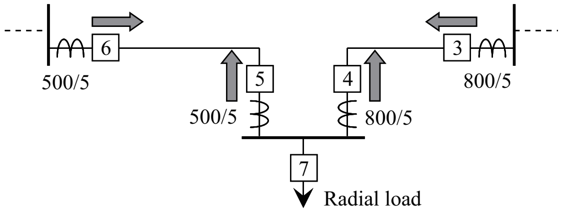


Fig. 8. Simplified system to explain a potential problem related to the pickup currents of the ground directional overcurrent functions.

If the load has a path for the ZSC in the example in Fig. 8 (or if the system topology is more meshed at the busbar where relays 4 and 5 are located), the ZSC at location 6 can be lower than the ZSC at location 4 for ground-faults in the line 3–4, because the ZSC at location 4 is the sum of the ZSC at location 6 plus the other ZSC going to the busbar. Therefore, the selection of 10% of rated currents of the CT as pickup currents for the ground DOCF could be selective in such cases, but all the possible system configurations should be analyzed since the ratio between currents at locations 4 and 6 is usually dependent on system topology.

B. Instantaneous Functions

Instantaneous overcurrent functions can be directional or not, and their pickup values must be set higher than the worst cases of forward currents seen by the relays for faults at the correspondent remote busbars. Furthermore, a non-directional instantaneous overcurrent function should be applied only if its pickup value is higher than the worst case of the reverse current at the relay location (i.e., current seen by the relay for a reverse fault at its own busbar). Safety factors are usually considered due to possible measurement errors and the effect of the DC offset of the fault currents on the relays' measurements.

The worst cases of the fault currents by the locations of the DOCP can be easily computed for systems in ring configuration with only one source because they occur when the other path is open-circuited (as shown in Section II). However, worst cases could not be evident for systems with multiple sources because the influence of different possible configurations could not be trivial. For example, in the system shown in Fig. 5, several configurations should be analyzed to know the worst cases of currents by location 6 for a fault at its remote busbar (e.g., with all the elements in service, or with a power line out-of-service, or with a source out-of-service). On the other hand, the possible convenience of the adaptive changes of the instantaneous settings should be carefully analyzed in order to avoid non-selective trips of the instantaneous functions due to transient changes of system topology.

Inverse-time DOCP should be coordinated once instantaneous settings have been defined. Thus, the instantaneous function of a relay with DOCP could operate for the nearest faults and, consequently, the fault location correspondent to its instantaneous setting should be computed because this fault location could define the worst cases to coordinate this inverse-time DOCP with its backup relays.

VIII. EFFECT OF MOTOR CONTRIBUTION TO SHORT-CIRCUIT CURRENTS ON DIRECTIONAL OVERCURRENT SETTINGS

The induction motor contributions to short-circuit currents are strictly transient (i.e., these contributions disappear after few cycles). Due to this fact, they are traditionally not considered during the computation of the settings of the DOCP. However, these contributions should be considered in order to compute the instantaneous overcurrent settings. Therefore, as instantaneous settings affect the coordination of the DOCP, induction motor contributions to short-circuit currents have an indirect effect on determination of the settings of the DOCP.

The induction motor contributions to short-circuit currents are more important in industrial systems because large motors could be electrically near to the system protected by the DOCP. In the case of traditional transmission systems, equivalent motors could be applied to represent contributions from motors of load buses, but determination of such equivalents is not trivial and some approximations should be performed. In the case of systems with induction generators (e.g., wind generators), their contribution to short-circuit currents should be considered.

IX. TRANSIENT CONFIGURATIONS DUE TO SEQUENTIAL TRIPS

For a fault in a transmission line, the circuit breaker at one line end (CB_1) can open before the circuit breaker of the other line end (CB_2). That is, there are sequential trips. After the operation of CB_1, there are changes in short-circuit currents at each location of the power system. Thus, the currents at CB_2 and at its correspondent backup relays have changes, which should be considered in the coordination of the DOCP. These transient configurations of the power systems have been seldom considered in the coordination of DOCP (reference [30] shows a way to consider them).

X. NEED OF AVOIDING POSSIBLE TRIPS OF REMOTE BACKUP RELAYS

The usual criterion to formulate the coordination of the DOCP is the comparison of the operation time of the DOCF which should operate with the operation time of its remote backup DOCF [10]–[16], [20]–[30]. However, sometimes it is necessary to check also with the operation time of the remote backup DOCF of some other remote backup DOCF. Fig. 9 is useful to illustrate this idea. For a fault in the line 1–2, the usual criterion only compares the DOCF at location 2 with the DOCF at locations 5 and 6, which only sees a fraction of the current seen by the relay at location 2 (for the shown configuration). However, the DOCF at location 8 sees the same value of the current as the relay at location 2, and consequently, this comparison could be more restrictive than the previous one. The example in Fig. 9 was chosen because it is very simple, but this problem is not necessarily obvious in meshed power systems with many interconnections.

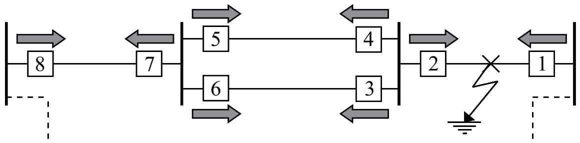


Fig. 9. Simplified system to explain the need of considering possible trips of the remote backup of remote backup relays.

XI. INFLUENCE OF OVERCURRENT FUNCTION DYNAMICS

The currents for the coordination of the DOCP are usually obtained by using traditional short-circuit analysis. That is, short-circuit currents at each point are considered constant, and they are obtained by using simple phasor analysis. During a fault, the magnitudes of the current seen by the relays can vary in time, due to transient and subtransient phenomena in electrical machines. Ideally, the dynamic behavior of the overcurrent functions can be considered as a simple integration of the current seen by the relays, but this integration depends on the inversion of the time-current curves [31], [32]. This dynamic behavior has been rarely considered in the detailed analysis of the overcurrent functions (reference [32] shows a way to consider it).

XII. INFLUENCE OF STABILITY CONSTRAINTS

The first document about the influence of stability constraints on the coordination of the DOCP was published in 1994 [33]. For a given transmission line, faults should be rapidly cleared at both line ends in order to avoid loss-of-stability. That is, while the DOCP is faster at one line end, the DOCP at the other line end can be slower (in order to be precisely in the limit to avoid the loss-of-stability). The relationships between time delay settings of the DOCP at both line ends are not evident, but they can be summarized as constraints between those time delay settings and their calculation requires the simulation of many cases of power system stability [32]. The afore-mentioned references [32] and [33] are related to transient stability (i.e., angle stability), but this concept can be extended to other stability problems (e.g., voltage stability and/or low-voltage ride through capabilities for distributed generators).

XIII. OTHER SPECIFIC CONSIDERATIONS FOR GROUND DIRECTIONAL OVERCURRENT FUNCTIONS

The coordination of the DOCP in meshed networks is not simple. Due to this fact, the use of distance protection can be attractive but distance functions could be less sensitive to ground faults because the apparent impedance can tend to be out for the distance characteristics [34], [35]. A possible solution, which has been applied in practice for many years [8], is the use of distance functions only as phase protection and the use of the DOCF only as ground-fault protection. Thus, the ground DOCF is more frequent in some power systems than the phase DOCF. From this perspective, coordination of the ground DOCF could be more relevant than coordination of the phase DOCF, but literature about coordination of the ground DOCF is not so abundant. In order to coordinate the ground DOCF, the proper selection of pickup currents (as mentioned in Section VII) should be complemented with the selection of the fastest feasible inverse-time curves (e.g., using optimization tools for this purpose).

On the other hand, instantaneous ground DOCF are frequently applied at both line ends as communication-based protection (using directional comparison), which is generally very fast. Tripping times are similar to those of differential line protection and can be considered almost instantaneous. The solution of the coordination of the ground DOCF could be easier in such cases because the remote backup inverse-time DOCF only needs to be slower than an instantaneous protection (main line protection). However, another possible criterion is to have a local backup inverse-time DOCF; in this case, the remote backup inverse-time DOCF should be slower than the local backup inverse-time DOCF (i.e., optimal coordination of the DOCP, as described originally in [10] and [11], can be formulated to solve the coordination between the remote and local backup DOCF).

As explained in Section VII, in the example in Fig. 8, the radial load has a path for zero-sequence currents (ZSC), and there are ZSC at location 7 for ground-faults in the line 3–4. These ZSC at location 7 could be relatively high because the equivalent zero-sequence impedance seen toward the load can be very low (e.g., if the radial load is fed through a YNynd transformer). This fact implies that the directional function could be necessary for the radial load in order to avoid operation of this ground overcurrent function for faults in the line 3–4 (or in the line 5–6). As this ground DOCP sees toward the radial load, it should be coordinated with the downstream ground overcurrent functions.

XIV. SOME SPECIFIC CONSIDERATIONS ABOUT USING DOCP IN SYSTEMS WITH DISTRIBUTED GENERATION (DG)

The main concerns about coordination of the DOCP in systems with DG are related to the magnitude of the short-circuit currents from DG and related to the coordination by itself.

Short-circuit currents from DG ($I_{\mathrm{SC-DG}}$) depend on DG types [36]–[39]. In case of DG based on synchronous machines (SMDG), the $I_{\mathrm{SC-DG}}$ can be several times greater than their rated currents and can be computed from well-known machine models, considering subtransient and transient models, DC offset, and sequence networks. In case of Inverter-Interfaced DG (IIDG), the $I_{\mathrm{SC-DG}}$ can be dependent on the control of power electronics and limited to be between 1.2 and 2 times their rated currents in order to avoid damage of the power electronics; it can be balanced for unbalanced faults and it cannot be still computed in a reliable and standardized way by short-circuit simple models. The low value of $I_{\mathrm{SC-DG}}$ in case of IIDG is a challenge for protection sensitivity. On the other hand, IIDG should include some types of a grounding transformer in order to provide a source of zero-sequence currents for ground fault protections. Due to the special features of $I_{\mathrm{SC-DG}}$ in case of IIDG, special protection algorithms should be developed in the future for systems predominantly fed by IIDG [36].

If a DG is installed in a network which was radial (Fig. 10), and the non-directional overcurrent protection at location 1 is kept, then 1 could trip due to the $I_{\mathrm{SC-DG}}$ for a fault at F, which would be considered an external fault for 1. This simple case of lack of selectivity has been named "sympathetic" or "false" tripping [37], [38]; it can be solved by changing the protection at location 1 by a DOCP, or sometimes by improving the coordination of non-directional overcurrent devices [37].

On the other hand, for a fault at F (Fig. 10), the fault current from the utility could decrease due to $I_{\mathrm{SC-DG}}$, in comparison with the case without DG, and it could be below the pickup value of the correspondent protection at location 2; this case has been named "blinding" of the protection [21], [38]. This phenomenon can also occur in traditional transmission systems with DOCP, and it usually implies that some backup DOCP will only operate after the clearing of the other backup DOCP (e.g., if 3 fails to operate for a fault at F, the current at 2 will be above its pickup value after the operation of 4).

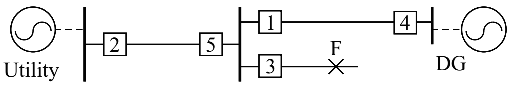


Fig. 10. Simplified system to explain cases of "sympathetic/false tripping" and "blinding of protection" in systems with distributed generation (DG).

As it was highlighted in Section III, adaptive protection could be considered a complicated solution if the power system is typically operating in its base configuration. However, a system with DG is expected to be frequently changing its configuration; therefore, the use of adaptive protection can be very justifiable to guarantee selectivity in such cases [39].

XV. CONCLUSION

A novel summary of concepts about coordination of directional overcurrent protections is presented in this paper. This summary should facilitate the inclusion of the analyzed topics in future coordination studies related to these protective functions.

Two deductions show that systems in ring configuration and with only one source of short-circuit currents can be analyzed with a simple method without the loss of generality. Subsequently, it is shown that for systems with multiple sources, the obtaining of selectivity can be impossible if all the system configurations are considered, and inverse-time functions are strictly necessary.

On the other hand, it is shown that the following topics should be considered during the coordination: a) overcurrent protection of radial loads; b) specific criteria to compare instantaneous and inverse-time functions, as well as inverse-time functions and definite-time functions; c) pickup currents of phase functions should be selected considering maximum load for different possible configurations as well as the specific effect of reverse load currents on the directional comparison method; d) ground functions can be very sensitive but sometimes a backup function could be more sensitive than the main protection if this point is not carefully checked; e) contributions from motors to short circuit currents can have an influence on the setting of instantaneous functions; f) transient configurations due to sequential trips at both line ends; g) the need of avoiding possible trips of remote backup relays. Furthermore, there are two points which are seldom considered during the coordination of these relays and they should be considered: a) the magnitude of current seen by a relay can vary in time, and consequently, the dynamic behavior of overcurrent functions should be considered; b) a delayed trip could imply loss of stability of the power system, and consequently, stability restraints should be included.

Finally, specific considerations about using directional overcurrent protections in systems with distributed generation are highlighted. These considerations can be related to the magnitudes of the short-circuit current or they can be related to the coordination by itself.

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REFERENCES

[1] J. L. Blackburn and T. J. Domin, *Protective Relaying. Principles and Applications*,4th ed., Boca Raton: CRC Press, 2014.

[2] W. A. Elmore, *Protective Relaying Theory and Applications*, 2nd ed., New York: Marcel Dekker, Inc., 2004.

[3] AREVA T&D, *Network Protection & Automation Guide*, 2002.

[4] *IEEE Guide for protective relay applications to transmission lines*, C37.113-1999, 1999.

[5] The Electricity Training Association, *Power System Protection. Volume 2: Systems and Methods*, London: The Institution of Engineering and Technology, 1995.

[6] A. R. V. C. Warrington, *Protective Relays. Their Theory and Practice*, London: Chapman & Hall Ltd., 1968.

[7] R. Mason, *The Art and Science of Protective Relaying*, New York: John Wiley & Sons Inc., 1956.

[8] R. B. Gastineau, R. H. Harris, W. L. Woodside, and W. V. Scribner, "Using the computer to set transmission line phase distance and ground back-up relays," *IEEE Transactions on Power Apparatus and Systems*, vol. 96, no. 2, pp. 478–484, Mar. 1977.

[9] H. Y. Tsien, "An automatic digital computer program for setting transmission line directional overcurrent relays," *IEEE Transactions on Power Apparatus and Systems*, vol. 83, no. 10, pp. 1048–1053, Oct. 1964.

[10] A. J. Urdaneta, R. Nadira, and L. G. P. Jimenez, "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Transactions on Power Delivery*, vol. 3, no. 3, pp. 903–911, Jul. 1988.

[11] A. Urdaneta and L. Pérez, "Optimal coordination of directional overcurrent relays in interconnected systems" ("Coordinación óptima de relés direccionales de sobrecorriente en sistemas interconectados" in Spanish), in: *IV Jornadas Nacionales de Potencia*, vol. "Operación y Mantenimiento", pp. 223–245, Puerto La Cruz, Venezuela, 1986.

[12] D. SolatiAlkaran, M. R. Vatani, M. J. Sanjari, G. B. Gharehpetian, and M. S. Naderi, "Optimal overcurrent relay coordination in interconnected networks by using fuzzy-based GA method," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3091–3101, Jul. 2018.

[13] M. H. Costa, R. R. Saldanha, M. G. Ravetti, and E. G. Carrano, "Robust coordination of directional overcurrent relays using a matheuristic algorithm," *IET Generation, Transmission & Distribution*, vol. 11, no. 2, pp. 464–474, Jan. 2017.

[14] E. Dehghanpour, H. K. Karegar, R. Kheirollahi, and T. Soleymani, "Optimal coordination of directional overcurrent relays in microgrids by using cuckoo-linear optimization algorithm and fault current limiter," *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 1365–1375, Mar. 2018.

[15] D. Saha, A. Datta, and P. Das, "Optimal coordination of directional overcurrent relays in power systems using Symbiotic Organism Search Optimisation technique," *IET Generation, Transmission & Distribution*, vol. 10, no. 11, pp. 2681–2688, Aug. 2016.

[16] M. Y. Shih, A. C. Enríquez, T. Y. Hsiao, and L. M. T. Treviño, "Enhanced differential evolution algorithm for coordination of directional overcurrent relays," *Electric Power Systems Research*, vol. 143, pp. 365–375, Feb. 2017.

[17] S. H. Horowitz, A. G. Phadke, and J. S. Thorpe, "Adaptive transmission system relaying," *IEEE Transactions on Power Delivery*, vol. 3, no. 4, pp. 1436–1445, Oct. 1988.

[18] G. D. Rockefeller, C. L. Wagner, J. R. Linders, K. L. Hicks, and D. T. Rizy, "Adaptive transmission relaying concepts for improved performance," *IEEE Transactions on Power Delivery*, vol. 3, no. 4, pp. 1446–1458, Oct. 1988.

[19] K. R. Shah, E. D. Detjen, and A. G. Phadke, "Feasibility of adaptive distribution protection system using computer overcurrent relaying concept," *IEEE Transactions on Industry Applications*, vol. 24, no. 5, pp. 792–797, Sep./Oct. 1988.

[20] Ł. Hucheland H. H. Zeineldin, "Planning the coordination of directional overcurrent relays for distribution systems considering DG," *IEEE Transactions on Smart Grid*, vol. 7, no. 3, pp. 1642–1649, May 2016.

[21] H. Mudaand P. Jena, "Sequence currents based adaptive protection approach for DNs with distributed energyresources," *IET Generation, Transmission & Distribution*, vol. 11, no. 1, pp. 154–165, Jan. 2017.

[22] H. M. Sharaf, H. H. Zeineldin, and E. El-Saadany, "Protection coordination for microgrids with grid-connected and islanded capabilities using communication assisted dual setting directional overcurrent relays," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 143–151, Jan. 2018.

[23] V. C. Nikolaidis, E. Papanikolaou, and A. S. Safigianni, "A communication-assisted overcurrent protection scheme for radial distribution systems with distributed generation," *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 114–123, Jan. 2016.

[24] V. A. Papaspiliotopoulos, G. N. Korres, V. A. Kleftakis, and N. D. Hatziargyriou, "Hardware-In-the-Loop design and optimal setting of adaptive protection schemes for distribution systems with distributed generation," *IEEE Transactions on Power Delivery*, vol. 32, no. 1, pp. 393–400, Feb. 2017.

[25] A. Yazdaninejadi, D. Nazarpour, and S. Golshannavaz, "Dual-setting directional over-current relays: An optimal coordination in multiple source meshed distribution networks," *International Journal of Electrical Power & Energy Systems,* vol. 86, pp. 163–176, Mar. 2017.

[26] R. M. Chabanloo, H. A. Abyaneh, S. S. HashemiKamangar, and F. Razavi, "Optimal combined overcurrent and distance relays coordination incorporating intelligent overcurrent relays characteristic selection," *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 1381–1391, Jul. 2011.

[27] C. A. CastilloSalazar, A. CondeEnríquez, and S. E. Schaeffer, "Directional overcurrent relay coordination considering non-standardized time curves," *Electric Power Systems Research*, vol. 122, pp. 42–49, May 2015.

[28] L. G. Pérez and A. J. Urdaneta, "Optimal coordination of directional overcurrent relays considering definite time backup relaying," *IEEE Transactions on Power Delivery*, vol. 14, no. 4, pp. 1276–1284, Oct. 1999.

[29] L. G. Pérez and A. J. Urdaneta, "Optimal computation of distance relays second zone timing in a mixed protection scheme with directional overcurrent relays," *IEEE Transactions on Power Delivery*, vol. 16, no. 3, pp. 385–388, Jul. 2001.

[30] A. J. Urdaneta, L. G. Pérez, and H. Restrepo, "Optimal coordination of directional overcurrent relays considering dynamic changes in the network topology," *IEEE Transactions on Power Delivery*, vol. 12, no. 4, pp. 1458–1464, Oct. 1997.

[31] S. E. Zocholl, "Testing dynamic characteristics of overcurrent relays," in *Proceedings of the 20th Annual Western Protective Relay Conference*, Spokane, USA, 1993.

[32] E. Sorrentino, O. Salazar, and D. Chávez, "Limit curves by power system's transient stability for the inverse-time overcurrent relays," *IEEE*

Transactions on Power Delivery, vol. 26, no. 3, pp. 1727–1733, Jul. 2011.

[33] L. G. Pérez, A. J. Flechsig, and V. Venkatasubramanian, "Modeling the protective system for power system dynamic analysis," *IEEE Transactions on Power Systems*, vol. 9, no. 4, pp. 1963–1973, Nov. 1994.

[34] E. Sorrentino, "Understanding the effect of pre-fault load flow on the effect of fault resistance on the impedance seen by the traditional ground distance function," *International Transactions on Electrical Energy Systems*, vol. 25, no. 7, pp. 1148–1157, Jul. 2015.

[35] E. Sorrentino, "Comparison of five methods of compensation for the ground distance function and assessment of their effect on the resistive reach in quadrilateral characteristics," *International Journal of Electrical Power & Energy Systems*, vol. 61, pp. 440–445, Oct. 2014.

[36] A. Hooshyarand, and R. Iravani, "A new directional element for microgrid protection," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6862–6876, Nov. 2018.

[37] M. Ghotbi, R. Chabanloo, and H. Javadi, "Method to resolve false trip of non-directional overcurrent relays in radial networks equipped with distributed generators," *IET Generation, Transmission & Distribution*, vol. 13, no. 4, pp. 485–494, Feb. 2019.

[38] F. Glinka, N. Schulte, R. Bertram, A. Schnettler, and M. Koprivšek, "Solutions for blinding of protection in today's and future German LV grids with high inverter penetration – simulative and experimental analysis," *The Journal of Engineering*, vol. 2018, no. 15, pp. 1256–1260, Oct. 2018.

[39] D. Sampath Kumar, D. Srinivasan, A. Sharma, and T. Reindl, "Adaptive directional overcurrent relaying scheme for meshed distribution networks," *IET Generation, Transmission & Distribution*, vol. 12, no. 13, pp. 3212–3220, Jul. 2018.

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