Nontraditional Relay Curves for the Coordination of the Ground Overcurrent Function With Downstream Fuses

Elmer Sorrentino

***Abstract*—This paper describes the details for the application of some nontraditional relay curves for the coordination of the ground overcurrent function with downstream fuses. These curves have a segmented shape in order to achieve the best combination of sensitivity, speed, and selectivity. For this segmented shape, greater current does not necessarily imply a shorter time. These curves can be programmed in different ways, according to the available features in the commercial relays, and the expected behavior of two options is analyzed. Both options would have satisfactory behavior although they would have different dynamic behavior.**

***Index Terms*—Ground overcurrent protection, overcurrent relay-fuse coordination, protection of distribution systems.**

I. Introduction

MICROPROCESSOR-BASED relays created new possibilities for the art and science of protective relaying. However, these devices sometimes have been applied to obtain basically the same functions as electromechanical and analog solid-state relays. In such cases, the benefits of digital relays often include measurement, recording, remote supervision, integration of different protective functions in only one device, and the application of smaller coordination time intervals.

On the other hand, many novel concepts for the protection of distribution systems have been developed or proposed; for example the use of: 1) negative-sequence overcurrent elements [1]; 2) advanced thermal models for motors, transformers and transmission lines [2]–[4]; 3) combination of different shapes for time–current curves [5], new curve shapes [6], [7], or curves created by the user [6]; 4) communication capabilities between overcurrent relays to accelerate the high-set definite-time function at the main circuit breaker (CB) when the downstream devices do not sense overcurrent [8]–[11]; 5) nontraditional logic of operation for overcurrent relays [12]; 6) pattern-recognition techniques in order to solve the high-impedance fault detection problem [13]–[15]; 7) pattern-recognition techniques in order to discriminate between inrush and fault currents [16]–[18]; 8) integration of protective relays and fault locators [12]; 9) relay information for planning CB maintenance [19] or for reducing the arc-flash hazard [20]; 9) application of the concept of adaptive relaying [21]–[23], based on changing the relay setting groups by using logical inputs [24], [25] or based on changing the sensitivity of overcurrent relays according to load currents [26], [27].

This paper is about the application of nontraditional relay curves for the coordination of the ground overcurrent function (51N) with downstream fuses. These nontraditional curves were briefly shown some years ago [28], [29] in documents without wide diffusion (which are only available in Spanish), and different details about these curves have not been previously shown. Now, this paper presents a detailed explanation of these nontraditional curves, a detailed analysis of two ways of implementing them in commercial relays, and the proposed solutions for cases with different downstream fuses. The ground overcurrent function based on residual currents (51N) is taken as an example for this article; however, the idea could be extended to the ground overcurrent function which is not based on residual currents (51G).

The 51N can be very sensitive because it is little influenced by the load current and, in many cases, its pickup value can be set below the minimum melting current of the downstream fuse. The fuse cannot be so sensitive because it does not have a special way to detect ground faults. Hence, in many cases, the 51N is more sensitive and faster than the downstream fuse for high-impedance faults. Reduction of the 51N sensitivity, or use of ground overcurrent devices instead of fuses, would avoid the lack of selectivity, but these options are not always justifiable. The nontraditional curves, described in this paper, give the best combination of sensitivity, speed, and selectivity for the coordination between the 51N and downstream fuses.

II. Traditional Coordination of the Ground Overcurrent Function With Downstream Fuses

The coordination of the 51N with a downstream fuse usually requires a compromise between sensitivity, selectivity, and speed. Fig. 1 shows the best traditional solution for this case.

For low values of fault current, the benefits of good sensitivity of the 51N are exploited. For high values of the fault current, the desired selectivity is achieved. On the other hand, there is a range of currents where both devices could operate because there is an overlap of the time–current curves. For currents above the maximum current value $(\mathrm{I_{fmax}})$ that are sensed simultaneously by the 51N and the fuse, an instantaneous function could be used.

There are crossings between curves, but this is the best traditional coordination for this case. The selectivity is obtained when it is feasible, and the sensitivity of the 51N is exploited when the fuse cannot be sensitive enough. This solution has

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The author is with Universidad Simón Bolívar, Caracas 1080, Venezuela (e-mail: elmersor@usb.ve).

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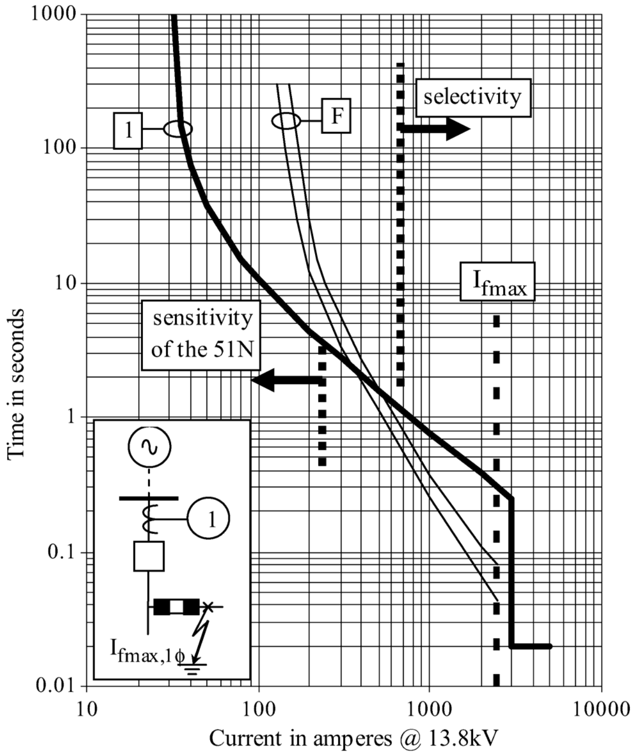

Fig. 1. Traditional coordination of the ground overcurrent function with downstream fuses. There are crossings between curves, but this is the best traditional solution for this case.

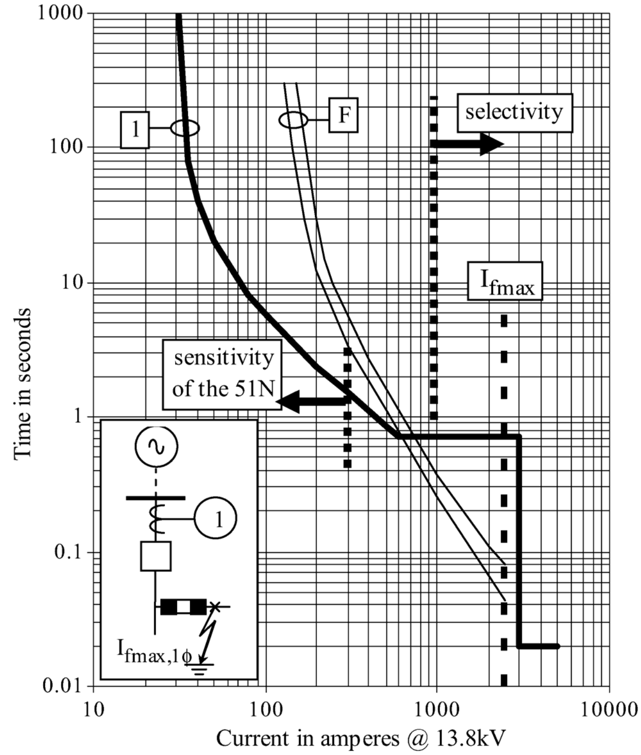

Fig. 2. Traditional coordination of the ground overcurrent function with downstream fuses. This is a good traditional solution for this case because the relay curve is limited to be inverse until $\mathrm{M} = 20$.

been explained here because it is not usually well known. However, this concept has been available for many years [30].

The case shown in Fig. 1 corresponds to a system whose loads are delta connected (and the single-phase loads are connected between two phases). For this case, the zero-sequence current in normal conditions is null (neglecting the unbalance of the capacitive currents of the insulation). Therefore, the pickup value of the 51N can be extremely low. This case is used as an example for this paper. The proposed ideas are also applicable to distribution systems whose loads are connected between phase and neutral, but the pickup value of the 51N would not be so low.

For the case shown in Fig. 1, the relay curve inversity has not been limited for high values of M (M is the ratio of the relay current to the pickup current.) Traditionally, the relay curves are inverse until a given value of M (e.g., $\mathrm{M} = 20$), even in modern relays [31], [32]. This limitation might be eliminated in the future, because there is available technology for it. If the inversity of the relay curves was limited for high values of M, then the optimal solution would not be so good as the case depicted in Fig. 1 (but exactly the same concepts could be applied, as shown in Fig. 2).

III. Proposed Nontraditional Curves for the Coordination of the 51N With Downstream Fuses

A. Without Recloser Function

Fig. 3 shows the nontraditional proposed solution, with a segmented time–current characteristic for the 51N. Obviously, this kind of curve contrasts with the traditional concept of "the greater current, the less the time", but it is the best choice to solve this case. Segmented curves with this nontraditional feature have also been proposed for other cases, but mainly for some special conditions of motor thermal protection [6].

When the recloser function is not required, it is often preferable to maximize the range of currents for obtaining selectivity between the 51N and the downstream fuse. For very low currents, selectivity is not feasible, and the 51N can be set as fast as possible. In this coordination, the 51N has: 1) a low pickup value; 2) low enough speed to allow transient currents without tripping, for currents below the breakpoint ($\mathrm{I_{bp}}$); and 3) low enough speed to operate selectively with the fuse, for currents greater than $\mathrm{I_{bp}}$.

The choice of breakpoint value of current should obey the engineer's design criteria. For example, the value of current where the fuse maximum clearing time is 6 s could be selected. Then, for current values where the fuse is not sensitive enough, or it is considered very slow, the CB should clear the fault. For greater current values, the 51N curve should be above the fuse clearing curve by enough time to achieve selectivity and to obtain the feasible fastest backup time.

B. With Recloser Function

When the recloser function is required, the same kind of segmented curves can be used. The low-current region is the typical "fuse saving scheme," and the high-current region is the typical "trip saving scheme." The main difference between this solution and a traditional application is that here both are simultaneously applied.

The design criteria to choose the breakpoint value could be different than the previous one. For example, if the fuse saving

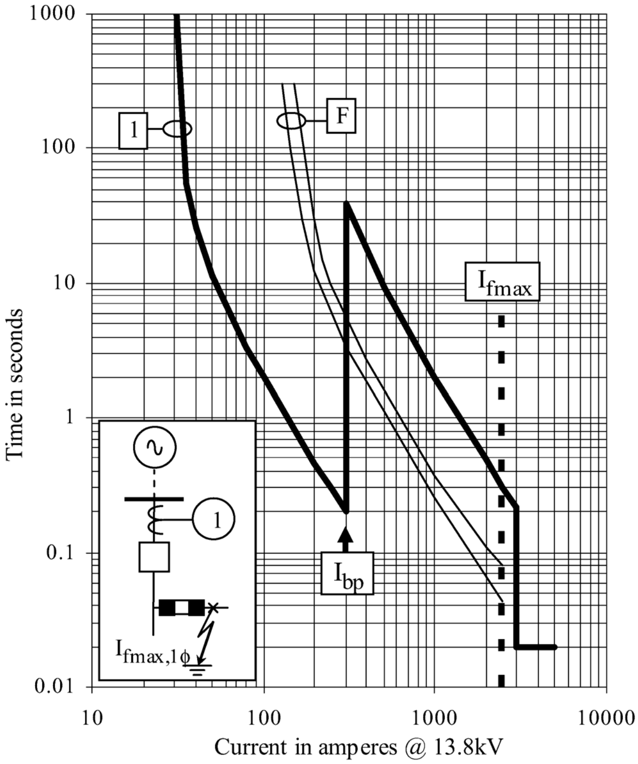

Fig. 3. Nontraditional coordination of the ground overcurrent function with downstream fuses. Case: without the recloser function.

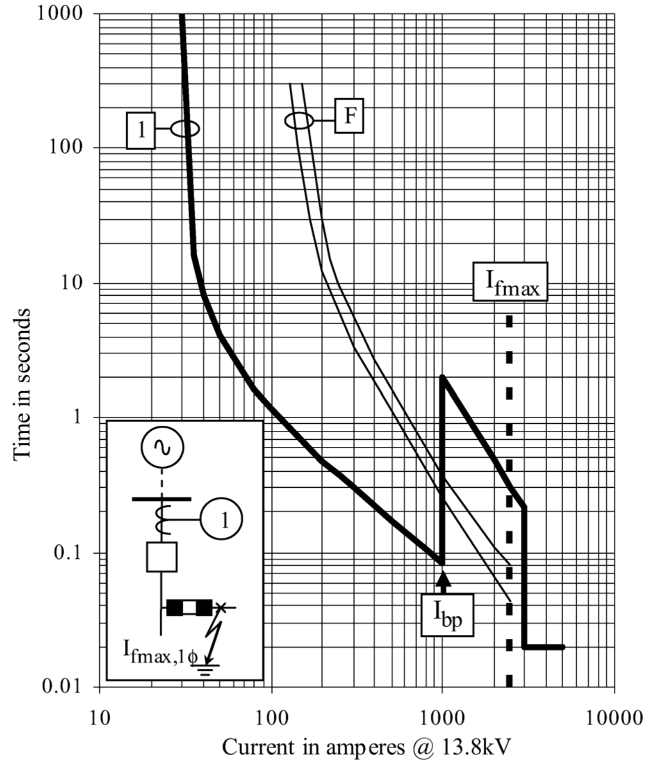

Fig. 4. Nontraditional coordination of the ground overcurrent function with downstream fuses. Case: with recloser function (first trips).

scheme is preferred, the breakpoint value could be chosen at the largest value of current where the CB could operate before the fuse minimum melting time, including the safety factor (Fig. 4). Then, the fuse saving scheme would be used when feasible; otherwise, the trip saving scheme would be used to avoid simultaneous operation of the fuse and CB.

In order to avoid the lockout condition for some low-current faults downstream of the fuse, the last 51N operation could use a curve equivalent to the nonrecloser case.

C. Effect of Relay Dynamic Behavior on the Probability of Occurrence of Simultaneous Operation of Both Devices

In the time–current graph, the zone where both devices can operate simultaneously is determined by the relay accuracy for the value of the breakpoint current. Considering the typical accuracy of pickup currents for digital relays, this zone is very small, especially in comparison with the traditional solution (intersecting inverse-time relay curve and fuse curve).

This fact by itself is not a real advantage of the proposed idea because the time–current graph only shows the relay static behavior. The dynamic behavior of the overcurrent relays should be considered. For real faults, the modulus of the fault current could be varying in time, and the overcurrent function integrates the effect of this current in order to have adequate dynamic behavior [33]. For example, the modulus of the fault current could be lower than $\mathrm{I_{bp}}$ for a time interval and greater than $\mathrm{I_{bp}}$ for the other time interval. Therefore, the overcurrent function would be dynamically integrating the current in these conditions, and it is not obvious if the 51N function would be faster or slower than the fuse.

However, for traditional and nontraditional cases, there are only three possible results: 1) the fuse clears the fault and the CB does not operate; 2) the CB clears the fault and the fuse does not melt; 3) both fuse and CB operate. The simultaneous operation of both devices is an undesired condition. An exact evaluation of the probability of occurrence of simultaneous operation of both devices would not be an easy task (because there are many possible cases for the variable behavior of fault currents), and it is out of the scope of this paper.

Another undesired condition is when the CB clears the fault and the fuse was very close to melting, because there is a risk of hidden damage to the fuse. The probability of occurrence of this event should be lower for nontraditional cases because their time–current curves are, in general, faster than traditional ones for high-impedance faults (but, again, an exact evaluation of these probabilities of occurrence would not be an easy task).

This discussion about the dynamic behavior of the relay is useful to properly understand the benefits and drawbacks of the proposed method. However, an analysis of dynamic events is not necessary to compute the relay settings nor to decide the practical implementation of the proposed method.

D. Criteria for the Minimum Operation Time at the Breakpoint (I_{bp})

As usual, the relay must allow normal transient overcurrents without tripping. Thus, a criterion for the minimum operation time at the breakpoint could be related to this fact. For example, a concern might be the “false” residual currents due to the simultaneous inrush of the downstream transformers. There are not any zero-sequence currents in these transformers, and the

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residual currents in the relay are due to the transient unequal behavior of the current transformers.

Another criterion might be related to the selectivity with the fuses for downstream distribution transformers. For example, the rated current of those fuses might be very low, and the nontraditional 51N function might be 100% selective with them. On the other hand, Section VI shows examples of coordination with different downstream fuses.

E. Effect of Limits for the Curve Inversity at High Values of M

For the example just shown, the instantaneous pickup is close to 70 times the 51N pickup. Thus, if there were limits for the relay curve inversity at high values of M, these limits would have an influence on the nontraditional cases (without or with the recloser function). This fact could imply the application of solutions that are not so good as the cases depicted in Figs. 3 and 4, but exactly the same concepts could be applied (as in the traditional case). For the sake of simplicity, these cases are discussed in Section V.

IV. Options for Implementing These Nontraditional Curves With Available Overcurrent Functions

There are two main options for implementing these nontraditional curves with the available functions of the commercial overcurrent relays. These options are: 1) by applying time–current curve shapes created by the user and 2) by applying the logic combination of traditional available curves.

This section describes the two options without considering the limits for the relay curve inversity at high values of M. These limits are considered in Section V. Parameters for these nontraditional time–current curves are shown in the Appendix.

A. Applying Curve Shapes Created by the User

The users can create their own shapes for the time–current curves, in some overcurrent relays (e.g., [31]). If this option is selected, in order to create the curves of Fig. 3 or 4, then the dynamic behavior of the 51N would be easily predictable. In this case, the 51N would integrate the curve created by the user, by using the current at each instant. This means that the 51N would always be incrementing a unique accumulated value (corresponding to a unique curve).

B. Applying a Logical Combination of Traditional Curves

The users can create logical combinations of time–current curves, in some overcurrent relays (e.g., [32]). If this option is selected, in order to create the curves of Figs. 3 or 4, the application of two independent functions (51N-H and 51N-L, in logical OR) would be necessary.

Fig. 5 shows the case corresponding to Fig. 3. (The case corresponding to Fig. 4 is conceptually similar.) The 51N-H would be a traditional curve, but it does not operate for currents below the breakpoint (I_{bp}) because the 51N-L would operate faster. The 51N-L would have a curve that does not operate for currents greater than I_{bp}; this function should be created by other logical

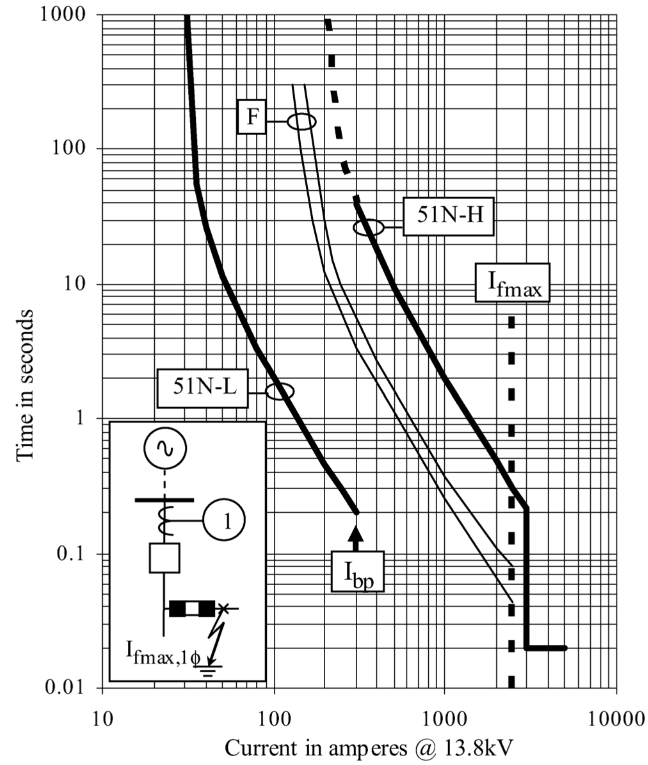

Fig. 5. Case of Fig. 3, implemented by applying a logical combination of traditional curves. (51N-L and 51N-H are 51N functions of relay 1.)

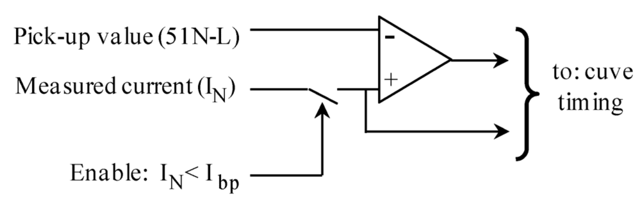

Fig. 6. Example of a way for programming the 51N-L function of Fig. 5 by applying the available options in a commercial relay [32].

combinations of conditions, because it is not a traditional overcurrent function. For example, Fig. 6 shows a way for programming the 51N-L, by using the available options in a commercial relay [32]. Fig. 6 shows that the enable condition ($I_N < I_{bp}$) is required for the comparison between the measured current (I_N) and the pickup value of the 51N-L; thus, this function only operates for $I_N < I_{bp}$.

Now, the dynamic behavior of these functions would also be easily predictable: each function (51N-H and 51N-L) would be integrating its own curve. Two examples are useful to illustrate this behavior:

1) if there is an overcurrent whose value varies from lower than I_{bp} to greater than I_{bp}, then the 51N-H would be simply integrating its traditional curve;
2) if there is an overcurrent whose value varies from greater than I_{bp} to lower than I_{bp}, then the 51N-L would not be integrating until the overcurrent reaches a value lower than I_{bp}.

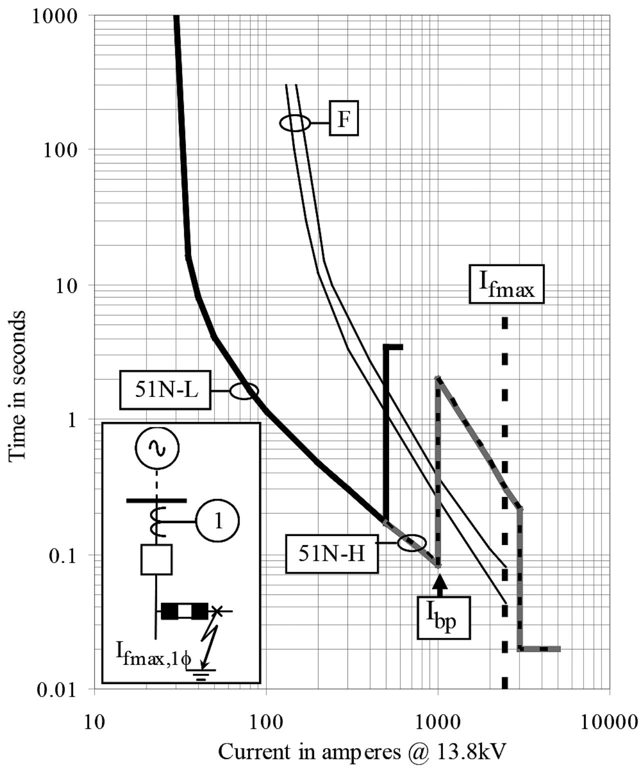

Fig. 7. Case of Fig. 4, implemented by applying curve shapes created by the user (limits in curve shapes for $\mathrm{M} \geq 20$ are considered).

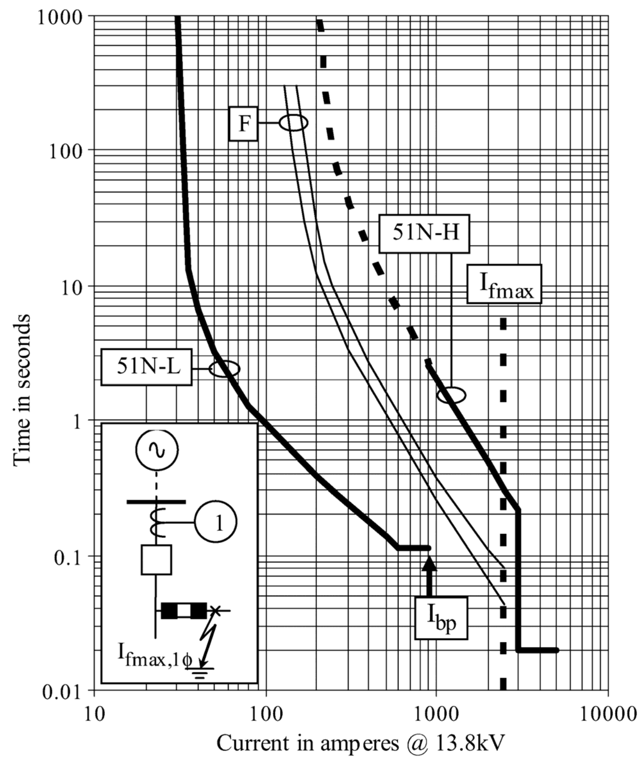

Fig. 8. Case of Fig. 4, implemented by applying logical combination of traditional curves (limits in curve shapes for $\mathrm{M} \geq 20$ are considered).

C. Comparison Between Both Options

The main differences between both options are: 1) the way of programming the required curves and 2) their dynamic behavior.

The dynamic behavior is apparently simpler to understand for the option with curve shapes created by the user. However, it is important to remember that there are only three possible results: 1) the fuse clears the fault and the circuit breaker (CB) does not operate; 2) the CB clears the fault and the fuse does not melt; 3) both fuse and CB operate. Thus, understanding the relay dynamic behavior is important for fault analysis, but there are many possible dynamic variations for the fault current (therefore, the differences in the dynamic behavior of the 51N function do not determine the probability of occurrence of simultaneous operation of both devices).

V. Effect of Limits for the Curve Inversity, at High Values of M, on the Nontraditional Cases

A. Applying Curve Shapes Created by the User

In this option, the desired curve should be simply divided into two functions. For example, the case of Fig. 3 would be similar to the case described in Section IV-B (Fig. 5). Instead of using a logical combination for avoiding the operation of 51N-L, for currents above the breakpoint, there would be a curve shape created by the user for that purpose. This curve would be similar to the 51N-L curve of Fig. 5, but its last points would have a large enough definite time, in order to avoid crossings with the 51N-H curve. The 51N-H might have a traditional curve. This case has similar dynamic behavior than the case described in Section IV-B (but the 51N-L would be integrating for currents greater than I_{bp} in this case).

For the case of Fig. 4, the 51N-L would be similar to the previous one, because its last points would have a large enough definite time, in order to avoid crossings with the 51N-H curve. However, the 51N-H must also be a curve shape created by the user because I_{bp} is greater than 20 times the pickup value of the 51N-L. Therefore, the 51N-H must have a segmented shape, from the end of the 51N-L until the beginning of the instantaneous function (Fig. 7).

B. Applying Logical Combination of Traditional Curves

In this option, there is not any change for the case of Fig. 3, due to the limits in the curve inversity for high values of M. Thus, Fig. 5 shows the solution for this case.

However, a change is necessary for the case of Fig. 4, because I_{bp} is greater than 20 times the pickup value of the 51N-L. Some solutions for this case are as follows.

1) The use of two functions for currents below the breakpoint (51N-L1 and 51N-L2) is in order to avoid the condition $\mathrm{M} \geq 20$ for the 51N-L. There would be a total of three functions for the 51N (51N-L1, 51N-L2, and 51N-H).
2) The use of only one function for currents below I_{bp}. This 51N-L would reach its limit ($\mathrm{M} = 20$), and the value of I_{bp} would be changed in order to obtain the desired time intervals for the separation with the fuse curve. This solution (Fig. 8) would imply a small reduction in the range of currents for the "fuse saving scheme," but it might be the simplest way to obtain the desired benefits.

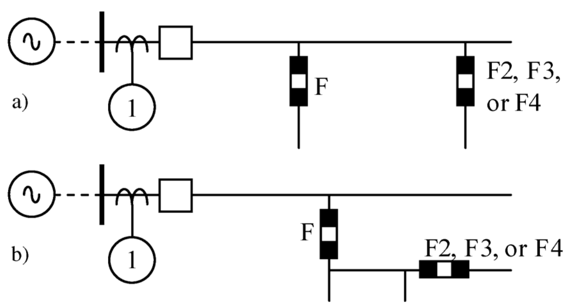

Fig. 9. Examples of configurations with downstream fuses: (a) F2, F3, or F4 are in a different branch than F. (b) F2, F3, or F4 are downstream of F.

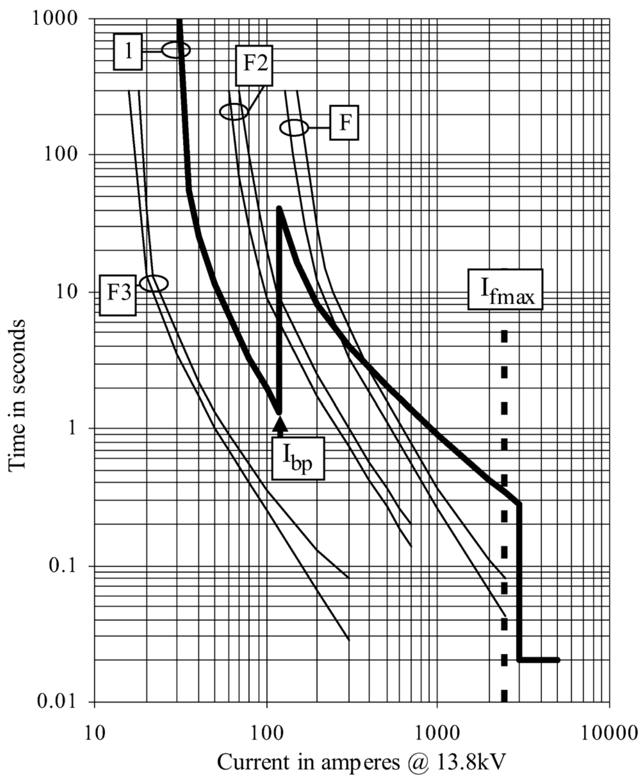

Fig. 10. Case of Fig. 3, considering three different downstream fuses and the aforementioned nontraditional curves for the 51N function.

VI. Examples of Application to Cases With Different Downstream Fuses

Fig. 9 shows two examples of configurations with different downstream fuses. For the sake of simplicity, only cases without recloser function are analyzed here. There are many possible configurations but, in general, selectivity is desired when it is feasible. Thus, the 51N function should be slower than the different downstream fuses when it is feasible.

For example, Fig. 10 shows a case where the 51N function can be 100% selective with a downstream fuse (F3), but a compromise is necessary to obtain the best coordination with fuses F and F2, by using the aforementioned nontraditional curves. In order to maximize selectivity, a different shape of nontraditional curves might be applied (Fig. 11).

Some zones could have a low probability of faults, and selectivity with fuses for those zones would not be a main concern. For example, if selectivity with F2 is not a concern, then the case

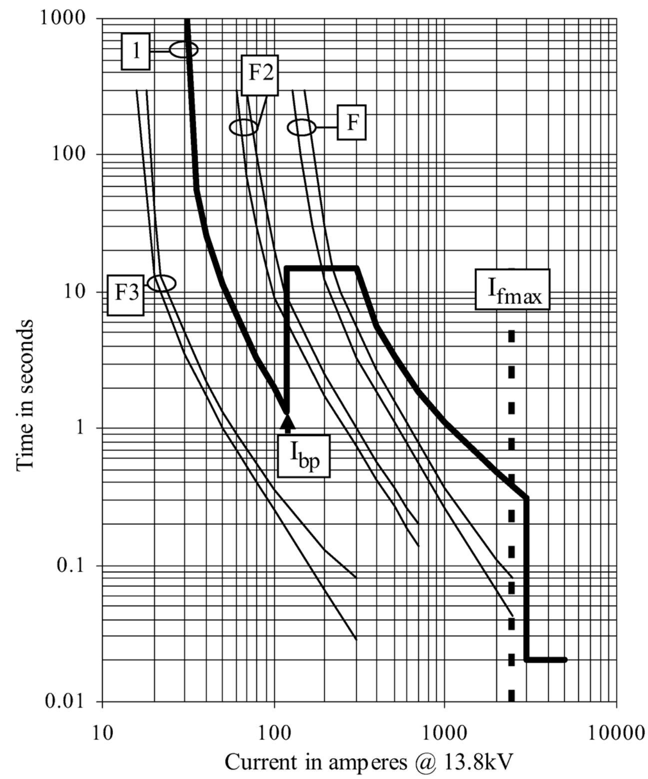

Fig. 11. Case of Fig. 3, considering three different downstream fuses and a different nontraditional curve (51N), in order to maximize selectivity.

of Fig. 3 might be directly applied, instead of solutions shown in Figs. 10 or 11.

On the other hand, some downstream fuses might have minimum melting current similar to the sensitive pickup of the 51N function. In such cases, the speed of the 51N function might be sacrificed in order to improve selectivity, as shown in Fig. 12. This 51N function only requires the combination of a definite-time function with an inverse function, in logical OR.

VII. Conclusion

The application of some nontraditional relay curves for the coordination of the ground overcurrent function with downstream fuses has been described in detail. For these nontraditional curves, greater current does not necessarily imply a shorter time, but they offer the best combination of sensitivity, speed, and selectivity for this coordination case.

These nontraditional curves have a segmented shape. They can be programmed in different ways, according to the available features in the commercial relays, and two different options were analyzed. One option is by applying time–current curve shapes created by the user, and the other option is by applying a logic combination of traditional available curves. Both options would have satisfactory behavior, and the main differences between them are: 1) the way for programming the required curves and 2) the dynamic behavior. The differences in dynamic behavior do not determine the probability of occurrence of simultaneous operation of fuse and the ground overcurrent function (this simultaneous operation would be an undesired condition).

If the pickup current of the ground overcurrent function is very low, then the desired curves might reach high values of

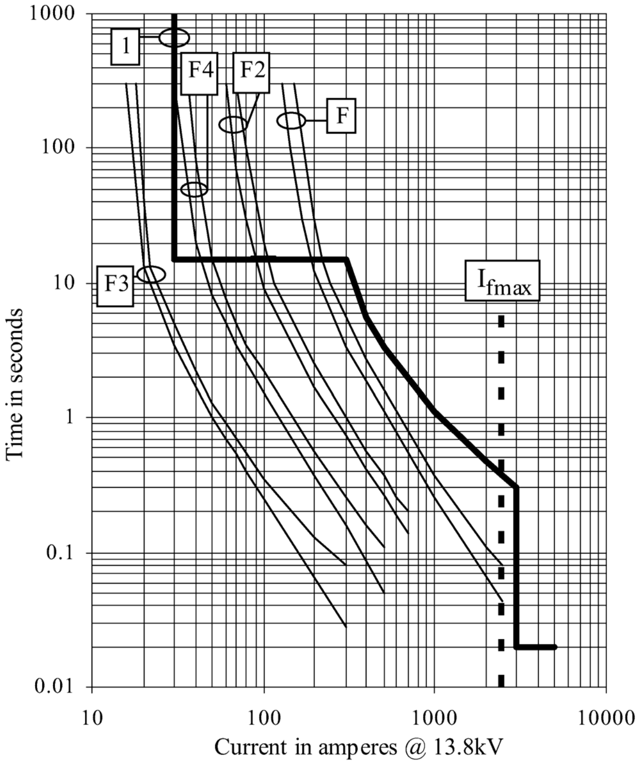

Fig. 12. Case of Fig. 3, considering four different downstream fuses, and the minimum melting current of one of them is similar to the pickup value of the nontraditional 51N function.

M (M is the ratio of the relay current to the pickup current). However, some relay curves are limited until a given value of M (e.g., $M = 20$), even in modern relays. This fact might imply an increase in the number of overcurrent functions, but exactly the same concepts would be applied.

Some examples of configurations with different downstream fuses were analyzed, in order to show the proposed solutions with these nontraditional curves. There are many possible configurations, but the same developed concepts can be applied in order to obtain the best combination of sensitivity, speed, and selectivity for these cases.

Appendix
Parameters of the Nontraditional Time–Current Curves of the Relays

For all of the figures: fuse F is 65 T, and the instantaneous pickup is 3000 A. The inverse functions are IEC type [31], [32], their pickup value is I_0, and their time dial setting is TM.

For Fig. 3: 1) extremely inverse, $I_0 = 30$ A and $\mathrm{TM} = 0.25$, for $I_N < I_{bp}$ and 2) extremely inverse, $I_0 = 200$ A and $\mathrm{TM} = 0.60$, for $I_N > I_{bp}$.

For Fig. 4: 1) very inverse, $I_0 = 30$ A and $\mathrm{TM} = 0.20$, for $I_N < I_{bp}$; 2) extremely inverse, $I_0 = 200$ A and $\mathrm{TM} = 0.60$, for $I_N > I_{bp}$.

For Fig. 5: 1) extremely inverse, $I_0 = 30$ A and $\mathrm{TM} = 0.25$, for 51N-L and 2) extremely inverse, $I_0 = 200$ A and $\mathrm{TM} = 0.60$ for 51N-H.

For Fig. 7, the curves are created by the user, and their lower limits are the pickup values of the 51N functions (I_{PU}):

a) 51N-L, with $I_{PU} = 30$ A: a table with the data of an IEC-curve (very inverse, $I_0 = 30$ A and $\mathrm{TM} = 0.20$) for $I_N \leq 495$ A, and $t = 3.5$ s for $I_N \geq 510$ A. Note: 495 A is $16.5 I_{PU}$, 510 A is $17.0 I_{PU}$, and the step for the curve created by the user is $0.5 I_{PU}$ in this range [31].
b) 51N-H, with $I_{PU} = 400$ A: a table with the data of the previous IEC-curve (very inverse, $I_0 = 30$ A and $\mathrm{TM} = 0.20$) for $400 \leq I_N \leq 960$ A, and with the data of a different IEC-curve (extremely inverse, $I_0 = 200$ A and $\mathrm{TM} = 0.60$) for $I_N \geq 1000$ A. Note: 960 A is $2.4 I_{PU}$, 1000 A is $2.5 I_{PU}$, and the step for the curve created by the user is $0.1 I_{PU}$ in this range [31].

For Fig. 8: 1) very inverse, $I_0 = 30$ A and $\mathrm{TM} = 0.16$, for 51N-L and 2) extremely inverse, $I_0 = 200$ A and $\mathrm{TM} = 0.60$, for 51N-H.

For Figs. 10–12, F2 is 25 T, F3 is 8 T, and F4 is 15 T.

For Fig. 10: 1) extremely inverse, $I_0 = 30$ A and $\mathrm{TM} = 0.25$, for $I_N < I_{bp}$ and 2) very inverse, $I_0 = 100$ A and $\mathrm{TM} = 0.60$, for $I_N > I_{bp}$.

For Fig. 11: 1) extremely inverse, $I_0 = 30$ A and $\mathrm{TM} = 0.25$, for $I_N < I_{bp}$ and 2) for $I_N > I_{bp}$, the logical OR of a definite-time function ($t = 15$ s) and a very inverse function ($I_0 = 250$ A and $\mathrm{TM} = 0.25$).

For Fig. 12, the logical OR of a definite-time function ($t = 15$ s) and a very inverse function ($I_0 = 250$ A and $\mathrm{TM} = 0.25$).

The programming of these functions might be obvious for some protection engineers. Nevertheless, these curves were programmed in commercial relays (and their static behavior was tested by using injectors) in order to obtain more academic rigor.

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Elmer Sorrentino received the Electrical Engineer (Cum Laude) degree and M.Sc. degree in electrical engineering (Hons.) from Universidad Simón Bolívar (USB), Caracas, Venezuela, in 1984 and 1986, respectively.

Since 1984, he has been a Professor at USB and a Consulting Engineer for several companies. His research interests are in power system protection, power system analysis, and electrical machines.