Adaptive Inverse-Time Elements Take Microprocessor-Based Technology Beyond Emulating Electromechanical Relays

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***Abstract*—Traditional microprocessor-based relays emulate the functionality of electromechanical relays; they have inverse-time elements (ITEs) with selectable operating characteristics. This paper describes a general-purpose ITE with added flexibility to address a variety of applications. This ITE replaces fixed and settable parameters in traditional relays with variables that are updated dynamically every processing interval based on programmable equations. The paper explains this powerful protection concept and illustrates its usefulness with a number of practical applications, including adaptive pickup based on changes in load, adaptive coordination in parallel transformer applications, and adaptive pickup according to the duration of power outages.**

I. INTRODUCTION

Overcurrent, undervoltage, and overvoltage protection elements use inverse-time characteristics to provide line, feeder, transformer, motor, and generator protection for power system faults and abnormal operating conditions. Relays that include these characteristics have been available for more than a hundred years. Fig. 1 shows an electromechanical relay from the early 1900s that provides overcurrent protection using an inverse-time overcurrent characteristic. With this operating characteristic, the relay operates faster for high current magnitudes than for low current magnitudes. Fast relay operation for high currents minimizes equipment damage. Additionally, the characteristic can be shifted in time to coordinate the relay operation with downstream and upstream devices. However, electromechanical relays provide only one specific inverse-time characteristic, such as inverse, very inverse, or extremely inverse. Relay engineers must select the relay model depending on the application. These relays have only two settings: time dial and pickup (tap). The pickup setting defines the relay sensitivity, and the time dial setting and the characteristic define the relay operating time.

Microprocessor-based or numerical relays provide the functionality available in electromechanical inverse-time overcurrent relays, plus the ability to select the operating characteristic [1] [2]. Fig. 2 shows the settings of an inverse-time overcurrent element in a numerical relay. The 51S1C setting provides ten inverse-time characteristic options. The flexibility of having multiple characteristics in a single relay prevents the need to specify different relay models for different operating characteristic requirements. Numerical relays include the pickup and time dial settings, as does the previously described electromechanical relay. In addition to choosing the operating characteristic, the relay engineer can choose the operating quantity (51S1O) from a selection of available analog quantities (e.g., IAL, IA1, IA2, …, 3I2L, 3I0L), where IA indicates Phase A current and I2 and I0 indicate negative- and zero-sequence currents, respectively. The ability to select the operating quantity optimizes the use of the available overcurrent elements in the relay.

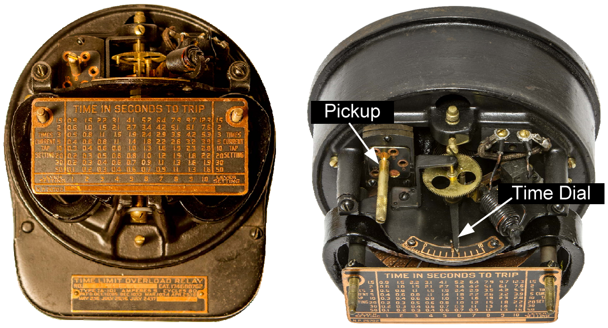
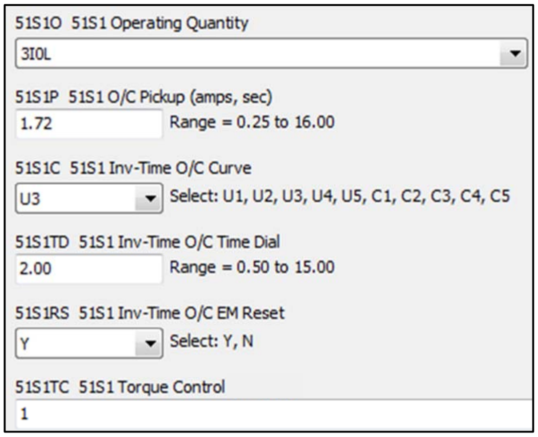


Fig. 1. The IA-101 electromechanical relay provides overcurrent protection using an inverse-time overcurrent characteristic.



51S1O 51S1 Operating Quantity
3I0L

51S1P 51S1 O/C Pickup (amps, sec)
1.72 Range = 0.25 to 16.00

51S1C 51S1 Inv-Time O/C Curve
U3 Select: U1, U2, U3, U4, U5, C1, C2, C3, C4, C5

51S1TD 51S1 Inv-Time O/C Time Dial
2.00 Range = 0.50 to 15.00

51S1RS 51S1 Inv-Time O/C EM Reset
Y Select: Y, N

51S1TC 51S1 Torque Control
1

Fig. 2. Numerical relay setting options for inverse-time overcurrent elements.

In this numerical relay, the overcurrent element reset characteristic can have a fixed delay or emulate the electromechanical relay characteristic (51S1RS = Y). The emulation of the reset characteristic permits the proper time coordination of the numerical relays with electromechanical relays. The numerical overcurrent relay also includes a torque-control equation (51S1TC) that emulates the opening or closing of the shading coil in the electromechanical relay [3].

If the shading coil circuit is open, the operating quantity to the electromechanical overcurrent relay appears to have zero magnitude, regardless of the fault current magnitude on the monitored power system. This feature is especially useful for directional control.

The previously described options improve the applicability of numerical relays, but their inverse-time characteristic functionality remains the same as that of their electromechanical relay predecessors. The adaptability of inverse-time elements (ITEs) in traditional microprocessor-based relays requires the relay to change settings groups. These relays usually have up to six settings groups with programmable equations for selecting the active group. The drawback of this approach is that settings group changes decrease relay availability because the relay disables itself for a short period of time (several cycles) while changing settings groups and resets the traveled distance of the ITEs to zero. The relay disables not only the overcurrent element but all the relay functions. Furthermore, changing settings groups can result in discrepancies among settings groups if the relay engineer does not enter the correct settings in the new settings group. The engineer must ensure that the settings of all enabled protection elements are applicable to the new conditions.

Reference [4] presents an adaptive overcurrent element that changes the characteristic of the protection element according to changes in temperature. Reference [5] studies the performance of an overcurrent element that adapts its pickup level based on the load current of a distribution feeder.

In this paper, we describe how to implement ITEs using programmable logic available in numerical relays. Some of these applications include inverse-time overvoltage and undervoltage elements and voltage-restrained overcurrent elements. We also present overcurrent elements that adapt their pickup levels according to feeder demand and perform adaptive time coordination for parallel transformer applications. We also introduce a dynamically configurable ITE that adapts to system operating conditions without the need for settings group changes.

II. IEEE C37.112 INVERSE-TIME CHARACTERISTIC EQUATIONS FOR OVERCURRENT RELAYS

IEEE C37.112 provides a mathematical model to emulate the dynamics of the induction disks of electromechanical relays (1) and define the pickup time characteristic of inverse-time overcurrent relays (2) [6] [7].

$$\int_0^{TT} \frac{1}{t(M)} \bullet dt = 1 \tag{1}$$

$$t(M) = \left(\frac{A}{M^N - 1} + B\right) \bullet TD \text{ for } M > 1$$
$$M = \frac{I_{Input}}{I_{Pickup}} \tag{2}$$

where:

A, B, and N are constants that define the relay characteristic.

TT is the operating time.

M is the relay pickup multiple.

I_{Pickup} is the relay pickup setting.

I_{Input} is the relay input current magnitude.

TD is the relay time dial setting.

Equation (3) defines the reset time characteristic of an ITE that emulates an electromechanical relay. This characteristic is implemented in numerical relays to coordinate with electromechanical relays. If this coordination is not needed, the numerical relays include other reset options, such as instantaneous or fixed delay. Notice that when M = 1, the reset time tends to infinity and there is no change in the *Travel* variable shown in Fig. 3.

$$t(M) = \frac{TR}{M^2 - 1} \bullet TD \text{ for } 0 \le M \le 1 \tag{3}$$

where:

TR is the reset time from *Travel* = 1 to *Travel* = 0 when M = 0.

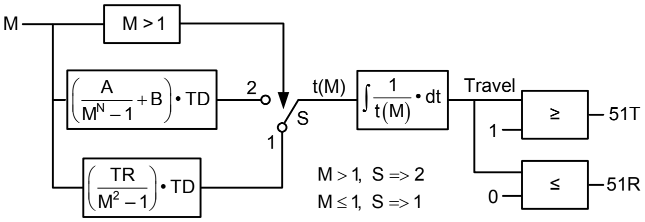


Fig. 3. Inverse-time overcurrent element implementation in a numerical relay.

Equations (1), (2), and (3) have been implemented in numerical relays using the constants shown in Table I. These constants define three inverse-time overcurrent characteristics that, when implemented in numerical relays, allow coordination with two families of historical induction relays used for decades in North America [7].

TABLE I
CONSTANTS TO OBTAIN THREE INVERSE-TIME CHARACTERISTICS ACCORDING TO IEEE C37.112

Characteristic	A	B	N	TR
Moderately inverse	0.0515	0.1140	0.02	4.85
Very inverse	19.6100	0.4910	2.00	21.6
Extremely inverse	28.2000	0.1217	2.00	29.1

The block diagram in Fig. 3 depicts an implementation of an ITE in a numerical relay. Switch S moves to Position 2 and selects (2) when the operating current is greater than the pickup threshold ($M > 1$) to calculate the operating time t(M), given the parameters M, N, A, B, and TD. Otherwise, the switch moves to Position 1 and selects (3) to calculate the operating time t(M), given the parameters M, TR, and TD. The integration of the inverse of t(M) determines the distance traveled (making the induction disk analogy). The maximum accumulated *Travel* value is 1, and the minimum accumulated *Travel* value is 0. When the distance traveled is equal to 1, the 51T bit asserts, indicating a trip condition. Likewise, when the distance traveled is equal to 0, the 51R bit asserts, indicating a reset condition.

The appendix shows an implementation example of the emulation of an overcurrent electromechanical relay with an inverse-time characteristic using programmable logic available in modern numerical relays.

III. SPECIAL APPLICATIONS OF INVERSE-TIME ELEMENTS

While the inverse-time overcurrent characteristics defined by the constants in Table I are extremely useful and allow numerical relays to coordinate with their electromechanical relay counterparts, there are applications that require different inverse-time characteristics and different operating quantities. The implementation principles and the dynamics imposed by IEEE C37.112 can still be useful in these applications. The following examples describe some of these applications:

- Inverse-time overvoltage element.
- Special inverse-time undervoltage element.
- Voltage-restrained overcurrent element.
- Overcurrent element with adaptive pickup according to load demand.
- Overcurrent element with adaptive pickup to accommodate cold load pickup (CLPU).
- Adaptive coordination in parallel transformer applications.

Numerical relays include programming capability that allows relay engineers to design ITEs according to a particular application.

Next, we show some application examples with the corresponding implementation details.

A. *Inverse-Time Overvoltage Element*

1) *Very and Extremely Inverse Characteristics*

In the first application example, we program an inverse-time overvoltage element with instantaneous reset. Typically, these elements are not available in feeder relays.

Relay engineers can program the numerical relay to implement an inverse-time overvoltage element for applications such as generator ground fault detection.

Fig. 4 shows the very inverse (red) and extremely inverse (blue) characteristics of an overvoltage element according to (4). The time to trip (TT) depends on the constants A, B, N, and TD and on the magnitude of the applied voltage. For this application, $A = 3.88$ and $B = 0.0963$ are the constants for the very inverse characteristic, $A = 5.64$ and $B = 0.02434$ are the constants for the extremely inverse characteristic, and $N = 2$ and $TD = 0.5$ apply to both characteristics.

$$t(V) = \left(\frac{A}{\left(\frac{V_{Input}}{V_{Pickup}} \right)^{N} - 1} + B \right) \bullet TD \quad (4)$$

$$t(V) = \left(\frac{3.88}{\left(\frac{VAFIM}{50} \right)^{2} - 1} + 0.0963 \right) \bullet 0.5 \quad (5)$$

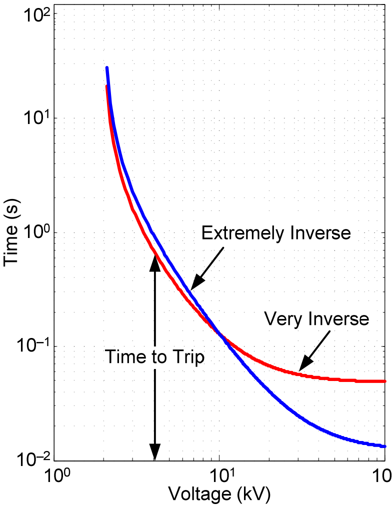


Fig. 4. Very inverse and extremely inverse characteristics of an inverse-time overvoltage element for applications such as generator ground fault detection. The time to trip (TT) depends on the applied voltage.

Fig. 5 shows the program to implement this element with the very inverse characteristic according to (5) for $M > 1$, where VAFIM is the fundamental frequency positive-sequence secondary voltage magnitude referred to Phase A. The algorithm also emulates instantaneous reset for $M \leq 1$. In this program, the protection logic variables (PSVs) are Boolean values and the protection math variables (PMVs) are real values. The algorithm runs eight times per cycle at 60 Hz.

```
# INVERSE TIME OVERVOLTAGE ELEMENT
# Settings
PMV20:=50                                                  # Pickup threshold, 59P = 50 V
PMV21:=0.5                                                 # Time dial, TD = 0.5
# Constants for very inverse characteristic
PMV22:=0.0963                                              # B constant
PMV23:=3.88                                                # A constant
PMV24:=2                                                   # N constant
# Calculate time to trip in seconds, TT
PMV25:=VAFIM/PMV20                                         # Multiple of pickup, M
PMV26:=EXP(PMV24*LN(PMV25))-1                              # Denominator, D = M^N-1
PMV27:=PMV21*(PMV23/PMV26+PMV22)                           # Time to trip, TT = (A/D + B)·TD
# Traveled distance per processing interval
# Processing interval one-eighth of a cycle = 1/480 second for 60 Hz
PMV28:=1/PMV27/480                                         # Travel increment, DeltaTravel = 1/TT/480
# If above pickup increment time counter else reset
PSV20:=PMV25>1                                             # Voltage magnitude greater than 59P, M > 1
PMV29:=(PMV28+PMV29)*PSV20                                 # Total travel
# Trip
PSV22:=PMV29>=1                                            # Trip
#************************************************************************
```

Fig. 5. Program to implement an overvoltage element with the very inverse time characteristic using the programming capability of the relay.

```
# INVERSE TIME UNDERVOLTAGE ELEMENT
# ENTER THE CONSTANTS HERE
PMV01:= 0.18             # Time dial, TD
PMV02:= 0.300            # A
PMV03:= 0.017            # N
PMV05:= 11.111           # B
PMV06:= 0.150            # Pickup setting in per unit. The voltage drop has to be greater than 15% for the element
                           to operate
PMV07:= 63.5085          # System nominal line to neutral secondary voltage in V, (110/sqrt(3))
PMV08:= 0.2 * PMV07      # Minimum voltage above which line is considered to be live (20% of nominal in this case)
PMV09:= 400              # Relay processing intervals in 1 second (programmable logic is run 8 times a
                           power system cycle or 400 times in 1 second at 50 Hz)
# EQUATION
PMV10:= (PMV07-V1FIM)/(PMV07*PMV06)          # Multiple of pickup, M
PMV11:= EXP(PMV03*LN(PMV10))-1               # Denominator, D = M^N-1
PMV13:= PMV01*(PMV02/PMV11+PMV05)            # Time to trip, TT = (A/D + B)·TD
# Voltage difference above pickup, line energized and no loss-of-potential condition
PSV01:= (PMV10>1)AND(V1M>PMV08) AND NOT LOP
PMV14:= 1/PMV13/PMV09                        # Incremental change in 1 processing interval
# Integration
PMV15:= (PMV14+PMV15)*PSV01                  # Total travel
PSV03:= PMV15 >= 1                           # Trip
```

Fig. 6. The inverse-time undervoltage element used by Eskom to avoid system voltage collapse.

2) *IEC Standard Inverse Characteristic*

To implement the IEC standard inverse characteristic, we only need to modify the A, B, and N constants in (2) [8]. For this application, A = 0.14, B = 0, and N = 0.02. Equation (6) defines the desired characteristic. The program to implement this element is the same as in Fig. 5 except for the modified constants A, B, and N.

$$t(V) = \left(\frac{0.14}{\left(\frac{V_{\text{Input}}}{V_{\text{Pickup}}} \right)^{0.02} - 1} \right) \bullet \text{TD} \tag{6}$$

B. *Special Inverse-Time Undervoltage Element*

Eskom, the South African national electrical utility, required an undervoltage element with a special inverse-time characteristic for shedding load when system voltage collapse is imminent that speeds up as the voltage decreases [9]. Eskom took advantage of the programmability available in numerical relays to implement the inverse-time undervoltage element according to (7). In this paper, we modified the original equation to express it in the form of (2). Equation (8) shows the A, B, and N coefficients that Eskom used for their load-shedding application.

$$t(V) = \left(\frac{A}{\left(\frac{V_{\text{Nominal}} - V_{\text{Input}}}{V_{\text{Pickup}}} \right)^{N} - 1} + B \right) \bullet \text{TD} \tag{7}$$

$$t(V) = \left(\frac{0.3}{\left(\frac{V_{\text{Nominal}} - V_{\text{Input}}}{V_{\text{Pickup}}} \right)^{0.017} - 1} + 11.111 \right) \bullet 0.18 \tag{8}$$

Fig. 6 shows the program to implement this undervoltage element, including voltage magnitude and loss-of-potential supervision. V1FIM is the input signal. In this case, the algorithm runs eight times per cycle at 50 Hz.

```
# VOLTAGE RESTRAINED OVERCURRENT ELEMENT
PMV01 := 63.51                                             # Nominal voltage
PMV02 := 0.5+V1FIM/PMV01                                   # Pickup control
PMV03 := 0.5+V1FIM/PMV01-3V2FIM/(3*PMV01)                  # Time dial control
PMV04 := LIAFIM/PMV02                                      # Multiple of pickup, M
PSV01 := PMV04>=1.0                                        # M > Pickup
PMV05 := EXP(0.02*LN(PMV04))-1                             # Denominator, D = M^N-1
PMV06 := PMV03*(0.14/PMV05)                                # Time to trip, TT = TD · (A/D)
# This logic runs 8 times a power system cycle or 400 times in 1 second at 50 Hz
PMV07 := 1/PMV06/400                                       # Travel increment, DeltaTravel = 1/TT/400
PMV08 := PMV08+PMV07*PSV01                                 # Total travel
PSV02 := PMV08>=1                                          # Trip
```

Fig. 7. Voltage-restrained overcurrent element that uses positive- and negative-sequence voltages to control pickup and time dial.

C. Voltage-Restrained Overcurrent Element

The next example corresponds to a voltage-restrained overcurrent element that was developed to replace old electromechanical relays with a special characteristic. The requirement was to add positive- and negative-sequence voltages to control the relay pickup and time dial according to (9), where I_A is the Phase A current magnitude. As positive-sequence voltage V_1 decreases for a fault condition, the voltage-restrained overcurrent element becomes more sensitive (has a lower pickup) and operates faster (has a lower time dial and operates on the faster portion of inverse-time overcurrent characteristic due to the increased multiple of pickup). Increasing negative-sequence voltage V_2 during a fault also contributes to faster operation. This characteristic can be used for generator protection because, in this application, the fault current level can be lower than the generator full load current. Fig. 7 shows the program to implement this element.

$$t\left(I,V_1,V_2\right)=\frac{0.14}{\left(\dfrac{\left|I_A\right|}{0.5+\dfrac{\left|V_1\right|}{V_{\text{Nominal}}}}\right)^{0.02}-1}\bullet\left(0.5+\frac{V_1-V_2}{V_{\text{Nominal}}}\right) \qquad (9)$$

D. Overcurrent Element With Adaptive Pickup According to Load Demand

Adaptability of the pickup level adds flexibility to the traditional inverse-time overcurrent element. For example, the pickup level can adapt to the feeder load demand. With this adaptability, the pickup value is low for light load conditions but increases as the load increases. This approach provides adequate sensitivity for different load conditions; the element is more sensitive for light load conditions than for heavy load conditions. Reference [5] provides time coordination examples for this adaptive element. Fig. 8 depicts the adaptive characteristic according to (10).

$$t\left(I\right)=\left(\frac{3.88}{\left(\dfrac{I_{\text{Input}}}{I_{\text{Demand}}+0.5}\right)^2-1}+0.0963\right)\bullet 0.5 \qquad (10)$$

In this equation, I_{Input} corresponds to the maximum magnitude of the phase currents and I_{Demand} corresponds to the maximum demand of the phase currents. I_{Demand} is traditionally a slower-responding current value (e.g., thermal demand) that follows general load trends and is less influenced by instantaneous current changes. The 0.5 factor in the denominator is the minimum allowable pickup value for this application.

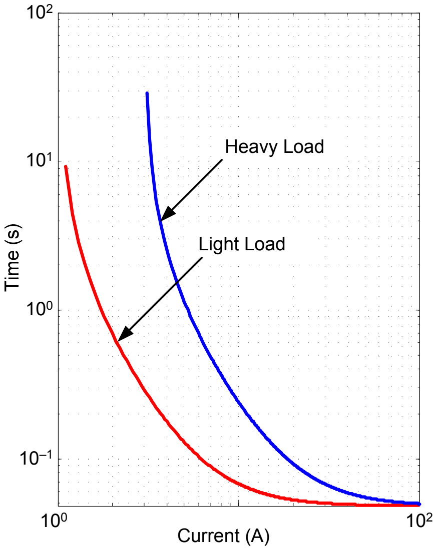


Fig. 8. Operating characteristic of the overcurrent element with a pickup that adapts to load conditions.

E. Overcurrent Element With Adaptive Pickup to Accommodate Cold Load Pickup

Cold load pickup (CLPU) is the increase in load current when re-energizing a circuit after an extended outage, primarily resulting from the loss of load diversity. One challenge when dealing with time-overcurrent (TOC) curves during CLPU conditions is to avoid tripping without losing coordination with other inverse-time overcurrent relays. Fig. 9 shows two inverse-time curves that are set in standard fashion so that Relay 1 (TOC Curve 1) operates faster (and is set more sensitive) than Relay 2 (TOC Curve 2) for all faults. Fig. 10 shows the case where the pickup setting of Relay 1 is increased to 51P3 to avoid tripping under cold load conditions. This setting change effectively shifts TOC Curve 1 to the right. However, increasing the pickup setting of TOC Curve 1 (and the resulting shift of TOC Curve 1) results in the loss of coordination between Relay 1 and Relay 2 and must be avoided. Fig. 11 shows a better method to avoid tripping under CLPU conditions where the two curves remain properly coordinated, but Relay 1 only responds to current values that exceed the 50P3 setting.

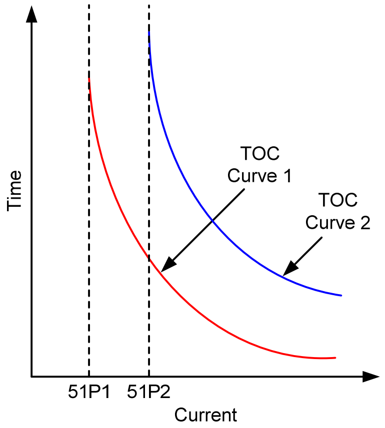


Fig. 9. Standard coordination.

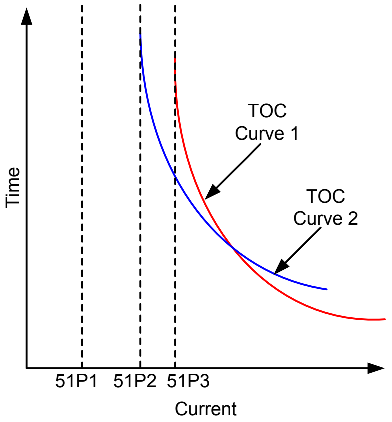


Fig. 10. Loss of coordination (TOC Curve 1 shifted to the right for CLPU).

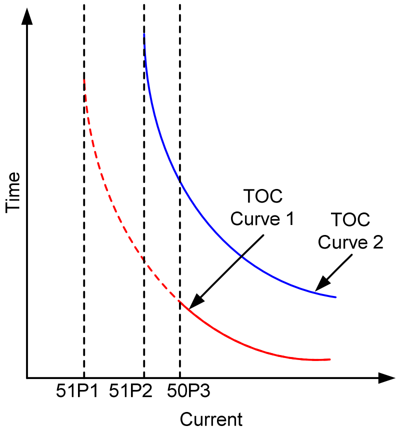


Fig. 11. Correct CLPU coordination.

The implementation of the solution for TOC Curve 1 shown in Fig. 11 involves inserting the output of a separate instantaneous overcurrent element (with pickup 50P3) in the torque-control equation of TOC Curve 1 to enable the integration of the overcurrent element. With this arrangement, TOC Curve 1 is active only when the 50 element picks up (for current above pickup setting 50P3).

The temporary engagement of this arrangement (TOC Curve 1 effectively operating on the higher 50P3 pickup setting) results from qualifying a loss of load diversity (e.g., the breaker at Relay 1 location has been open for longer than a loss of load diversity time). The portion of TOC Curve 1 below the 50P3 pickup setting is effectively inoperative until normal operating conditions are restored.

In Fig. 11, TOC Curve 2 is not modified from the preceding Fig. 9 and Fig. 10. In fact, TOC Curve 2 is shown to be more sensitive than TOC Curve 1 (50P3 > 51P2) in Fig. 11. TOC Curve 2 can also be modified, if deemed necessary, to avoid tripping under cold load conditions (and avoid temporarily overreaching TOC Curve 1). This would be most easily facilitated if there was communications of some sort between Relay 1 and Relay 2, wherein Relay 1 operating in the CLPU mode (due to its breaker being open for a loss of load diversity time) could signal Relay 2.

F. Adaptive Coordination in Parallel Transformer Applications

Fig. 12 shows the inverse-time overcurrent protection (ANSI 51) for a typical distribution substation with two transformers in parallel. The overcurrent elements 51T1 and 51T2 at the transformer location provide backup transformer protection. These overcurrent elements must coordinate with the overcurrent elements located at the feeders. When one of the transformers does not supply current for feeder faults (e.g., T2 does not supply fault current when Breaker 4 is open), the time coordination of these relays is affected. Overcurrent element adaptability is desired for optimum coordination for all operating conditions. A typical solution is to use different settings groups. Using different settings groups optimizes coordination because each settings group has the appropriate overcurrent element settings for the corresponding substation configuration.

We can also design an element with a time dial setting that is a function of how many transformers are in service using the previously described relay programmability. In the next section, we introduce an overcurrent element with a programmable time dial setting and show how to address proper coordination for this application without changing the settings group.

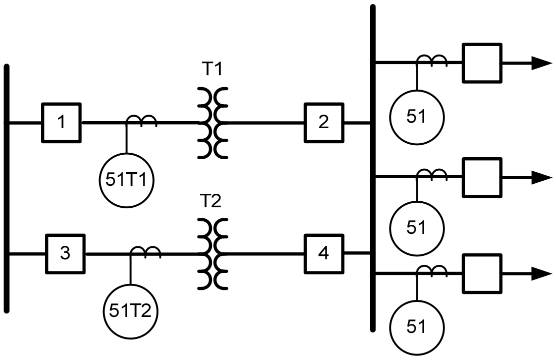


Fig. 12. Transformer and feeder overcurrent protection must have proper time coordination for all operating conditions. Transformer and feeder overcurrent protection coordination is affected when one of the transformers is out of service.

G. Dynamically Configurable Inverse-Time Element

The previously described solutions work for each of the described applications; however, these solutions require programming and, in some cases, can reduce relay availability. A solution that does not require the relay engineer to write a specific program is more desirable. As we mentioned previously, settings group changes disable the relay for a fixed amount of time, reducing relay availability. Additionally, multiple settings groups increase the complexity of creating, maintaining, and handling relay settings files. In multifunction numerical relays, all the protection elements are disabled while the relay replaces its settings. A dynamically configurable ITE provides a better solution for addressing multiple applications. This ITE replaces the fixed and settable parameters with variables that are updated dynamically, based on equations that relay engineers program. For example, rather than having a time dial setting that has a fixed value and only changes when the relay engineer enters a new setting value, the new element has a time dial variable that is calculated dynamically every processing interval (e.g., eight times per power system cycle) based on a user-customized equation. Similarly, the input current magnitude (I_{Input}) can be replaced with a variable that is the result of a calculation based on any of the relay-measured values (e.g., current, voltage, frequency, power, and so on).

To summarize, in existing relays, TD, A, B, N, TR, and the operating quantity OQ are fixed once the relay is set, and the operating time is solely a function of the multiple of pickup M of the applied current for a given group setting. In the dynamically configurable ITE, the operating time is a function of the following parameters:

- Variable operating quantity OQ_v
- Variable pickup PU_v
- Variable time dial TD_v
- Programmable constants A_p, B_p, and N_p
- Programmable reset time TR_p

The equations for the new ITE are:

$$t_v = \left(\frac{A_p}{\left(\frac{OQ_v}{PU_v} \right)^{N_p} - 1} + B_p \right) \bullet TD_v \text{ for } \frac{OQ_v}{PU_v} > 1 \tag{11}$$

$$t_v = \frac{TR_p}{\left(\frac{OQ_v}{PU_v} \right)^{2} - 1} \text{ for } 0 \le \frac{OQ_v}{PU_v} \le 1 \tag{12}$$

where:

TR_p is the reset time at $\frac{OQ_v}{PU_v} = 0$.

The relay calculates OQ_v, PU_v, and TD_v every processing interval, before calculating t_v according to (11) and (12), as shown in Fig. 13. 51T indicates a trip condition, and 51R indicates a reset condition.

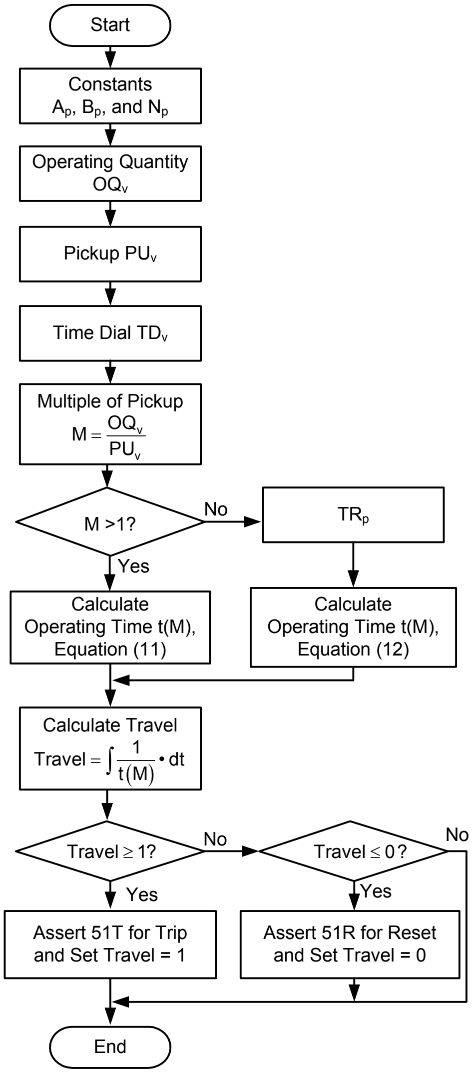


Fig. 13. Dynamically configurable inverse-time element calculation sequence.

IV. APPLICATION EXAMPLES

Now, we revisit each of the previous applications and provide the corresponding settings for the dynamically configurable relay.

A. Inverse-Time Overvoltage Element

This application implements a traditional very inverse time overvoltage element. The ITE operating quantity (Phase A voltage magnitude), pickup, time dial, A constant, B constant, and N constant settings are shown in Fig. 14.

```
OQ:=VAFIM
PU:=50
TD:=0.5
A:=3.88
B:=0.0963
N:=2
```

Fig. 14. Settings for the very inverse time overvoltage element.

B. IEC Standard Inverse-Time Overvoltage Element

This application implements the traditional IEC standard inverse-time overvoltage element. The ITE operating quantity, pickup, time dial, A constant, B constant, and N constant settings are shown in Fig. 15.

```
OQ:= VAFIM
PU:=50
TD:=1
A:=0.14
B:=0
N:=0.02
```

Fig. 15. Settings for the IEC standard inverse-time overvoltage element.

C. Special Inverse-Time Undervoltage Element

In this application, the multiple of pickup M is a function of the difference between the nominal voltage and the input voltage. The ITE operating quantity, pickup, time dial, A constant, B constant, and N constant settings are shown in Fig. 16.

```
OQ:=63.51-V1FIM
PU:=0.15*63.51
TD:=0.18
A:=0.3
B:=11.111
N:=0.017
```

Fig. 16. Settings for the special inverse-time undervoltage element.

D. Voltage-Restrained Overcurrent Element

In this application, the multiple of pickup M is a function of the positive-sequence voltage and the time dial is a function of the difference between the positive-sequence voltage and the negative-sequence voltage. The ITE operating quantity, pickup, time dial, A constant, B constant, and N constant settings are shown in Fig. 17.

```
OQ:=LIAFM
PU:=0.5+V1FIM/63.51
TD:=0.5+V1FIM/63.51-3V2FIM/(3*63.51)
A:=0.14
B:=0
N:=0.02
```

Fig. 17. Settings for the voltage-restrained overcurrent element.

E. Overcurrent Element With Adaptive Pickup According to Load Demand

In this application, the pickup PU is a function of the maximum demand of the phase currents. The ITE operating quantity, pickup, time dial, A constant, B constant, and N constant settings are shown in Fig. 18.

```
OQ:=<Maximum phase current magnitude>
PU:=<Maximum phase demand current> + 0.5
TD:=0.5
A:=3.88
B:=0.0963
N:=2
```

Fig. 18. Settings for the adaptive pickup overcurrent element according to load demand.

F. Addressing Cold Load Pickup With the Dynamically Configurable ITE by Reducing the Input Current

The settings in this section describe the case where the operating quantity is the maximum of the three phase current magnitudes (see Fig. 19). PSV01 represents the output of separate logic that identifies CLPU conditions (i.e., PSV01 is logical 1 when CLPU conditions exist and logical 0 when no CLPU conditions exist). PSV02 is equivalent to the 50P3 setting shown in Fig. 11 (i.e., during CLPU conditions, the 51 element becomes active only when current is sufficient to assert PSV02). The operating quantity equation OQ includes three mutually exclusive terms to identify the following three conditions:

- Term 1 for no CLPU conditions (normal load).
- Term 2 for CLPU conditions without a fault.
- Term 3 for CLPU conditions with a fault.

Term 1 is active when no CLPU conditions exist (normal load), making the full value of the current available to the relay.

```
PSV01:=<Cold load pickup conditions>
PMV01:=<Maximum phase current magnitude>
PSV02:= PMV01 < 8
OQ:= (NOT PSV01)*PMV01 + 0.5*PSV01*PSV02*PMV01 +
     PSV01*(NOT PSV02)*PMV01
PU:= 6
TD:= 0.2
A:= 0.14
B:= 0
N:= 0.02
```

Fig. 19. Settings for CLPU applications.

When Term 2 is active, the input current is multiplied by 0.5 to reduce the operating quantity. Reducing the operating quantity prevents the 51 element from picking up for the increased load current during CLPU conditions but does not shift the curve to the right. If, however, a fault occurs during the CLPU condition, the full value of the current must be made available to the relay to coordinate with other devices. Term 3 is active when a fault occurs during CLPU conditions.

In this example, we assume the normal secondary load current is 4 A secondary but increases to as much as 8 A secondary during CLPU conditions. When PSV01 asserts (indicating CLPU conditions), PSV02 checks if the secondary current is below 8 A (indicating CLPU conditions without a fault). If the secondary current exceeds 8 A during CLPU conditions, the scaling factor is removed to feed the full current to the overcurrent element algorithm.

Fig. 20, Fig. 21, and Fig. 22 show the conditions that the three terms address. In Fig. 20, normal load current of 4 A secondary flows and there are no CLPU conditions (Term 1 is active). In Fig. 21, CLPU conditions exist without a system fault (Term 2 is active). Cold load current of 7.8 A secondary flows, but the scaling factor of 0.5 reduces this value from 7.8 A to 3.9 A. Because 3.9 A is below the

51P1 pickup setting of 6 A, the 51 element does not pick up. Fig. 22 shows the case when a fault occurs during CLPU conditions (8.5 A > 8 A). When PSV02 deasserts (with PSV01 still asserted), Term 3 of the OQ equation is active. When Term 3 is active, the current is no longer scaled by 0.5 and the full current (8.5 A) is applied to the 51 element, causing the element to pick up. Because TOC Curve 1 is not shifted to the right, proper coordination is maintained.

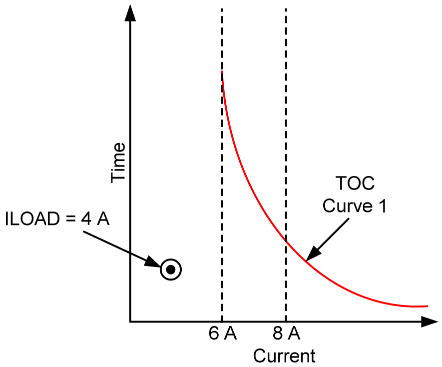


Fig. 20. Normal load (no CLPU conditions).

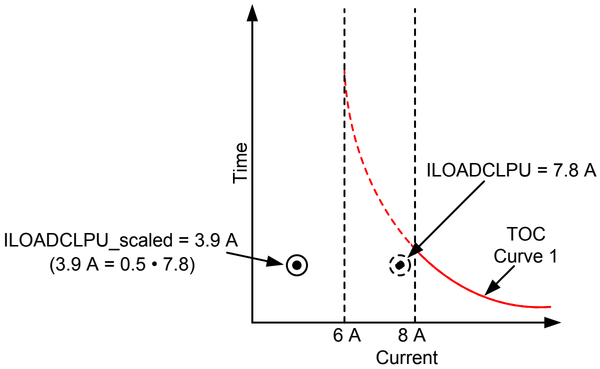


Fig. 21. CLPU conditions without fault.

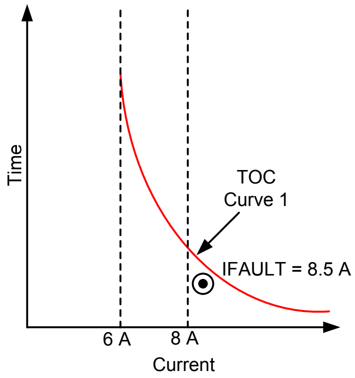


Fig. 22. CLPU conditions with fault.

G. Adaptive Coordination in Parallel Transformer Applications

In parallel transformer coordination applications, the time dial is a function of the number of transformers that are in service. Assuming that the parallel transformers in Fig. 12 have approximately the same impedance, we can make the following observations:

- When both transformers are in service (electrically in parallel), feeder fault current is highest and feeder relays trip faster on their inverse-time overcurrent characteristics. But, current splits between paralleled transformers, and thus each transformer relay sees about half the fault current that the feeder relay sees.
- When only one transformer is in service, feeder fault current is lower and feeder relays trip more slowly on their inverse-time overcurrent characteristics (as compared with the paralleled transformer scenario). But, current is not splitting between paralleled transformers (only one transformer is in service), and thus the one transformer relay sees the same fault current that the feeder relay sees.

If the system impedance (to the source side of the transformers) is low (compared with the transformer impedances), then for either scenario, a given transformer relay sees about the same fault current magnitude (for faults right in front of a feeder relay), but the feeder relay (for the paralleled transformer scenario) sees about double the fault current of the scenario with one transformer in service. Thus, the time dial of a transformer relay can be set lower (faster) for the paralleled transformer scenario. Example transformer relay settings (applicable to both transformer relays) for proper coordination are as follows:

- TD_v is 0.4 when only Transformer 1 (T1) is in service.
- TD_v is 0.4 when only Transformer 2 (T2) is in service.
- TD_v is 0.2 when both transformers are in service.

For this application, A_p, B_p, N_p, and PU_v are constants. A_p, B_p, and N_p define the very inverse time characteristic. OQ_v is the maximum of the phase current magnitudes. The value of TD_v depends on the status of the inputs IN101 and IN102. These inputs indicate when the transformers are in service; the low-side and high-side breakers of the corresponding transformer are closed (e.g., IN101 asserts when Breakers 1 and 2 are closed). The settings for the phase overcurrent element of T1 are shown in Fig. 23.

```
OQ:=<Maximum phase current magnitude>
A:=19.61
B:=0.491
N:=2
PU:=3
TD:=0.4*(IN101 AND NOT IN102) + 0.2*(IN101 AND IN102)
```

Fig. 23. Settings for the adaptive phase overcurrent element of T1.

The settings for the phase overcurrent element of T2 are shown in Fig. 24.

```
OQ:=<Maximum phase current magnitude>
A:=19.61
B:=0.491
N:=2
PU:=3
TD:=0.4*(IN102 AND NOT IN101) + 0.2*(IN101 AND IN102)
```

Fig. 24. Settings for the adaptive phase overcurrent element of T2.

V. CONCLUSION

Electromechanical overcurrent elements have proven operating characteristics for a number of applications, but they lack adaptability.

Traditional numerical relays provide adaptability using settings groups. Settings group changes reduce relay availability not only for the inverse-time overcurrent element but all relay functions.

Advanced programmability allows relay engineers to implement the required characteristic for special applications, such as load shedding and adaptive coordination, but requires detailed analysis.

The dynamically configurable inverse-time element presented in this paper provides relay adaptability without disabling the relay and is suitable for multiple applications without the need for extensive programming.

VI. APPENDIX

Fig. 25 shows the program implemented in a numerical relay to emulate the moderately inverse time characteristic of an overcurrent electromechanical relay according to IEEE C37.112. This program uses the secondary ground current (LIGFIM) as the operating quantity.

Fig. 26 shows the simulation results of the emulation of the disk of an electromechanical relay for a pulse input (operating quantity). Fig. 26 shows the operating quantity, the travel value, and the trip 51T and reset 51R bits. In this example, PU := 1, TD := 5, A := 0.0104, B := 0.0226, N := 0.02, and TR := 1.08. The time reference is seconds.

```
# INVERSE TIME OVERCURRENT ELEMENT
# Settings
PMV20:=1                                                   # Pickup threshold, 51G=2 A
PMV21:=5                                                   # Time dial, TD=5
# Constants for very inverse characteristic
PMV22:=0.00226                                             # B constant
PMV23:=0.0104                                              # A constant
PMV24:=0.02                                                # N constant
PMV25:=1.08                                               # TR constant
# Calculate time to trip in seconds, TT
PMV26:=LIGFIM/PMV20                                        # Multiple of pickup, M
PMV27:=EXP(PMV24*LN(PMV26))-1                              # Trip denominator, D = M^N-1
PMV28:=PMV21*(PMV23/PMV27+PMV22)                           # Time to trip, TT = (A/D + B)·TD
# Calculate time to reset in seconds, TTR
PMV29:=PMV21*(PMV25/((PMV26*PMV26)-1))                     # Time to reset, TTR = (TR/(1 – M^2))·TD
PSV20:=PMV26>1                                             # M > 1
# M > 1, true use TT, false use TTR
PMV32:=PSV20*PMV28 + (NOT PSV20)*PMV29
# Traveled distance per processing interval
# Processing interval one-eighth of a cycle = 1/480 second for 60 Hz
PMV30:=1/PMV32/480                                         # Travel increment, DeltaTravel = 1/TT/480 or 1/TTR/480
PMV31:=PMV30+PMV31                                         # Total travel
# Trip
PSV22:=PMV31>=1                                            # TRIP if travel >= 1
# Reset
PSV23:=PMV31<=0                                            # RESET if travel < 0
PMV31:=PSV22 + (NOT PSV22)*PMV31                           # Limit maximum travel to 1
PMV31:=(NOT PSV23)*PMV31                                   # Limit minimum travel to 0
```

Fig. 25. Program to emulate the inverse-time characteristic of an overcurrent electromechanical relay.

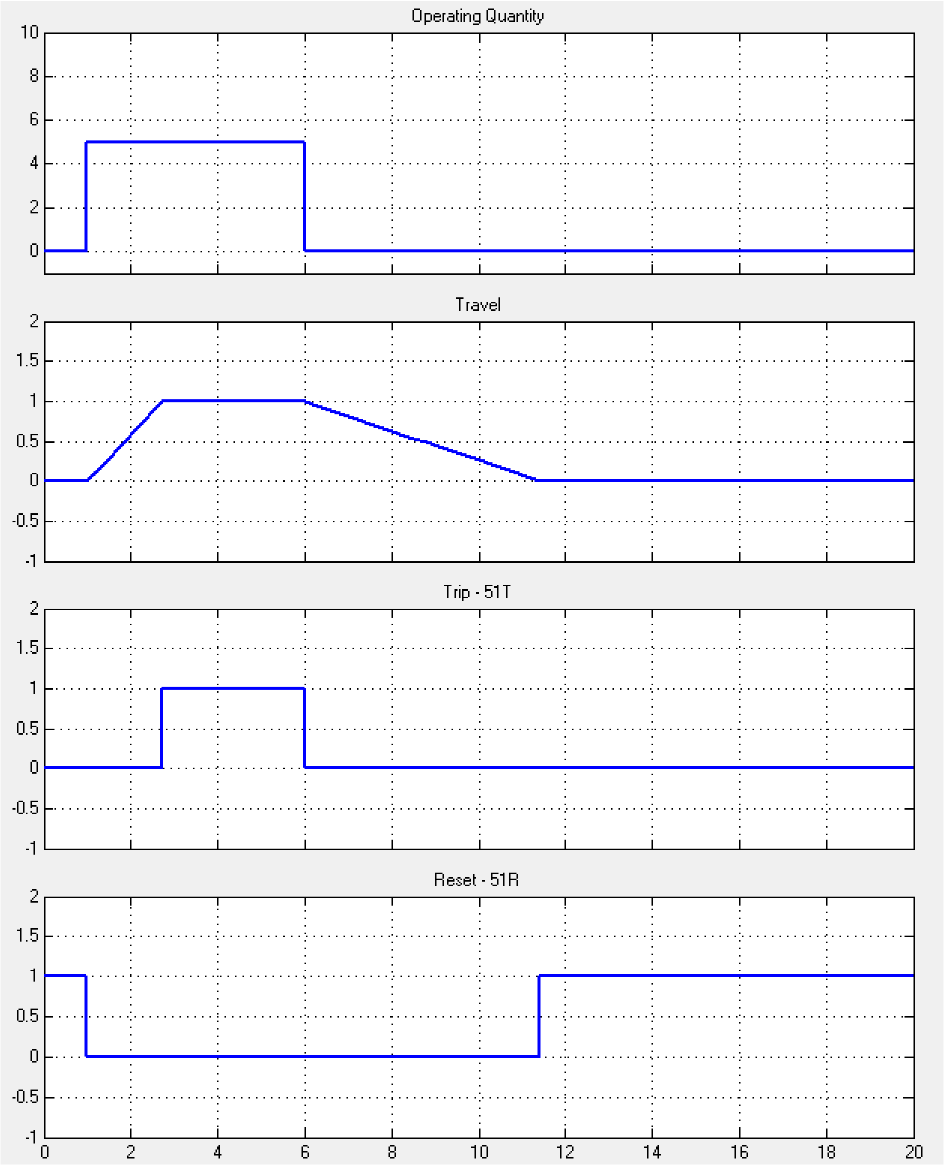


Fig. 26. Emulation of the dynamics of the disk of an electromechanical relay with an inverse-time characteristic (time units are seconds).

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

Armando Guzmán received his BSEE with honors from Guadalajara Autonomous University (UAG), Mexico. He received a diploma in fiber-optics engineering from Monterrey Institute of Technology and Advanced Studies (ITESM), Mexico, and his MSEE and MECE from the University of Idaho, USA. He served as regional supervisor of the protection department in the Western Transmission Region of the Federal Electricity Commission (the Mexican electrical utility company) in Guadalajara, Mexico, for 13 years. He lectured at UAG and the University of Idaho in power system protection and power system stability. Since 1993, he has been with Schweitzer Engineering Laboratories, Inc., in Pullman, Washington, where he is a fellow research engineer. He holds numerous patents in power system protection and metering. He is a senior member of IEEE.

Luther (Scott) Anderson earned his bachelor of science in electrical engineering (1986) and master of science in electrical engineering (1988) from Gonzaga University, USA. After graduating, he held a position as a research associate with the university until joining Schweitzer Engineering Laboratories, Inc. (SEL) in 1989. He joined SEL as a development engineer and currently holds the position of fellow engineer. He holds over a dozen patents related to power system protection.

Casper Labuschagne earned his diploma (1981) and master's diploma (1991) in electrical engineering from Vaal University of Technology, South Africa, and is registered as a professional technologist with ECSA, the Engineering Council of South Africa. After gaining 20 years of experience with the South African utility Eskom, where he served as senior advisor in the protection design department, he began work at Schweitzer Engineering Laboratories, Inc. in 1999 as a product engineer. He transferred in 2003 to the research and development division, where he held the position of senior power engineer. In 2009, he was promoted to transmission engineering development manager. His responsibilities include the specification, design, testing, and support of protection and control devices. Casper holds one United States patent and has three more patents pending. He has written and coauthored several technical papers in the areas of protection and control.

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