UDC 621.3 https://doi.org/10.20998/2074-272X.2022.3.10

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Modelling and performance testing of a digital over-current relay enhanced designed model

Introduction. *The over-current relay is widely used to protect distribution and transmission electrical systems against excessive currents occurring due to short circuit or overload conditions. Many works have been carried out in the field of models simulation design of digital over-current relays in the literature, but unfortunately many of them are more complex design models, have very slow execution time and only work in simple faults cases.* ***Purpose.*** *The purpose of this work is to present the performance of a modified and improved model of a digital over-current relay designed in Simulink/MATLAB environment with more simplified design, faster execution time, and able to operate under more complex fault conditions.* ***Methodology.*** *Before starting tests, modelling of over-current relay is presented in details, of which the basic logics of the proposed model to implement inverse and instantaneous characteristics are well explained. Afterwards, various tests are carried out for the performance analysis of the enhanced designed relay model in terms of: operating speed for eliminating faults that has arisen, ability to distinguish between a fault current and load starting current, capacity distinguish between real and temporary fault currents, the way to manage variable faults over time, and the degree of harmony between primary protection relay and back-up protection relay.* ***Originality.*** *The originality of our proposed work consists in the development and improvement of a digital over-current relay model designed in Simulink/MATLAB environment in such way that it becomes able to operate under new harsh test conditions. This developed designed model is implemented and applied in a 400V radial distribution power system with a load that causes a starting current.* ***Results.*** *The obtained values of simulation are compared with the theoretically calculated values and known existing models. The obtained results after various tests validate the good performance of our enhanced designed model.* References 18, tables 3, figures 18.

Key words: **digital over-current relay, inverse and instantaneous characteristics, load starting current, primary protection, back-up protection.**

Вступ. *Реле надструму широко використовується для захисту електричних систем розподілу та передачі від надмірних струмів, що виникають внаслідок короткого замикання або перевантаження. У літературі було виконано багато робіт у галузі моделювання цифрового реле надструму, але, на жаль, багато з них є більш складними моделями конструкції, з дуже повільним часом виконання, і вони працюють лише у випадках простих несправностей.* ***Метою*** *даної роботи є представлення продуктивності модифікованої та вдосконаленої моделі цифрового реле надструму, розробленої в середовищі Simulink/MATLAB, з більш спрощеною конструкцією, швидшим часом виконання та здатністю працювати в більш складних умовах несправностей.* ***Методологія***. *Перед початком випробувань детально представлено моделювання реле надструму, з якої добре пояснено основні логіки запропонованої моделі для реалізації зворотних і миттєвих характеристик. Після цього проводяться різноманітні випробування для аналізу продуктивності вдосконаленої розробленої моделі реле з точки зору: швидкості роботи для усунення виниклих несправностей, здатності розрізняти струм несправності та пусковий струм навантаження, можливості розрізняти реальні та тимчасові струми несправності, спосіб управління змінними несправностями в часі та ступінь відповідності реле первинного захисту та реле резервного захисту.* ***Оригінальність*** *запропонованої нами роботи полягає в розробці та вдосконаленні моделі цифрового реле надструму, розробленої в середовищі Simulink/MATLAB таким чином, щоб вона стала здатною працювати в нових жорстких умовах випробувань. Ця розроблена модель реалізована та застосована у радіальної розподільчої енергосистемі 400 В з навантаженням, що викликає пусковий струм.* ***Результати***. *Отримані результати моделювання порівнюються з теоретично розрахованими значеннями. Результати, отримані після різноманітних випробувань, підтверджують хорошу продуктивність нашої покращеної розробленої моделі.* Бібл. 18, табл. 3, рис. 18.

Ключові слова: **цифрове реле надструму, зворотні та миттєві характеристики, пусковий струм навантаження, первинний захист, резервний захист.**

Introduction. According to the International Electrotechnical Commission (IEC), the protection of electrical networks is the set of monitoring devices intended for the detection of faults and abnormal situations such as short-circuits, variation in voltage, machine faults, etc. and ensuring the stability of an electrical network with the aim of ensuring an uninterrupted power supply and avoids the destruction of expensive equipment. Generally, this protection is provided by relays which are devices that continuously compare electrical variables such as: current, voltage, frequency, etc. with predetermined values, and when the monitored value exceeds the threshold they automatically give opening orders to its associated circuit breakers [1]. Many types of relays have been employed by electric power utilities such as over- and under-voltage, over- and under-frequency and over-current relays (OCR), etc. However, this latter is the most commonly used, and they can be applied in any zone in the power system for both primary and back-up protection [2, 3].

Currently, in view of growing demand for precise, selective and reliable OCR due to the increasing complexity and capacity of power systems on the one hand, and the development of logic, communication, information storage and processing capacities of modern microprocessors on the other hand, traditional electromechanical and solid state relays are replaced by digital relays which are faster, more compact, more reliable in operation, ensuring minimal power outage in case of fault and has advantages in terms of data logging and adaptive functionality, etc. [2, 4, 5].

The goal of the paper is to present the performance of a modified and improved model of a digital over-current relay designed in Simulink/MATLAB environment for some new cases.

The performance of the proposed digital OCR is sought and tested on a line between two buses of a 400 V radial distribution power system where the objectives of this work are summarized in testing the following characteristics: operating speed, ability to distinguish between a fault current and load pickup current, capacity distinguish between real and temporary fault currents, the way to manage variable faults, degree of harmony between primary protection and back-up protection.

The remainder of the paper is organized as follows. First, the current-time characteristic of an OCR is explained. Then, the OCR modelling is presented on details. Next, the enhanced designed digital OCR is implemented in a 400 V radial network to carry out a different test. Finally, we conclude our paper with some remarks, and a prospect.

Current-time characteristic of an OCR. OCR has the function of detecting single-phase, two-phase or three-phase over-currents. The protection can be time-delayed and will only be activated if one, two or three phases of the monitored current exceed the specified setting threshold for a period at least equal to the selected time delay also called «operating time», and is calculated based on the protection algorithm incorporated in the relay microprocessor [1, 6]. According to this delay the current-time characteristic of a typical OCR shown in Fig. 1 can be one of two as follows.

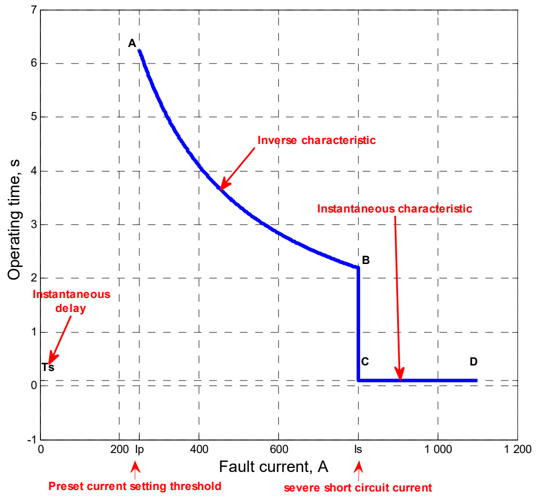

Fig. 1. Current-time characteristic of an OCR

Inverse characteristic. This characteristic means that the operating time of the relay is inversely proportional to the fault current i.e. the higher the current, the shorter the operating time (see curve AB in Fig. 1). This characteristic is used for the protection of electrical installations against excessive fault currents below severe fault levels but able enough that they will damage such installations if maintained for a certain period [2, 6, 7].

On the other hand, inverse characteristic of a relay may have to be modified depending on the characteristics and the required operating time of other protection devices used in the electrical network. This is why IEC defines several types of inverse delay protection which are distinguished by the gradient of their curves: Standard Inverse (SI), Very Inverse (VI), Extremely Inverse (EI) and Long Inverse (LI) [7, 8].

The operating time in inverse characteristic of OCR (noted *T*) is depicted as per IEEE standard by the following general expression [3]:

$$T = \frac{K}{\left(I_f / I_p\right)^n - 1}, \qquad (1)$$

where *K* is the constant for relay characteristic; I_f is the actual fault current; I_p is the pre-set current setting threshold; *n* is the constant representing inverse-time type.

By selecting suitable values of *n* and *K* any desired relay curve can be obtained. Equation (1) can be modified in terms of actual faults as:

$$T = \frac{K}{I_f^n}, \qquad (2)$$

with $I_p < I_f < I_s$, where I_s is the short circuit current.

It is important to note that the fault current I_f detected by the relay is implicitly assumed constant. Otherwise, during a transient or a variable fault current this will lead to an inaccurate operating time by the relay.

Instantaneous characteristic. This characteristic (shown in curve BCD of Fig. 1) means that the relay operates in the fastest possible time i.e. as soon as the fault current becomes greater than the value of the short circuit current I_s. In this case the operating time is only of the order of a few milliseconds:

$$T = T_s, \qquad (3)$$

with $I_f > I_s$, where T_s is the instantaneous operating time.

Relays with instantaneous characteristic are graded by a time interval of Definite Time (DT sec) between them, e.g. the relay R_3 imposed at the end of the network of Fig. 2 is set to operate as fast as possible with an instantaneous operating time Ts_3, while its upstream relay R_2 is set to a higher independent operating time ($Ts_2 = Ts_3 + DT$). The instantaneous operating times of the remaining relays increase sequentially at DT sec on each section, moving back up to the source [9].

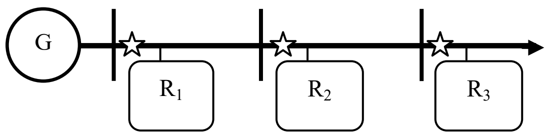

Fig. 2. Graded relays in radial network [9]

Modelling of OCR. Digital relays also called «programmable relays» based on microprocessors are of great importance in the protection field, especially in industry in view of their ability to protect against various faults (over-currents, over-voltages, thermal overloads, etc.) [10, 11]. The general functional diagram of a microprocessor-based OCR implemented in a power system is shown in Fig. 3.

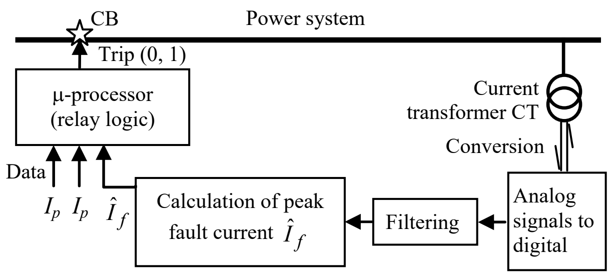

Fig. 3. General block diagram of a microprocessor-based OCR implemented in a power system

The digital relay operation is based on continuous data sampling [10]. Firstly, it takes the signal during run time via an analog-to-digital converter. Then, the digital signal is filtered from any harmonics which can cause the relay to malfunction as well as to avoid the operating time reduction of the relay which causes coordination problems [12]. After that, the relay calculates the peak value of the measured fault current ($\hat{I}_f$) (also noted I_f), then the data (I_f, I_p, I_s) entered into the relay logic (μ-processor) which finally gives the opening (0) or closing (1) order to its associated circuit breaker (CB).

The global output of the digital OCR is the logical multiplication (AND) of the outputs of inverse and instantaneous characteristics elements [13].

Modelling of inverse characteristic. The basic logic for implementing the inverse characteristic is summarized as follows.

Measuring fault current peak value I_f. To detect the fault current, it must firstly compare the alternating current value (I) of frequency (f) entering the OCR with the pre-set current constant value of the latter. For this, it is mandatory to convert the fundamental sinusoidal filtered signal of the current into DC form [14, 15], and by measuring its slope (S) at zero crossing we obtain its peak value (I_f) as follows.

The instantaneous equation of the sinusoidal current is:

$$I(t) = I_f \cdot \sin(2 \cdot \pi \cdot f \cdot t). \tag{4}$$

The derivative of (I) as a function of time is:

$$\frac{\mathrm{d}I(t)}{\mathrm{d}t} = I_f \cdot 2 \cdot \pi \cdot f \cdot \cos(2 \cdot \pi \cdot f \cdot t). \tag{5}$$

The slope «S» at zero crossing is taken from (5) such that $t = 0$:

$$S = \frac{\mathrm{d}I(0)}{\mathrm{d}t} = I_f \cdot 2 \cdot \pi \cdot f . \tag{6}$$

From (6) we extract:

$$I_f = \frac{S}{2 \cdot \pi \cdot f}. \tag{7}$$

The designed block diagram of the peak current measurement I_f calculated by (7) in Simulink is shown in Fig. 4 in which the peak obtained at each zero crossing is held constant by the sample and hold the block until the next zero crossing.

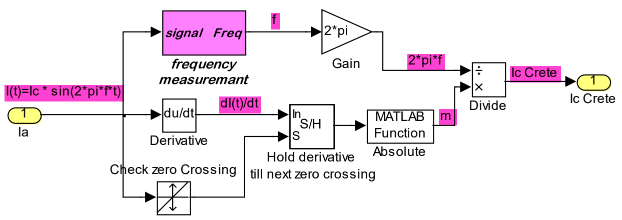

Fig. 4. Designed block diagram of peak current measurement

Frequency measurement and block design. The fundamental signal frequency entering the relay is determined by measuring the time between two consecutive zero crossings (T_1 and T_2), which gives half the time period (T) [2]:

$$T/2 = T_2 - T_1. \tag{8}$$

From (8), frequency is determined by:

$$f = \frac{1}{T} = \frac{1}{2 \cdot (T_2 - T_1)}. \tag{9}$$

Figure 5 depicts the frequency measurement block designed in Simulink. Firstly, the signal enters the «Hit Crossing» block which transmits it only at its zero crossings to the «If» block, and the latter sends the value of the ramp signal at that instant to the output. The duration of the generated ramp can be calculated and saved in a variable «A». By temporarily storing «A» in another variable «B» using the «Transport Delay» block, «B» is therefore can be subtracted from the instant of the next zero crossing «A» at any time and this will give half of the period of time whose value is retained by the «Sample and Hold» block, until the next zero crossing. After having carried out the calculations according to (9), on the value retained, we obtain the instantaneous frequency [2].

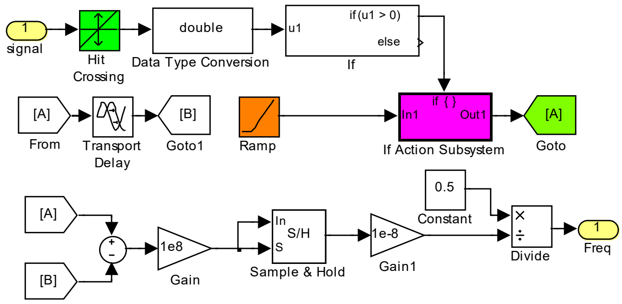

Fig. 5. Designed block diagram of frequency measurement

Measuring and design of the remainder basic logic of the inverse characteristic. After measuring the frequency and peak value of current I_f, the latter must be compared with the constant preset value of pickup current I_p of the relay using the comparator block «Relational Operator». If $I_f > I_p$ the value of I_f is raised to an appropriate power n to reach the desired relay curve, then integrated in the «Integrator» block [2].

As long as $I_f > I_p$, the integrator output continues to increase until it becomes equal to the pre-set value of constant K, causing the relay to send a trip signal («0»). If the excess current is temporary (due to load starting, or any switching action, etc.) and when it dies out to below I_p before reaching K, the rising integrator output is reset by the feedback reset logic to prevent any relay malfunction [2].

If the fault current is permanent and has a constant level, the value of I_f^n will also remain constant and therefore the output of the integrator will be:

$$C_{st} = \int_0^t I_f^n \mathrm{d}t = I_f^n . \tag{10}$$

Equation (10) is the equation of a straight line with slope I_f^n. On the other hand, the greater the fault current magnitude, the greater the rate of rise of integrator output and therefore a shorter time to reach the value of the constant K.

Modelling of instantaneous characteristic. As mentioned previously, when I_f is greater than short-circuit current I_s, OCR operates in instantaneous characteristic mode and sends a «0» trip signal to its associated circuit breaker after a shorter fixed delay of «Ts» seconds. The logic for implementing the instantaneous characteristic is shown in Fig. 6 below.

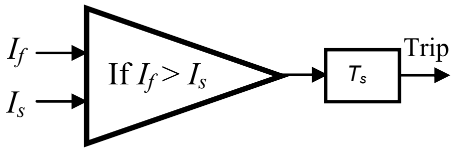

Fig. 6. Block diagram for implementing instantaneous characteristics of a digital OCR

Simulation and performance testing. In order to test the performances of the enhanced digital OCR model, the considered power system is a radial distribution network (see Fig. 7), with a load causing a starting current. It is worth to mentioning that the considered network is supposed without losses. Further, the electrical network parameters are summarized in Table 1, where U is the network voltage; P is the active power; Q is the reactive power; P_F is the power factor; T_{acc} is the accelerating period of the load; I_{isc} is the initial starting current; I_r is the nominal (rated) current.

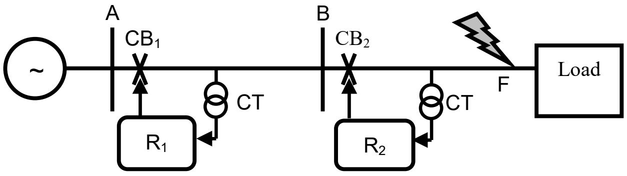

Fig. 7. Single line diagram of the proposed radial power network with coordination of relays (primary and backup protection)

Table 1

Electrical network parameters

U, V	P, kW	Q, kVAr	P_F	f, Hz	T_{acc}, s	I_{isc}, A
400	100	61.97	0.85	60	2	$3 \cdot I_r$

Parameters calculation and relays settings choice. In this sub-section, before starting to carry out the tests, it is firstly essential to calculate some necessary parameters and to make an adequate choice for relay setting of primary protection as well as for relay of backup protection. This choice is based on the parameters given in previous Table 1 and those calculated.

Calculation of the rated current at full load and the initial starting current. The rated current I_r at full load is calculated as follows:

$$I_r(rms) = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi} = \frac{100 \cdot 10^3}{\sqrt{3} \cdot 400 \cdot 0.85} \cong 169.81\,\text{A}. \quad (11)$$

From (11), the peak value of I_r is:

$$\hat{I}_r = \sqrt{2} \cdot I_r \cong 240.15\,\text{A}. \quad (12)$$

From Table 1 the initial starting current is I_{isc}:

$$I_{isc}(rms) = 3 \cdot I_r \cong 509.43\,\text{A}. \quad (13)$$

The peak value of I_{isc} is:

$$\hat{I}_{isc} = \sqrt{2} \cdot I_{isc} \cong 720.44\,\text{A}. \quad (14)$$

Relays settings choice. The pickup current I_p (peak value) must be set to a value greater than the rated current I_r. We therefore choose a value somewhat close (I_p = 250 A) and similar for both primary (R$_2$) and emergency (R$_1$) protection relays. On the other hand, severe fault current setting I_s (as a peak value) must be greater than the initial starting current ($\hat{I}_{isc}$≅720.44 A). Consequently, a relatively close value (I_s = 800 A) is chosen for the relay R$_2$. In addition, the instantaneous operating time is chosen as Ts_{R2} = 0.1 s, and the constant K is selected such that it does not cause false tripping during start-up and transient conditions (K_{R2} = 900).

Furthermore, for a good relays coordination, R$_1$ must have a higher setting of I_s, K and T_s than that of R$_2$. Therefore, the setting of these parameters is maintained as: I_{sR1} = 1000 A, K_{R1} = 1000 and Ts_{R1} = 0.2 s. The parameters settings of R$_1$ and R$_2$ relays chosen in this sub-section are collected and tabulated in Table 2.

Moreover, in this work the constant representing inverse-time type is chosen as n = 0.9, the total simulation time is t = 10 s and the contact operating time of circuit breakers is assumed to be zero.

Table 2

Selected parameters settings of R1 and R2 relays

	I_p, A (peak)	I_s, A (peak)	K	T_s, s
R_2	250	800	900	0.1
R_1	250	1000	1000	0.2

Test 1: Start-up, temporary fault and permanent fault test. To see and verify the enhanced designed relay behavior, it is considered three different situations: starting period [0-2 s], temporary fault period [3-4 s] and permanent fault period [5-end] whose fault current value is I_f = 400 A. The models of [2], [16], [17] and [18] were invested so that the inverse characteristic was added to the last three models and the first model was developed and improved and then the four models were combined to obtain a final modified and improved model that illustrated in Fig. 8 to be able to operate under hard conditions tests.

Start-up period. From Fig. 9 below, during the acceleration period, the initial starting current I_{isc} (peak value) is greater than the pickup current I_p of R$_2$, which increases the output of its integrator. At t = 2 s, when I_{isc}<I_p, the integrator output being less than K setting and drops to zero, and R$_2$ is reset.

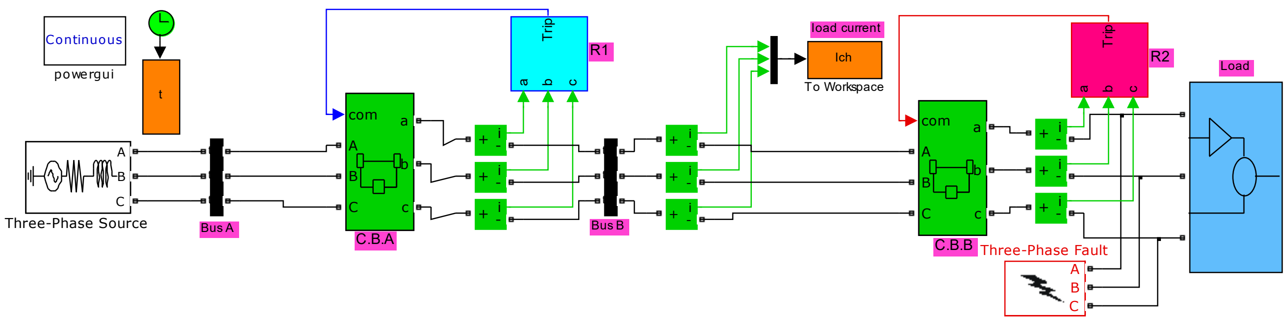

Fig. 8. Overall developed simulation model of the two OCRs implemented in the power system

The R_2's K value is deliberately set above its maximum integrator output during the acceleration period to avoid any false tripping of relays R_1 and R_2.

On the other hand, it can be seen also that the line representing R_2 integrator output in the load acceleration period is not straight seeing that the starting current is nonlinear (decreasing current). It is noted that if we drawing slopes in some points of this line (see Fig. 9) we notice that a large amplitude of the starting current (beginning of the current) results in a higher rate of rise of the integrator output and therefore a shorter time to reach the value of the constant K. Consequently, this remark applies to all other fault currents.

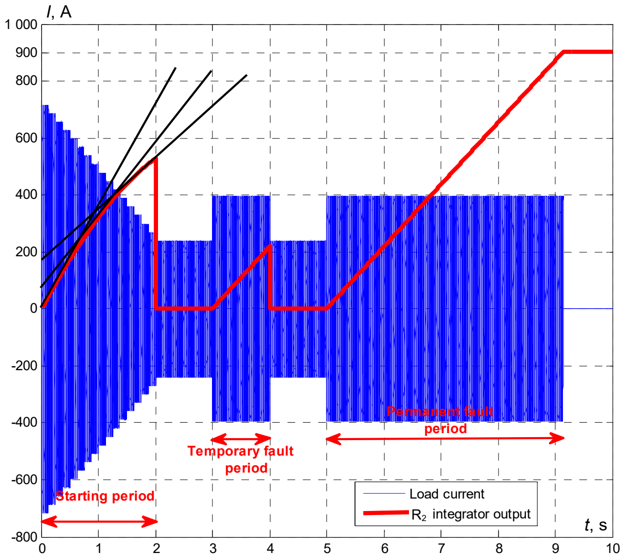

Fig. 9. Relay performance for test 1

Temporary fault period. In this case, it is clear from Fig. 9 above, that the R_2 integrator output is straight-shaped seeing that the fault current in this case is constant during this period.

As the fault is of a short duration (1 s in the interval [3-4 s]), this can't allow the output of the rising integrator of R_2 to reach the value of $K = 900$; so it goes back to zero. Relay R_2 stops counting its inverse characteristic operating time:

$$T = \frac{K}{I_f^n} = \frac{900}{400^{0.9}} \cong 4.1 \text{ s} . \qquad (15)$$

As the fault time (1 s) is less than R_2 relay operating time (4.1 s), the latter therefore does not send any trip signal to its associated CB and ensures continuity of service at rated current I_r.

Permanent fault period. Contrary to the previous case, R_2 relay integrator output in this situation has sufficient time to reach the value of $K = 900$ after the same operating time of inverse characteristic calculated in (15) ($T = 4.1$ s) counted from instant $t = 5$ s.

Relay R_2 therefore sends its trip signal to its associated CB at the instant: $t = 5$ s + 4.1 s = 9.1 s, while the backup protection relay R_1 remains inactive, as shown in Fig. 10, 11.

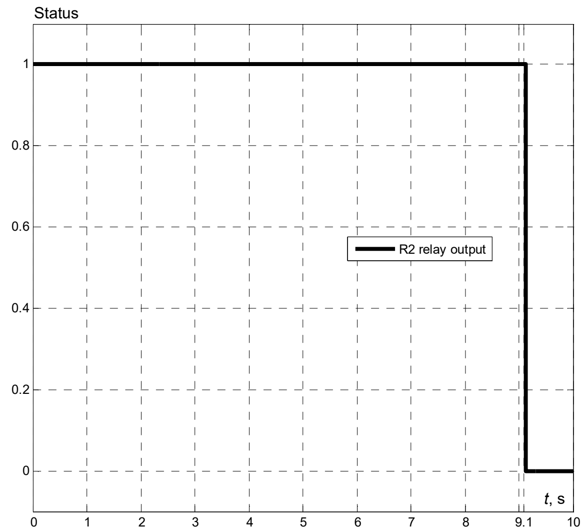

Fig. 10. R_2 status for test 1

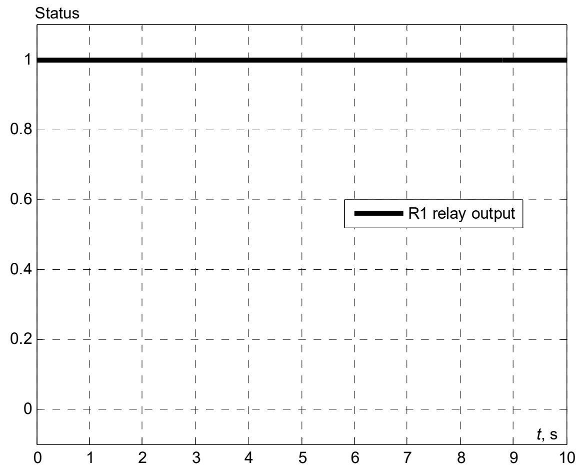

Fig. 11. R_1 status for test 1, 2, and 3

Test 2: Variable fault test. In this 2nd test, we will create a variable fault current for a relatively long duration of 3 s in the interval [3-6 s]. The considered variable fault current starts from $I_f = 270$ A at $t = 3$ s until $I_f = 960$ A at $t = 6$ s. From Fig. 12, it can be seen that unlike the falling starting current whose rising integrator output has the convex parabola shape, the rising variable fault current is also having a rising integrator output but in a concave parabola form. In addition, it is clear from the Figure that before the R_2 relay integrator output reaches the predefined value $K = 900$ (fixed only at 694.4 at $t = 5.35$ s) so that R_2 gives its tripping order in order to eliminate the fault current which is located in its inverse operating zone, the fault current reaches the severe current level ($I_f = 810.5$ A > $I_s = 800$ A) despite the long fault duration and enter in the instantaneous operating zone at $t = 5.25$ s. Therefore, R_2 relay switches from inverse mode to instantaneous mode and interrupts the fault current after the pre-set instantaneous delay $T_s = 0.1$ s, i.e. at $t = 5.35$ s (see Fig. 13). On the other hand, R_1 backup protection relay remains inactive because there is no reason to make it work (the same of Fig. 11).

The conclusion of this test is that the relay R_2 has eliminated the variable fault in instantaneous operating mode ($T_s = 0.1$ s, [5.25-5.35 s]), but after a certain period of inverse operating time ($T_{inv} = 2.25$ s [3-5.25 s]), so after a total time of $T = 2.35$ s.

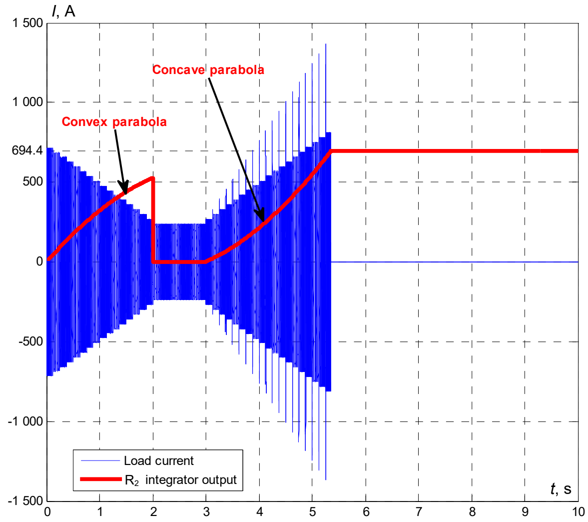

Fig. 12. Relay performance for test 2

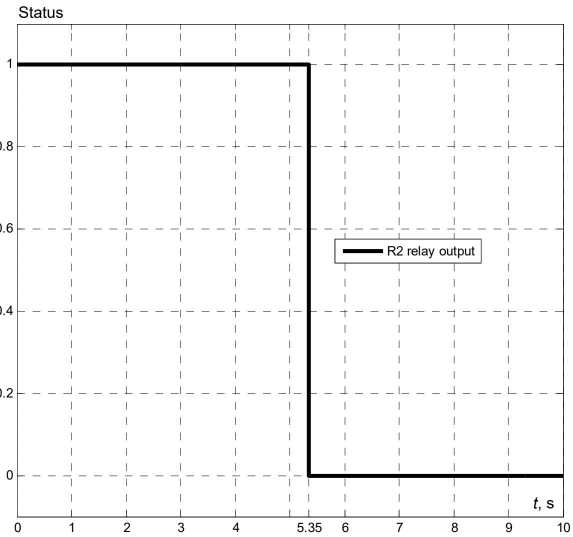

Fig. 13. R_2 status for test 2

Test 3: Testing of a fault during the acceleration period. In this 3rd test, a permanent fault current of constant value I_f = 780 A is considered, appeared at the instant t = 1 s during the acceleration period [0-2 s]. In the normal state, theoretical operating time of R_2 in inverse characteristic is:

$$T = \frac{K}{I_f^n} = \frac{900}{780^{0.9}} \cong 2.25\ \text{s}\,. \qquad (16)$$

Hence, the fault theoretical interruption instant counting from their appearance instant (t = 1 s) is: 1 s + 2.25 s = 3.25 s whereas according to Fig. 14 it can be seen that the fault is eliminated in advance at t= 2.44 s. i.e. 0.81 s ahead. This is explained by the fact that R_2 integrator output began to rising from the initial start-up instant (t = 0 s), and at the fault appearance instant (t = 1 s) it has reached the value 319.25; therefore, it needs only a little time to reach the pre-set value K = 900. It should be noted that R_2 integrator output in this case is a line composed of two parts of which the first is a convex parabola in the interval [0-1 s] due to the starting current, and the second is a straight line in the interval [1-2.44 s] due to the constant value of the fault current.

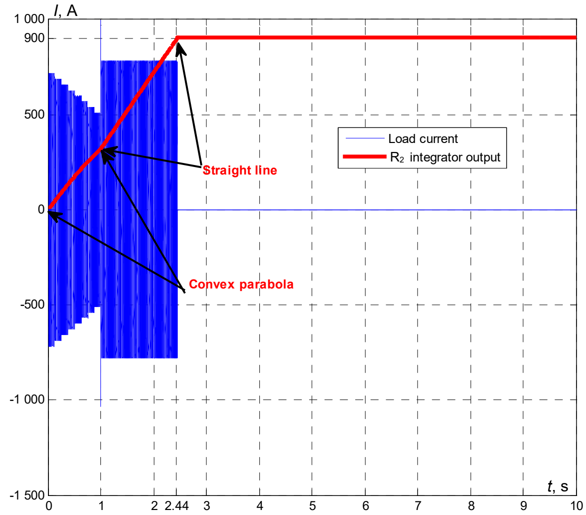

Fig. 14. Relay performance for test 3

The status of R_1 and R_2 are shown respectively in Fig. 11 (the same status of previous cases) and Fig. 15. The performance presented by the relay according of this test resides in that it has the ability to distinguish between starting current which must let it to pass and fault current which must eliminate it.

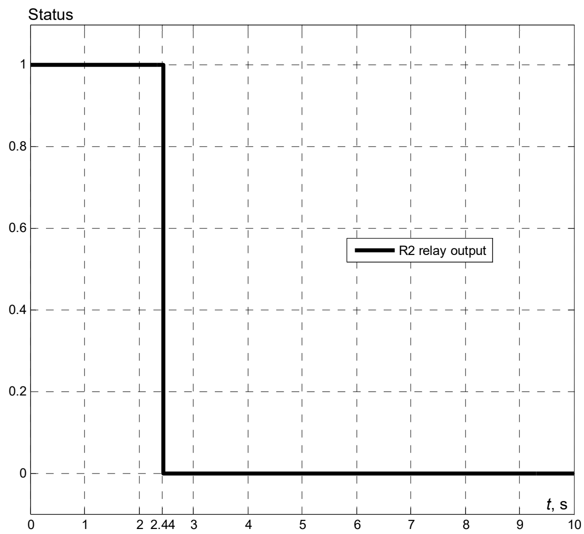

Fig. 15. R_2 status for test 3

Test 4: Fault test with broken down primary protection. In this test, it is assumed that R_2 relay of primary protection is broken down (cannot give its tripping order to its associated CB). At t = 3 s, a fault current which exceeds the severe current threshold of R_2 (I_f = 840 A> I_{sR2} = 800 A) is appeared. Thus, it was supposed that R_2 must eliminate this fault after an instantaneous operating time (T_s = 0.1 s), but in view of it is in break-down, the fault current still remains present. Consequently, the back-up protection is activated to operate through the R_1 relay; and since ($I_p < I_f < I_{sR2}$) the fault current is therefore in the inverse operating zone of R_1, whose the operating time is:

$$T = \frac{K}{I_f^n} = \frac{1000}{840^{0.9}} \cong 2.33\ \text{s}\,. \qquad (17)$$

According to Fig. 16-18, it appears that R_1 relay gives its tripping order at t = 5.33 s counted from the fault appearance instant (t = 3 s) i.e. after 2.33 s; it is exactly the theoretically calculated value in (17).

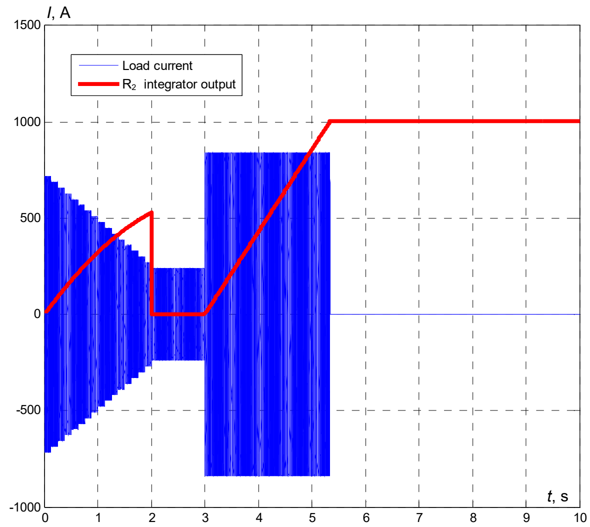

Fig. 16. Relay performance for test 4

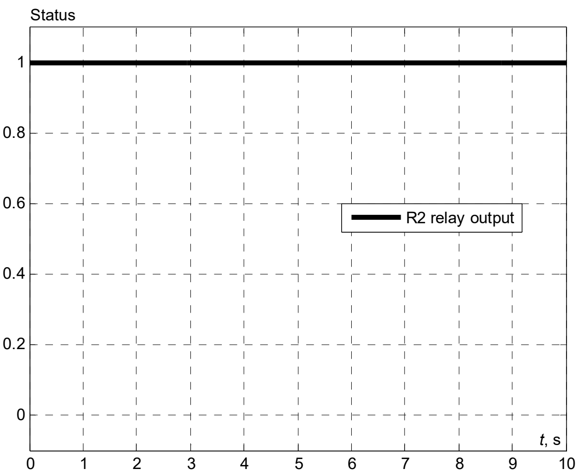

Fig. 17. R_2 status for test 4

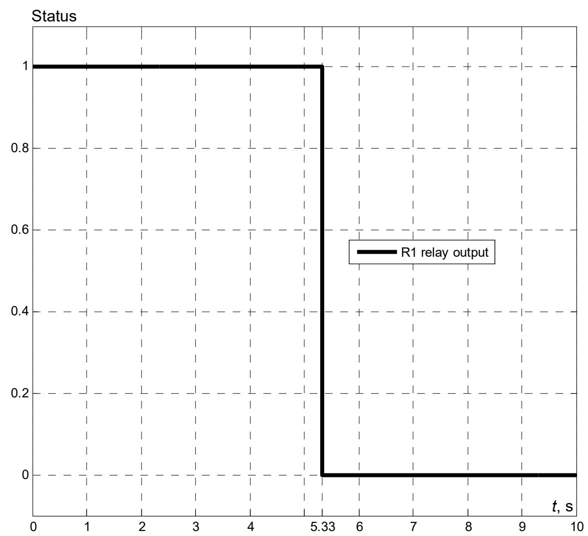

Fig. 18. R_1 status for test 4

From this test, it appears the service continuity performance guaranteed by both relays: R_2 of primary protection at the receiving end of the network, and R_1 of backup protection at the sending end to avoid any break-down problem and ensure a good protection of the power system.

On the other hand, some numerical data on improving operating speed (operating time T) of inverse characteristic of OCRs used for eliminating faults that has arisen are provided in the Table3.

Through the comparison table above, it is clear that the operating time value obtained in our test 4 is exactly the theoretically calculated value, as well as the higher accuracy of the inverse characteristic of our modified model compared to the results of other models.

Table 3

Operating time comparison with known existing models

Source	Simulation value T, s	Theoretically calculated value
[2] (case 1)	0.8	$\begin{cases} K = 3600; \\ n = 1; \\ I_f = \frac{6540}{\sqrt{2}}; \end{cases} \Rightarrow T = \frac{3600}{6540/\sqrt{2}} = 0.77$
[13] (case 3)	1.25	$\begin{cases} K = 3600; \\ n = 1; \\ I_f = \frac{4580}{\sqrt{2}}; \end{cases} \Rightarrow T = \frac{3600}{4580/\sqrt{2}} = 1.11$
Our result (test 4)	2.33	$\begin{cases} K = 1000; \\ n = 0.9; \\ I_f = 840; \end{cases} \Rightarrow T = \frac{1000}{840^{0.9}} = 2.33$

*as a reminder: K is the constant for relay characteristic; I_f is the actual fault current; n is the constant representing inverse-time type.

Conclusions.

In this paper, an enhanced designed model in Simulink/MATLAB of a digital over-current relay used as a primary protection and backup protection is presented on details. The proposed model is tested in a radial 400 V distribution network to carry out a various tests under new harsh test conditions. The simulation results proves the good and the high performance of the improved designed over-current relay on terms of: operating speed (time) for eliminating faults that has arisen, ability to distinguish between a fault current and load starting current, capacity distinguish between a real (permanent) and a temporary fault currents, the way to manage variable faults over time, and the degree of harmony (coordination) between primary relay and back-up relay. Finally, the enhanced designed digital over-current relay can be extended to design a directional over-current relay for a possible work in the future.

Conflict of interest. The authors declare that they have no conflicts of interest.

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Received 01.02.2022
Accepted 27.03.2022
Published 01.06.2022

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How to cite this article:
Sekhane H., Labed D., Labed M.A. Modelling and performance testing of a digital over-current relay enhanced designed model. *Electrical Engineering & Electromechanics*, 2022, no. 3, pp. 71-78. doi: https://doi.org/10.20998/2074-272X.2022.3.10