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Fuzzy-based Non-communicating Adaptive Overcurrent Relay ⋆

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Abstract: The technological advances of the electrical power system have brought several benefits including more robust and safe operation. Microprocessor-based digital relays may provide important features such as allowing quick and efficient setting according to the network changes. Considering the load variations throughout the day, such function becomes essential to maintain the coordination of the protection system. Adjusting the parameters of an overcurrent protective device manually may introduce non-optimal settings, mostly due to the difficulties in dealing with many possible solutions. This paper shows the modeling of an adaptive protection system based on Fuzzy Logic which parametrizes the pick-up current of inverse-time overcurrent relays by not demanding a centralized processing structure and communication among them. Two variables are taken into account: the pre-fault current and the variation of current. The IEEE 4-bus test system is used in ATP-EMTP program to illustrate the method considering several load, short-circuit and fault resistance values. The results confirms the benefits of smart protection system which adapts automatically according to the changes and has considerable sensitivity for high impedance faults. The proposed method is not dependent of system size.

Keywords: Adaptive Relays, ATP-EMTP, Fuzzy Logic, Implementation, Protection

1. INTRODUCTION

The development of advanced techniques to keep safe and stable the Electric Power System (EPS) within safe operating margins is of great importance. This characteristic may be obtained by supplying the non-affected parts of the network even after contingencies and by allowing a quick restoration of the section subject to transient fault reducing the downtime.

In order to achieve such objectives, the Protection System (PS) must fulfill certain requirements, such as good selectivity and coordination, fast action, sensitivity and reliability. Therefore, the rapid and accurate detection of any anomalies is essential for the system to operate under normal conditions. For this reason, a PS must be able to detect abnormal conditions of operation in the EPS and to start the isolation of the faulty portion. Consequently, the damage caused by faults in the transmission lines, transformers, and even generators is limited, maintaining the integrity and stability of the remainder of the system.

The relay assumes a prominent position in the PS due to its functional importance. Generally, the relay is set after short-circuit studies under steady state in order to achieve better coordination and selectivity of the equipment (Bottura et al., 2017, 2014). But in some cases, it is necessary, to satisfy all contingency conditions in the EPS, to establish more than one setting group in the relay. However, such adjustments are only possible thank to the advent of digital relays with appropriate software and communication feature (Codling et al., 1996). The microprocessors have facilitated the adaptation of multiple groups of settings, which allow dealing with different contingencies. Thus, it is possible to configure adjustments to achieve the best coordination and selectivity of the PS for each operating condition. Moreover, the digital technology creates an opportunity to develop intelligent tools which improve the protection performance, such as Artificial Neural Networks, Particle Swarm Optimization, Fuzzy Logic and Genetic Algorithms (Bottura et al., 2017; Bernardes et al., 2013).

In addition, some papers emphasizes the benefits such as in Souza et al. (2016) which updates the settings of relays by means of frequency estimation method when a modification on the EPS occurs. In Coffele et al. (2015) an adaptive overcurrent protection system which automatically modifies the protection configurations of all overcurrent relays influenced by distributed generators, demand management and islanding operation. Finally, scientific works that discuss adaptive protection systems also may be viewed in Abdulhadi et al. (2014) and Monaro et al. (2015).

Differently of Souza et al. (2016); Coffele et al. (2015) and Shih et al. (2016), the proposed method does not require a centralized processing system to determine the relay settings, since each relay has its own fuzzy system, which

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allows independent decision making without the need for communication. In this way, the use of an adaptive pick-up allows remedying some difficulties encountered in the utilization of the conventional overcurrent relay, such as non-actuation due to high fault resistance, and the costs associated with the communication infrastructure.

In summary, the objective of this paper is to propose a method that automates the pick-up current (I_p) setting of the inverse-time overcurrent relays by means of the application of Fuzzy Logic. The fuzzy system determines the best value of pick-up current according to the current measurement. However, performing manual adjustments not only makes the network more vulnerable to human failure, but also entail labor-intensive calculation, depending on the size of the electrical system.

This paper is organized as follows: Section 2 defines the problem and the solution of the problem. Section 3 outlines the implementation of the method propose. Section 4 shows and analyzes the results of the implementation. Finally, the conclusions are presented in Section 5.

2. DEFINITION AND SOLUTION OF THE PROBLEM

As stated earlier, the central objective of the PS is to operate only the devices closest to the fault, in order to isolate the smallest portion of the EPS within the shortest time, and still protect the remaining system components.

With the objective of reducing the operation time and keeping the selectivity between the relays, the use of inverse-time overcurrent relays is recommended, with non-fixed tripping, but dependent on the fault current and variable I_p, according to the (1) from IEC 60255-151 standard (IEC, 2009).

$$T_{op} = \frac{k_1 \times TMS}{\left(\frac{I}{I_p}\right)^{k_2} - k_3} \tag{1}$$

where: k_1, k_2 and k_3 are the terms that define the relay's operating curve, TMS is the time multiple setting and I is the current seen by the relay from the secondary side of the Current Transformer (CT).

Note in (1) that, the smaller the I_p value is, the faster the operation becomes, and consequently, the protection system against the damage caused by faults is more robust. Therefore, one of the problems is to find a way to set the minimum I_p value while ensuring the relay will not operate when a new load or motor starts. With this in mind, an adaptive relay based on Fuzzy Logic in Alternative Transients Program - The Electromagnetic Transients Program (ATP-EMTP) (Høidalen, 2017) have been developed by using a dynamic I_p that monitors the changes on the loading and also the fault situations.

The proposed algorithm estimates the output (I_p) through two input variables: pre-fault current (I_{pre}) and variation of current (ΔI). Initially, I_p which was considered as a static value becomes a dynamic variable, which is updated throughout the period. It is worth mentioning that the standard actuation of relays is not modified. The fuzzy system is used as an intelligent module to vary the I_p value and consequently improving the operation time. In the experiment, a fuzzy controller performs a decision making according to *If-Then* fuzzy rules (Table 1). When there is a small ΔI, the I_p tends not to be sensitized, otherwise when large ΔI happens, the I_p is reduced so that the relay acts faster.

Table 1. Summary of Adopted Fuzzy Rules

AND	*Very low I_{pre}*	*Low I_{pre}*	*Medium I_{pre}*	*High I_{pre}*	*Very high I_{pre}*
Small ΔI	*Low I_p*	*Medium I_p*	*High I_p*	*Very high I_p*	*Extra high I_p*
Big ΔI	*Very low I_p*	*Low I_p*	*Medium I_p*	*High I_p*	*Very high I_p*

The input parameters, shown in Figs. 1 and 2, are processed by the fuzzy system to obtain the value of the output through the linguistic parameters of Fig. 3. Therefore, the output of the fuzzy system is a real number ($\mathbb{R}^+$) which will be sent to the relay.

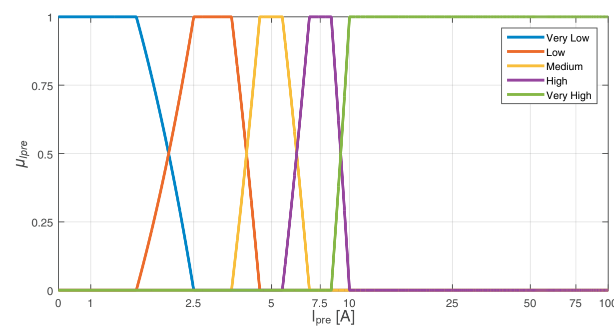

Fig. 1. Input 1 – I_{pre} parameter in the fuzzy system.

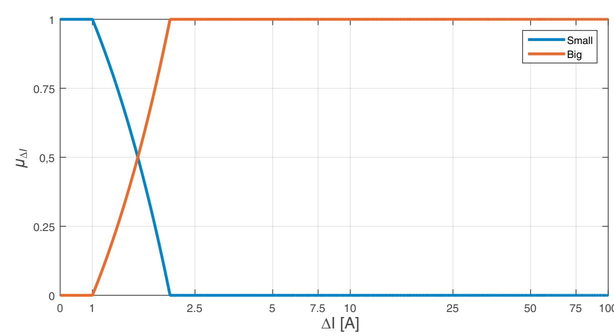

Fig. 2. Input 2 – ΔI parameter in the fuzzy system.

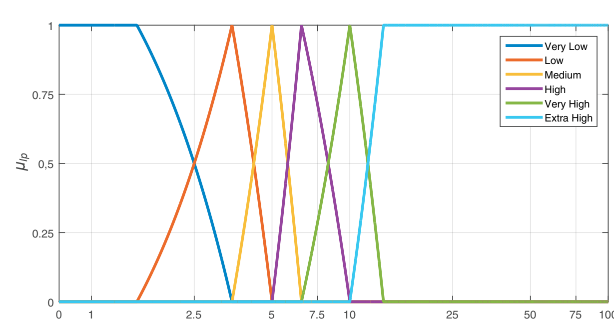

Fig. 3. Output – I_p parameter in the fuzzy system.

Five membership functions have been used for the input I_{pre} and two membership functions have been specified for the input variable ΔI. Moreover, six membership functions have been chosen for the output in order to ensure a less abrupt transition of the I_p. Thus, the I_{pre} variable has been classified into *very low*, *low*, *medium*, *high* and *very high*, the ΔI variable has been divided into *small* and *big*, and the I_p has be classifying into *very low*, *low*, *medium*, *high*, *very high* and *extra high*. The universe of discourse for these variables has been set between 0 and 100 A, considering that the CT could saturate when the current magnitude supersedes 100 A. More fuzzy rules could increase the relay sensitivity, but it would lead to increase the processing requirement.

3. SOLUTION IMPLEMENTATION

The ATP-EMTP simulator has been used for the development of the inverse-time overcurrent relay model using Fuzzy Logic. A brief explanation of the modeling via MODELS language for ATP-EMTP program is presented.

The first step is to discretize the membership functions of the inputs and output. 14 vectors (13 for the membership functions and one for the I_p values) with 500 points have been created in *Matlab*® (*The MathWorks, Inc*) program for posterior utilization on the ATP-EMTP program.

With the values of the current magnitude obtained by the phasor estimator (Modified Cosine Filters with 960 Hz sampling frequency), the next stage is to convert these values to 60 Hz sampling frequency for determining the I_{pre} value. The ΔI value is determined by the difference between the I_{pre} and the current constantly estimated by the relay. Therefore, the I_{pre} variable is updated once in a fundamental wave cycle (60 Hz) and the ΔI is calculated sixteen times. The update of the I_{pre} variable is done with the value of the last cycle sample.

After calculating the values of the input variables (x and y), it is necessary to determine the membership degrees ($\mu_{I_{pre}}(x)$ and $\mu_{\Delta I}(y)$) for each function. The next step is to perform the aggregation of membership degrees (μ_{agg}) of the input terms associated with each rule through the connective *and*. So, in this case, the *minimum* operator has been used in the study (2). For example, for the rule 1, the lowest membership degree found between the *very low* I_{pre} and *small* ΔI variables are collected and stored. As for rule 2, the lowest membership degree between the *low* I_{pre} and *small* ΔI variables are stored. The same procedure has been done for all remaining rules.

$$\mu_{agg} = min\{\mu_{I_{pre}}(x), \mu_{\Delta I}(y)\} \tag{2}$$

Aggregating the membership degrees of the input terms, the next step is to make the implication of them with their respective outputs. Thus, the *Mamdani* operator was used for this function (3). This operation consists of taking the lowest value between the aggregation of membership degrees of the inputs and the membership degrees of the output term corresponding to that rule. For example, for rule 1, we store the minimum operation between the aggregation of the found membership degree and all membership degrees of the output membership function *low* I_p. Regarding rule 2, the lowest membership degree between those obtained from connective *and* and all membership degrees of the next output membership function *medium* I_p are stored.

$$\mu'_{I_p}(k) = min\{\mu_{agg}, \mu_{I_p}(k)\} \quad \text{for } k = 1 \text{ to } N_d \tag{3}$$

where: N_d is the number of discretization points (we set at 500).

After finding six resulting output membership functions, the aggregation of all these functions by the *maximum* operator is performed (4). This operation consists of getting the highest membership degree for each element of the resulting output membership functions, generating a single output membership function. Having found this area, the defuzzification is carried out by the *center of area* method (5) (COA), resulting in a single value of the I_p that must be entered in the relay.

$$\mu''_{I_p}(k) = max\{\mu'_{I_{p_{vl}}}(k), \mu'_{I_{p_l}}(k), ..., \mu'_{I_{p_{eh}}}(k)\} \tag{4}$$

$$COA = I_p = \frac{\sum_{k=1}^{N_d} \mu''_{I_p}(k) \times I'_p(k)}{\sum_{k=1}^{N_d} \mu''_{I_p}(k)} \tag{5}$$

where: $I'_p(k)$ is the value of the variable I_p for the k-th discretization point.

After computed the I_p value, we checked in the next stage whether the current in the system surpasses such value. If this fact is confirmed, the time for sending the trip signal is calculated according to (6) (Benmouyal, 1990; Sorrentino et al., 2011), which takes into account the current value since the moment in which I_p has been exceeded.

$$\Delta t_{samp} \sum_{n=1}^{n_{op}} \left(\frac{1}{T_{op}(n)} \right) = 1 \tag{6}$$

where: Δt_{samp} is the sampling interval and n_{op} is the number of samples processed until sending the trip signal.

Thus, the last stage is to verify whether the number of samples is sufficient to send the trip signal. Having satisfied this condition, a signal is sent to open the circuit breaker. Due to space limitation, the authors do not provide a step by step algorithm (flowchart) for the proposed relay.

Fig. 4 shows the schematic diagram of the fuzzy system. In summary, the fuzzification interface consists of determining the membership degrees of the input variables based on the data provided by the database, where in the database are stored all the membership functions in discrete form, both the inputs and the output. On the other hand, the inference process block executes the aggregation of input membership degrees, the implication of them with their respective outputs and the aggregation of output functions. The defuzzification interface is responsible for determining the output point value of the fuzzy system. Finally, it is in the fuzzy rules that the set of linguistic rules is found (Table 1).

The Fig. 5 shows the behavior of the I_p value when some loads are connected or disconnected. Observe when the load current is incremented to certain values, I_p is also increased. The opposite occurs when the current decreases. Fig. 6 shows the behavior of I_p when a fault occurs at instant 0.5 s. Moreover, I_p decreases when the current increases significantly. In these examples, the relay starts to process the data after 0.1 s, justifying the zero value of I_p in the beginning of the simulation. These currents correspond to the secondary side of the CT.

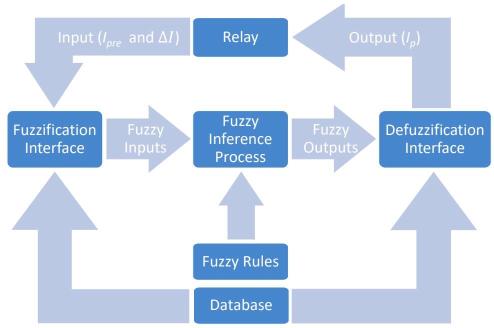

Fig. 4. Flowchart of the designed fuzzy system.

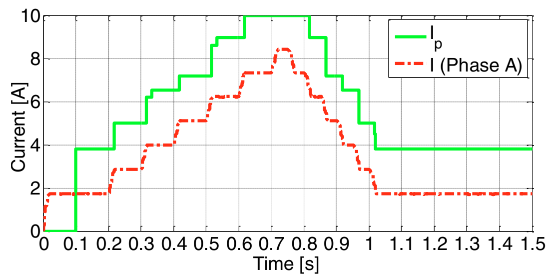

Fig. 5. Variation of the I_p following the system current.

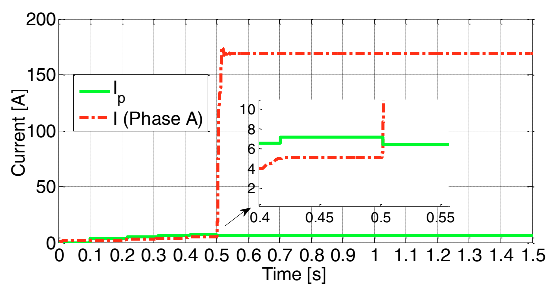

Fig. 6. Variation of the I_p due to occurrence of fault.

4. SIMULATION RESULTS

The IEEE test system composed by 4 nodes and 4 wires (distribution) has been used to study the proposed adaptive relay (Fig. 7). The balanced load had its value changed during the tests. The transformer connection is delta at the high voltage side (7.2 kV - phase-neutral) and grounded wye at low voltage side (2.4 kV - phase-neutral) with nominal power of 2,000 kVA IEEE (2013).

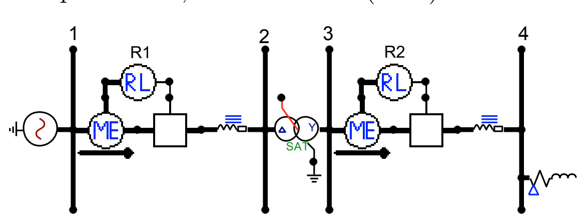

Fig. 7. IEEE test system used in the validation.

The results are based on two relays used in the simulations. They are allocated between the nodes 1-2 and 3-4, close to node 1 (relay 1) and node 3 (relay 2), respectively. For both, the parameters follow the IEC Standard Inverse curve IEC (2009) ($k1$=0.14, $k2$=0.02 and $k3$=1), with TMS equal to 0.1 and 0.05 for relays 1 and 2, respectively. The CT's 1 and 2 present a transformation ratio of 10 and 30, respectively. In the first study was used a delta load with resistance of 36.8 Ω and inductive reactance of 15.7 Ω per phase (180 A), resulting in current values shown in Fig. 8, in secondary side of CT.

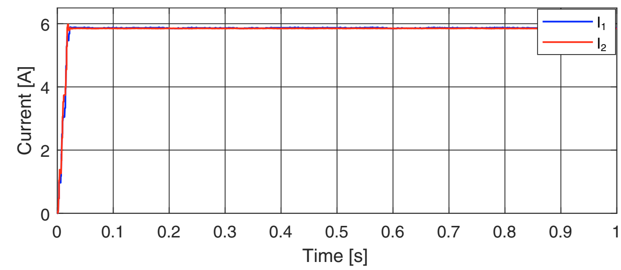

Fig. 8. Electric current measured by the relays 1 and 2.

A three-phase short-circuit was applied to the node 4 when the simulation reached 0.5 s,. Notice the I_p value provided by the fuzzy system as well as the operation time of relay 2 (Fig. 9). As the actuation of relay 2 has been faster than the relay 1, the device 1 did not have its trip activated due to extinction of the fault current by the relay 2.

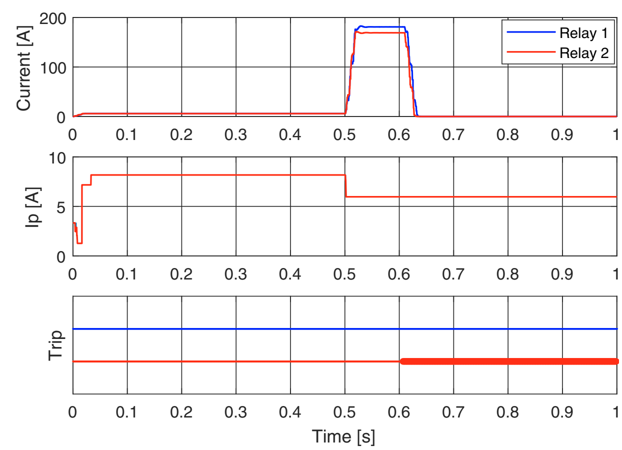

Fig. 9. Phase currents in the secondary CT's, pick-up currents and trip signals of relays 1 and 2 with the Fuzzy Logic.

According to Fig. 9, the I_p of relays 1 and 2, initially set as 8.17 A, changed to 5.96 A during the fault. This change resulted in a operation time of 0.1064 s for relay 2. To make a performance comparison, the fuzzy module has been removed and a constant value has been included by fixing I_p. So, I_p provided by the fuzzy system before the fault was adequately set. I_p's of relays 1 and 2 as well as the trip signal of relay 2 are shown in Fig. 10. Observe that I_p remains unchanged during the short circuit. As a consequence, the operation time of relay 2 resulted in 0.1179 s, which corresponds to a difference of 0.69 cycles of 60 Hz, in relation to the test in Fig. 9. Using fixed I_p value, as earlier, the drawn current by the load on the secondary side of the distribution transformer is limited at 245 A. If the load drained a higher current, it would be necessary to adjust I_p to a higher value. Such an increase would imply a longer time to eliminate the fault, as can be deduced from the (1).

Considering that the maximum load demands current of 275 A (nominal power of the distribution transformer), it becomes necessary to define new values for the I_p. In this way, the relays without the fuzzy system had the I_p set at 10 A in both relays 1 and 2, which corresponds to a current

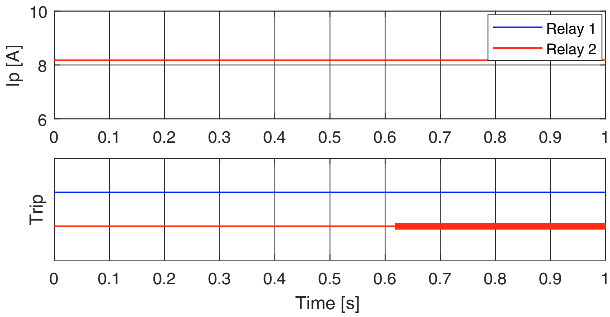

Fig. 10. Operating time for three-phase short-circuit applied to the node 4 with $I_p's$ fixed (8.17 A for both the relays).

in the CT primary of 100 A and 300 A (approximately 10% greater than the maximum load current). Thus, the Fig. 11 shows the behavior of the relay with these new values of I_p for the case studied so far.

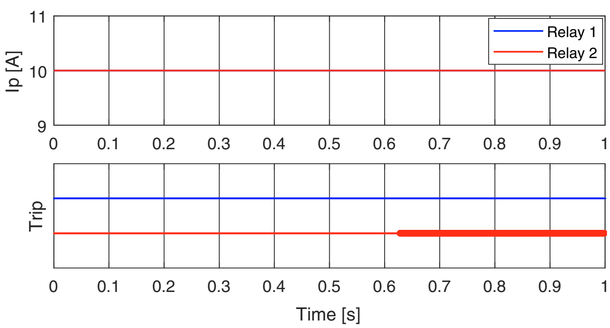

Fig. 11. Operating time for three-phase short-circuit applied to the node 4 with $I_p's$ fixed (10 A for both the relays).

Based on the new values of the I_p, it is possible to verify that the operation time of relay 2 is 0.1262 s after the fault, which corresponds to a difference of 1.19 cycles of 60 Hz, compared with the simulation of Fig. 9. It can be concluded that, if the I_p values are adopted as 10 A for both relays 1 and 2, regardless of the load current value, for a three-phase short-circuit at node 4, we would obtain the same operation time for relay 2 (0.1262 s).

By employing the proposed fuzzy system, the I_p changes according to the load current, being possible to obtain various operating time for relay 2. Two cases are shown in this context, where the first one consists of a load draining 80 A and in the second case a load draining 250 A.

For a delta load with resistance of 82.8 Ω and inductive reactance of 35.3 Ω per phase, draining a current of approximately 80 A, obtains, according to Fig. 12, a value of the I_p before the fault of 5 A and during the fault, a value of 3.33 A for both relays 1 and 2. In this case, the operating time for relay 2 was 0.0908 s, which corresponds to a difference of 2.12 cycles of 60 Hz, when compared with a conventional relay time with new values of the I_p (0.1262 s).

Other experiments have been taken into consideration. For a delta load with resistance of 26.5 Ω and inductive reactance of 11.3 Ω per phase, draining a current of approximately 250 A, was obtained according to Fig. 13, I_p equals to 10 A for both relays before the fault, and a value of 7.17 A and 9.23 A during the fault for the relays 1 and 2,

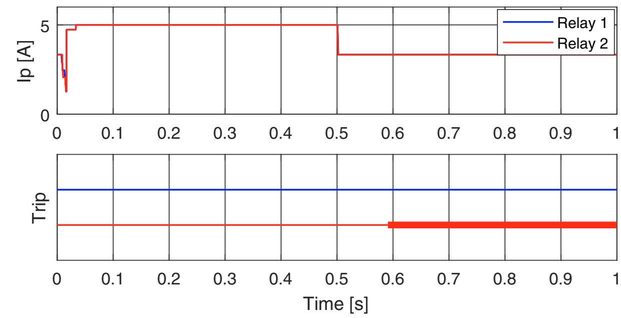

Fig. 12. Operating time obtained using the proposed fuzzy system for three-phase short-circuit applied to the node 4 (load current equals to 80 A).

respectively. In this way, the operating time found for the relay 2 was 0.1127 s, which corresponds to a difference of 0.81 cycles of 60 Hz, when compared with the conventional relay time with new values of the I_p.

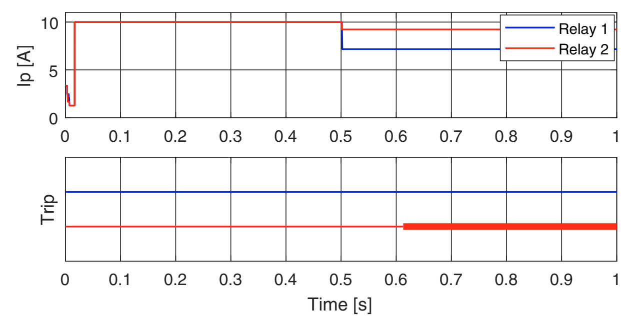

Fig. 13. Operating time obtained using the proposed fuzzy system for three-phase short-circuit applied to the node 4 (load current equals to 250 A).

The actuation time is shown in Table 2 with the use or not of the Fuzzy Logic. The simulations were performed for 3 types of loads located at node 4, and for each load, three-phase fault (ABC), two-phase fault (AC), two-phase to ground fault (ACT) and single-phase (B) were applied in several points in the electrical system. In the experiment, the relays without the Fuzzy Logic had their $I_p's$ set at 10 A. It is possible to notice the relay with Fuzzy Logic has been faster than the conventional relay for all types of loads and faults. The less the load, the faster the actuation time of the relay with the Fuzzy Logic is. In addition, it can be seen that this characteristic is not observed for the conventional relay, because the actuation time is fixed at a single value regardless of the load current.

Additional tests were performed to show the actuation time obtained by the variation of the fault resistance (FR) for the relays with and without the Fuzzy Logic (Table 3). In this case, the load current located at node 4, was fixed in 180 A and the faults were applied in several points on the electrical system. As can be seen in Table 3, the relays with Fuzzy Logic had shorter operating times than conventional relays, with the largest difference being 2.7832 s for three-phase fault at node 3 with a fault impedance of 20 Ω, and the smallest difference of 0.0125 s for three-phase fault at node 2 with a fault impedance of 0.01 Ω. This finding reinforces the usefulness of our methodology. In addition, observe that for low impedance faults, the difference in the actuation time between the relay with and without the fuzzy system is smallest for the smallest impedance

Table 2. Actuation Time [s] for Faults Applied with Load Variation

Load (A)	With the Fuzzy Logic				Without the Fuzzy Logic			
	ABC	AC	ACT	B	ABC	AC	ACT	B
	Node 2				Node 2			
80	0.1085	0.1096	0.1085	0.1127				
180	0.1200	0.1210	0.1210	0.1252	0.1325	0.1335	0.1335	0.1388
250	0.1242	0.1252	0.1252	0.1294				
	Node 3				Node 3			
80	0.1450	0.1450	0.1450	0.1627				
180	0.1658	0.1658	0.1658	0.1888	0.1898	0.1898	0.1909	0.2200
250	0.1731	0.1731	0.1731	0.1981				
	Node 4				Node 4			
80	0.0908	0.0960	0.0939	0.1002				
180	0.1064	0.1127	0.1117	0.1190	0.1262	0.1346	0.1325	0.1429
250	0.1127	0.1190	0.1179	0.1262				

fault values. As the distance increases from the source, the lower the sensitivity of the conventional relay, however this effect is not so accentuated when using the proposed relay with fuzzy update.

Table 3. Actuation Time [s] for Variation of the Fault Resistance

FR Ω	With the Fuzzy Logic				Without the Fuzzy Logic			
	ABC	AC	ACT	B	ABC	AC	ACT	B
	Node 2				Node 2			
0.01	0.1200	0.1210	0.1210	0.1252	0.1325	0.1335	0.1335	0.1388
10	0.2732	0.2273	0.2732	0.2763	0.3440	0.2742	0.3430	0.3472
20	0.3628	0.2878	0.3617	0.3649	0.4962	0.3680	0.4962	0.4993
50	0.5837	0.4284	0.5847	0.5858	1.0276	0.6295	1.0255	1.0297
100	0.9244	0.6285	0.9234	1.2599	2.8813	1.1693	2.8865	2.2823
	Node 3				Node 3			
0.01	0.1658	0.1658	0.1658	0.1888	0.1898	0.1898	0.1909	0.2200
10	0.8629	0.5535	1.2016	1.2693	1.5830	0.9369	2.3697	3.0730
20	1.4694	1.2016	2.8354	8.6248	4.2526	2.3707	4.3453	>20
50	-	3.6659	-	-	-	-	-	-
100	-	-	-	-	-	-	-	-
	Node 4				Node 4			
0.01	0.1064	0.1127	0.1117	0.1190	0.1262	0.1346	0.1325	0.1429
10	0.4461	0.3336	0.4472	0.4461	1.2610	0.5795	1.2756	1.2620
20	0.7587	0.4920	0.7567	1.3204	-	1.7184	-	-
50	-	2.9480	-	-	-	-	-	-
100	-	-	-	-	-	-	-	-

5. CONCLUSION

The results of this research indicate the objective has been reached. The fuzzy module was able to reduce the operating time of the inverse-time overcurrent relay, obtaining a difference of 2.12 cycles of 60 Hz, compared with a conventional relay for the tree-phase short-circuit at node 4. Analyzing the results, the differences on the operating time become more noticeable as the loading current becomes smaller than the fixed I_p. When the currents are close, the fuzzy approach becomes similar to conventional relay operation. In addition, there is an improvement in sensitivity for high impedance faults compared to conventional relays. Such aspects make the operation of the protection system more robust and secure. The proposed method is not dependent of system size and the fuzzy system can be improved over time. Finally, it is worth mentioning the increase on the line loading in the network, the fault clearing is improved with more accuracy and speed. The use of fuses with the proposed system is also aimed for a future investigation.

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