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APPLICATION OF FUZZY LOGIC TO A LEAKAGE CURRENT RELAY*

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Abstract – The design and application of a fuzzy logic based controller to a leakage current relay was presented in this paper. A novel approach based on fuzzy logic to form the tripping action of leakage current relay was investigated. In addition to the theoretical aspect of fuzzy logic, detection of a leakage current, measurement of the leakage current, determination of its duration, trip opening of faulty cases and detailed system architecture were also introduced. The inspected fuzzy logic technique to control the tripping action of the leakage current relay was intended to improve the performance of conventional leakage current relay control for human safety and system reliability. The relationship between the controlled output of the fuzzy processor and properties of leakage current for the proposed relay was explored by using a graphical output expression. It was observed that the proposed leakage current relay based on fuzzy logic was more reliable than conventional leakage current relay.

Keywords – Fuzzy logic, leakage current relay, intelligent protection, rule-base design, radial power system

1. INTRODUCTION

Maintenance and reliability for continuous operation is a very important problem in power systems. In order to have continuity in operation the power outages must be minimized or prevented completely. The power outages are caused mainly by faults that may occur unexpectedly at anytime, anywhere in the power system. Therefore, faults must be detected very quickly in order to start necessary actions as soon as possible and isolate the faulted parts of the system so that the outages are prevented or made minimum. The reliability of a power system is based upon its continuity while in operation. The continuity depends on the protective relays, which are used to detect faults; they are very important research areas in electrical power systems.

Research in the field of protection and relaying techniques of power systems have increased in the past decade. The basis of these techniques is to measure voltage, current, phase angle, frequency, impedance, etc. between the fault point and relay position. Substantial research towards better algorithms has been carried out for protective relaying. Computer based applications [1-3], adaptive architecture [4-7], experts [8, 9] and intelligent systems [10], fuzzy logic [11], artificial neural networks [12], genetic algorithms [13], hybrid systems [14], various software [4, 15] and hardware [16] can be shown among the previous research. Reasons for the above extensive research is that the magnitude of current and voltage at a fault instant that may occur unexpectedly at anytime, anywhere in the power system has high values and varies over a wide range. By means of the current and voltage properties, processing and investigation are becoming easier. To solve safety and reliability

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problems in radial and low voltage system applications, classical control and protection methods are currently used. In order to protect power systems against short circuit faults, circuit breakers which are working at especially low current magnitudes are used. Leakage current relays are important for human safety and system reliability. In a field station or a laboratory, a human operator may accidentally come into contact with live voltage. This contact could be due to faulty insulation of the live wire or an ungrounded metallic chassis of an instrument. Albeit the leakage current has low magnitude, it is more important for human health and may be fatal. An electrical current passes from the live point to the ground through the body of the operator who experiences an electrical shock. The intensity of the shock depends upon some elements such as live voltage, the resistance of the body of the operator, the floor resistance, contact type and duration of the contact, etc. This contact has sometimes proven to be fatal, thus the utmost preventive care should be taken to avoid it in the first place.

A novel approach based on fuzzy logic was investigated in order to control the tripping action of leakage current relay in this study. A prototype low voltage system was designed, and the proposed approach was applied to the prototype system. Both magnitude of leakage current and its duration were used as input variables for fuzzy logic based leakage current relay. The relay proposed here was developed using conventional leakage current relay characteristics by adding some abilities such as improvement in human safety and system reliability, distinguishing whether the fault is transient or permanent, and determining correct action. The prototype experimental setup was considered as a radial system tested for the proposed method, and satisfactory results were obtained for both single phase and three phases.

2. DESIGN BASIS OF FUZZY LOGIC CONTROLLER

Fuzzy set theory was used to control the tripping action of leakage current relay purposes in this study. Figure 1 shows the control algorithm based on fuzzy logic. The fuzzy logic based control process has three steps as shown in Fig. 2. These steps are:

1. Fuzzification (Converting crisp values into fuzzy values)
2. Inference mechanism (Rule base and If-Then rules)
3. Defuzzification (Converting fuzzy values into crisp values)

a) Fuzzification Process of the Fuzzy Logic Controller

Triangular type membership functions were used for fuzzification of measured current, I_L, and duration of the current, t_L, respectively. u_L was controlled output of the fuzzy logic based leakage current relay. The reason for using triangular type membership functions is that triangular type membership functions are more suitable for assembling hardware.

A graphical illustration of the membership functions and their ranges were shown in Fig. 3. The range of the membership functions was selected as classical leakage current relay set points.

The ranges of the input variables I_L and t_L were in [0, 0.03] and [0, 0.025], respectively. The interval of the output variable of u_L was in [0, 5]. Membership degrees of input and output values are determined with the assistance of the membership functions as shown in Fig. 3. This converting process is the first step of the fuzzy logic based leakage current relay (FLBLCR).

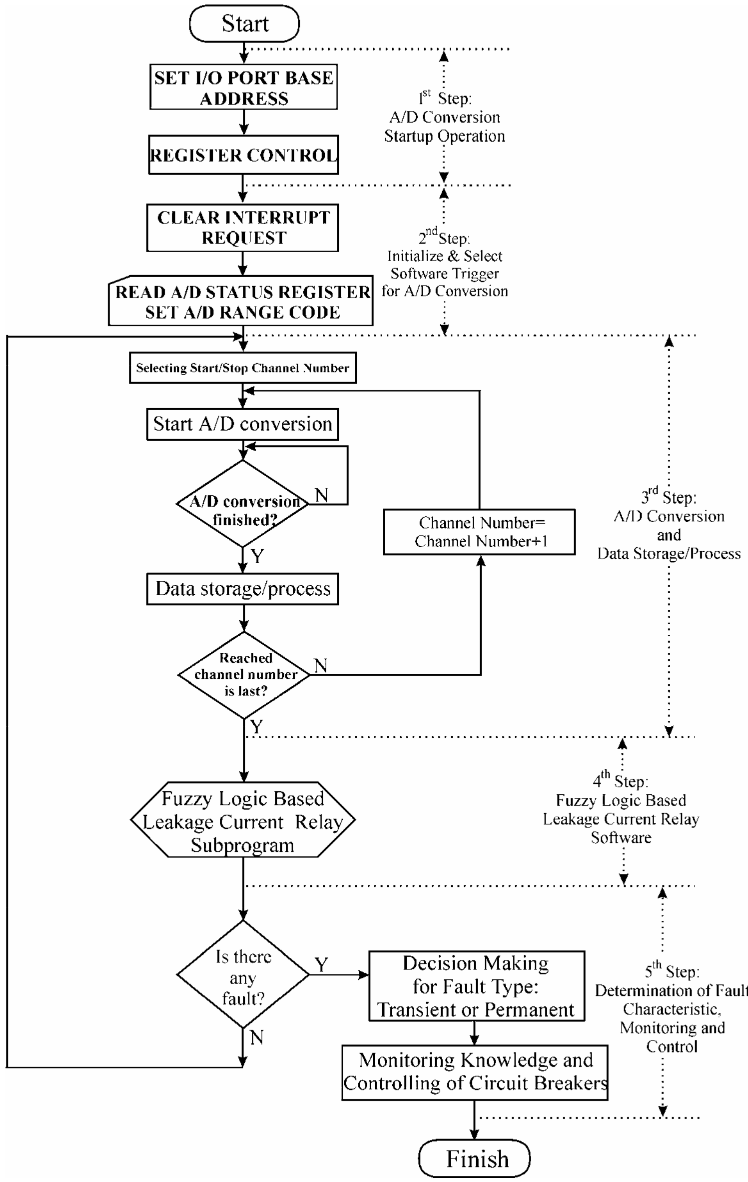

Fig. 1. Control algorithm of FLCLCR

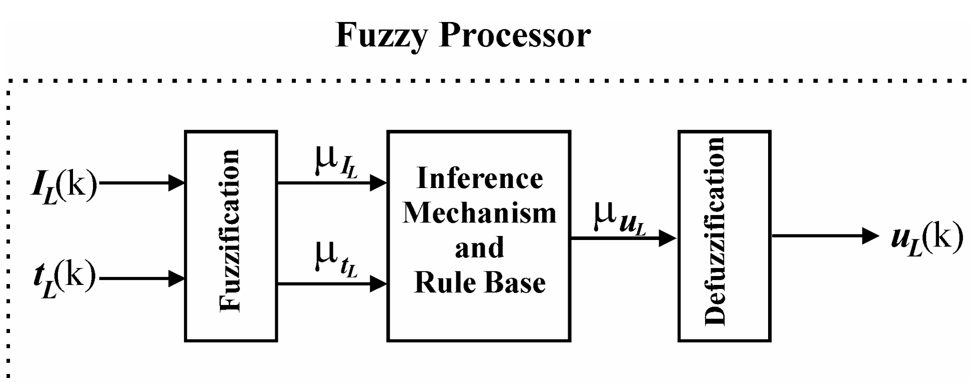

Fig. 2. Fuzzy logic based control process

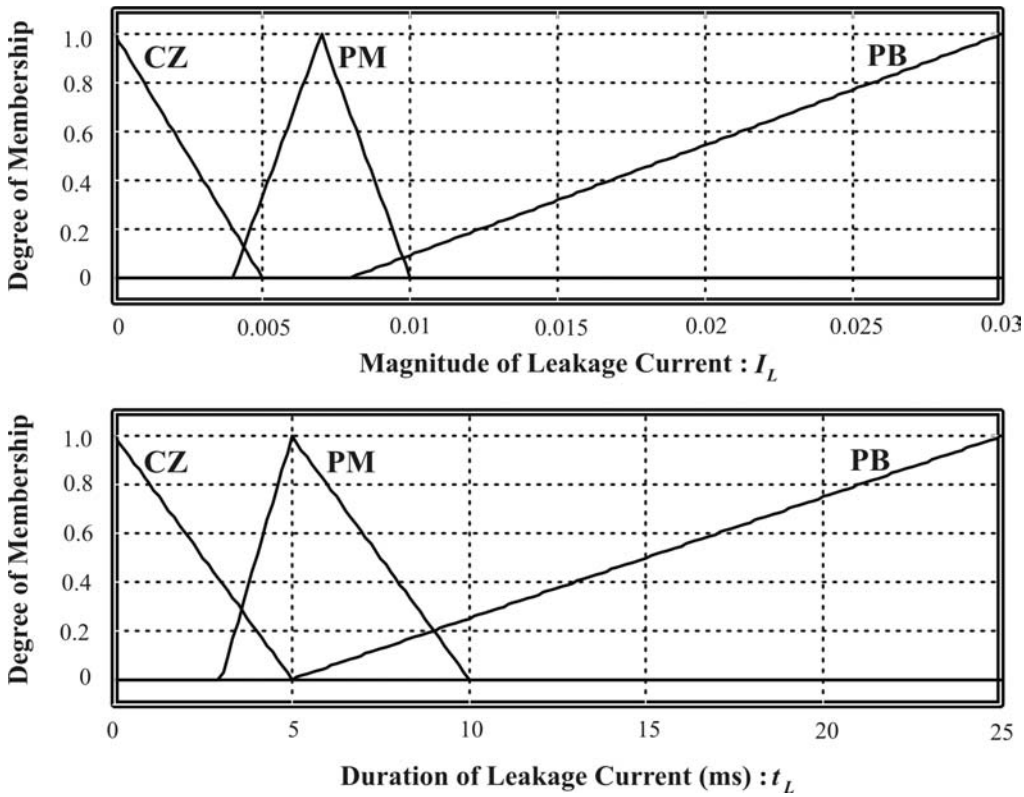

Fig. 3. Membership functions

b) Rule Base Design

The relationship between input and output of the system is the most important part of the FLBLCR. This relationship must be obtained correctly to improve the performance of the fuzzy logic based control system. This relationship is called rule base or If-Then rules. While forming the rules, magnitude and duration of the leakage current were considered. Both magnitude and duration of the leakage current were acting as the most important role to determine the rules. It is necessary to observe the physiological effects of the electric current to define rules. As pointed out in Fig. 4, the chart which shows the effects of AC current (15 to 100 Hz) was divided into four zones [17]. The risks of non-release, respiratory arrest or irreversible cardiac fibrillation increase in proportion to the time during which the human body is exposed to the electrical current. The chart in Fig. 4 identifies, in particular, zones 3 and 4 in which danger is real. For this reason, in order to determine the value of the controlled signal, u_L, the following assumptions were made:

a. If I_L is closure to zero (CZ) and t_L is closure to zero (CZ), then u_L is closure to zero (CZ).
b. If I_L is closure to zero (CZ) and t_L is positive medium (PM), then u_L is closure to zero (CZ).
c. If I_L is closure to zero (CZ) and t_L is positive big (PB), then u_L is closure to zero (CZ).
d. If I_L is positive medium (PM) and t_L is closure to zero (CZ), then u_L is positive medium (PM).
e. If I_L is positive medium (PM) and t_L is positive medium (PM), then u_L is positive medium (PM).
f. If I_L is positive medium (PM) and t_L is positive big (PB), then u_L is positive big (PB).
g. If I_L is positive big (PB) and t_L is closure to zero (CZ), then u_L is positive big (PB).
h. If I_L is positive big (PB) and t_L is positive medium (PM), then u_L is positive big (PB).
i. If I_L is positive big (PB) and t_L is positive big (PB), then u_L is positive big (PB).

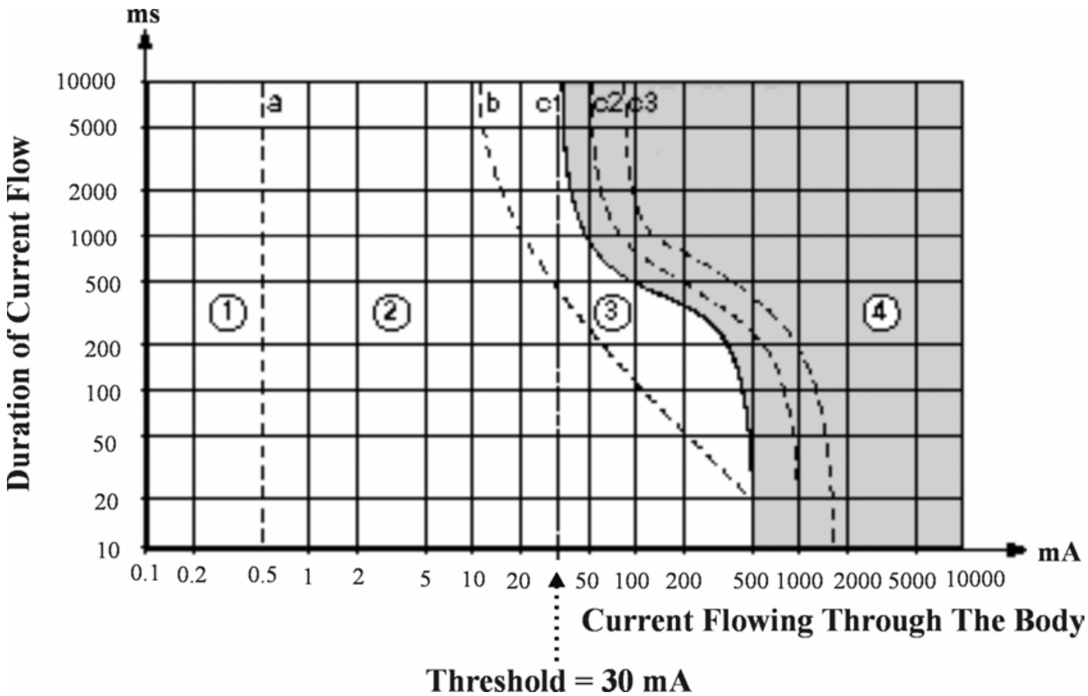

Fig. 4. Time/Current characteristics

The above assumptions could be converted into a table as drawn out in Table 1. In Table 1 and the above assumptions, CZ, PM and PB were labels for membership functions defining varying ranges. The controlled output u_L was determined with the aid of the above statements. For example, when I_L was CZ and t_L was PB, the state of u_L was CZ since there was not any dangerous or fatal effect as shown in Fig. 4. The duration of the current had no important effect at low current magnitude. However, when I_L was PM and t_L was CZ, the value of u_L had to be PM and a warning alert had to be given. Whereas duration of the current was small enough, the magnitude of the current approached a hazardous boundary. This situation had to be tracked carefully. Similar to the previous assumption, if I_L was PM and t_L was PM, the value of u_L also had to be PM and a warning alert also had to be given. To constitute If-Then rules, the current between 5 and 10 mA that had no harmful physiological effects was considered. The trip signal was produced when leakage current exceeded 10 mA related to the duration of the current. This is the second step of the fuzzy logic based control process employed to the control of current relay leakage.

Table 1. Rule-base for FLBLCR

I_L	t_L		
	CZ	**PM**	**PB**
CZ	CZu_L^1	CZu_L^2	CZu_L^3
PM	PMu_L^4	PMu_L^5	PBu_L^6
PB	PBu_L^7	PBu_L^8	PBu_L^9

c) Defuzzification Process

As a third and final step, results obtained from overall rules were entered to the defuzzification process. To convert fuzzy values into crisp values, the Center Of Area (COA) method proposed by Mamdani was used. This method could be expressed as follows:

$$u_{L\,COA} = \frac{\sum_i \mu_i (u_L).u_L}{\sum_i \mu_i (u_L)} \tag{1}$$

where $\mu_i(u_L)$ was membership degree of the u_L. The aim of the defuzzification process was to combine the individual control actions of fired rules. More than one rule could be activated or fired for a particular pair of input values. Implementing the compositional rule of inference performs this combination. Resultant fuzzy values of fuzzy rules were converted into crisp values with defuzzification.

The above three steps mentioned in sections a, b, and c, called fuzzy logic based controller, could be summarized as shown in Fig. 5.

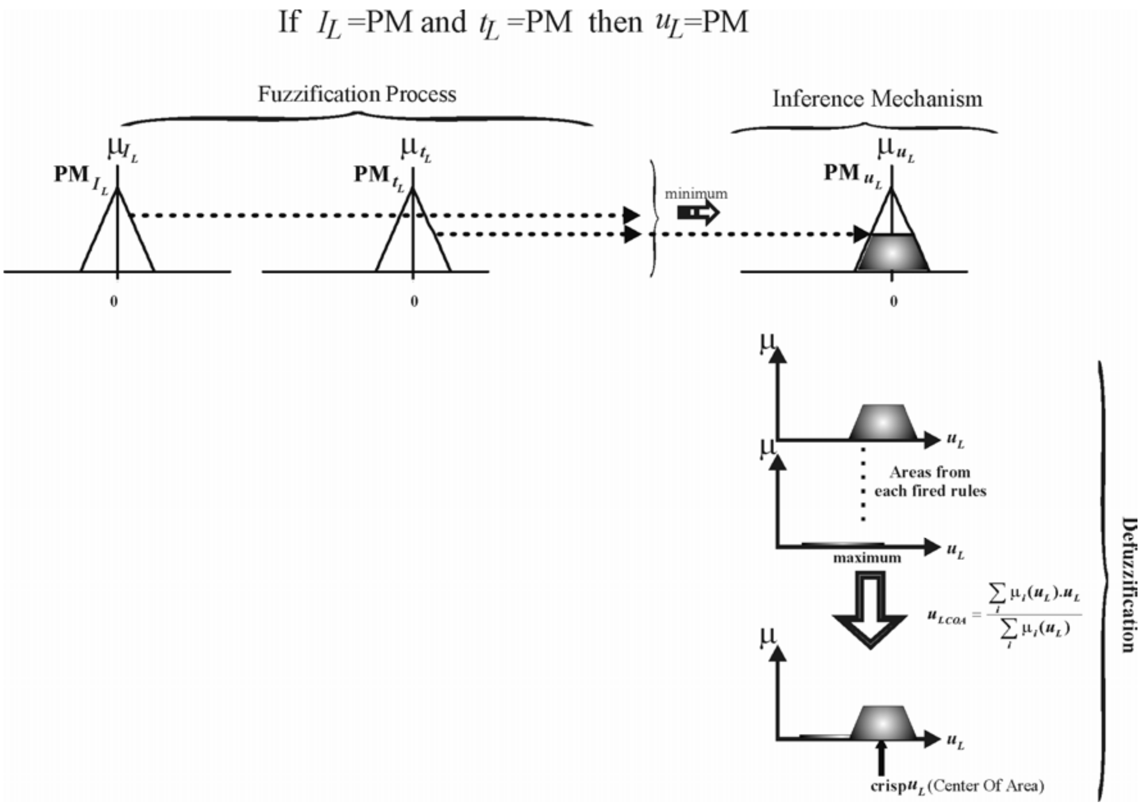

Fig. 5. Flow schema of a fuzzy logic based controller

3. PRINCIPLES OF LEAKAGE CURRENT RELAY AND DESIGNED PROTOTYPE SYSTEM STRUCTURE

The human body is very sensitive to the passage of electric current. A small current passing through the chest can cause serious harm. The magnitude of the current is proportional to the supply voltage (i.e. 240V in the case under consideration) and inversely proportional to the impedance value of the current path. The complete current path must be available for the current to flow. In general, with electric shock situations, this path is provided by the current flowing through the body to the general ground earth, or to a local earth such as a water pipe. A simple pictorial view of a typical electric shock situation is shown in Fig. 6. The victim of Fig. 6 is touching a 240V active conductor and the current that flows will depend upon the body resistance and the impedance Z between the body and earth. Predicting the current that is likely to flow is very difficult because many factors influence it, such as whether the body skin is moist or dry, the contact area and pressure (i.e. whether the object is touched or gripped) and the impedance between the body and general mass of earth. The skin resistance of the human body may vary from 1,000 Ohms for wet skin to over 500,000 Ohms for dry skin. Table 2 shows human resistance for various skin-contact conditions.

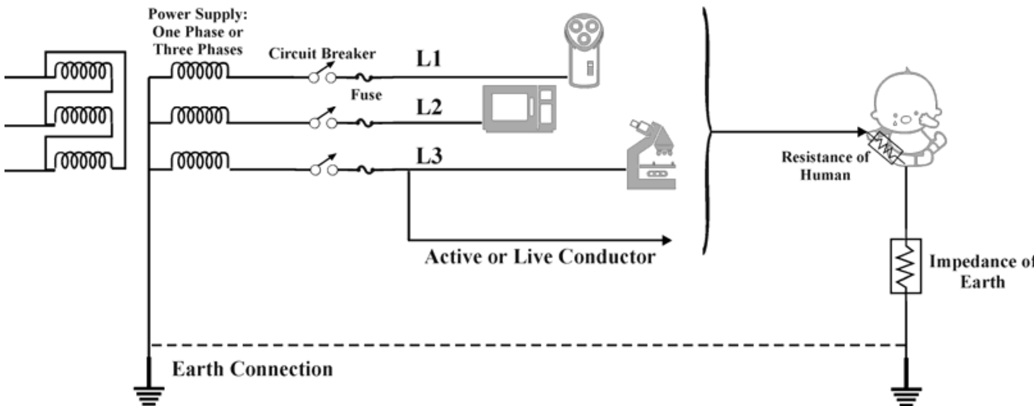

Fig. 6. Occurrence of leakage current and its path

Table 2. Human resistance for various skins

Condition of contact	Resistance in Ohms	
	Dry	Wet
Finger touch	40k-1M	4-15k
Hand holding grasp	15-50k	3-6k
Finger thumb grasp	10-30k	2-5k
Hand holding pliers	5-10k	1-3k
Palm touch	3-8k	1-2k
Hand around 37 mm pipe (or drill handle)	1-3k	0.5-1.5k
Two hands around 37 mm pipe	0.5-1.5k	250-750
Hand immersed	---	200-500
Food immersed	---	100-300
Human body, internal, excluding skin	200 to 1,000 ohms	

Consequently, a multitude of possibilities exist, depending upon the resistance to earth, which could theoretically be as low as 1,000 Ohms (or even less) for wet skin, a large contact area with the active connection and direct contact with earth, or as high as several million Ohms if the body is well insulated from earth.

Taking the case of 1,000 Ohms would give 240 mA, which is potentially lethal as it is shown in Fig. 7. The 240 mA is not sufficient to blow the fuse and theoretically this current could flow indefinitely satisfying the duration requirements of Fig. 4. If the extreme of high resistance to earth were taken, then the electric shock would be below the threshold of sensation and would not even be detected. The physiological effect of various current magnitudes and the effect of current duration are shown in Fig. 7 and Fig. 4, respectively. Different zones have various effects on human health as shown in Fig. 4. Usually, no reaction effects occur in zone 1. No harmful physiological effects are observed in zone 2. But, in zone 3 situated between curves b and c1, there is normally no organic damage for people. However there is a likelihood of muscular contractions, breathing difficulties and reversible perturbation of the formation of impulses in hearth and of their propagation. All these phenomena increase with current strength and exposure time. The most dangerous zone is zone 4 and situated to the right of curve c1. In addition to the effects of zone 3, the probability of ventricular fibrillation is:

- Approximately 5% between curves c1 and c2,
- Less than 50% between curves c2 and c3,
- More than 50% beyond curve c3.

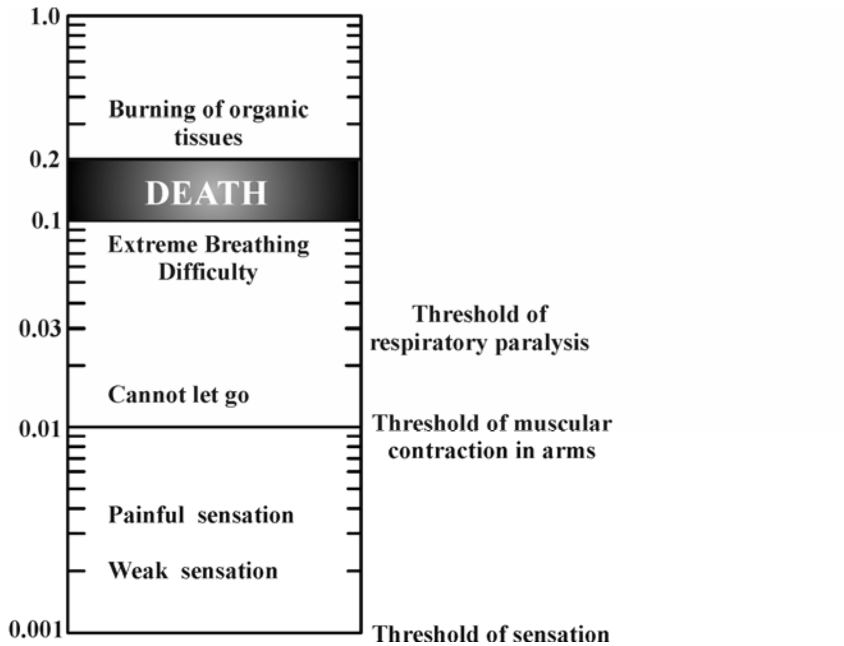

Fig. 7. Physiological effects of electric currents

Patho-physiological effects such as cardiac arrest, respiratory arrest and serious burn increase with current strength and exposure time. Therefore, it is accepted that the use of a leakage current relay with instantaneous operation and with a threshold of less than 30 mA and 25 milli-seconds ensures that the situation is never obtained and such risks never incurred [18].

The structure of a complete system that contains a fuzzy logic based relay software and leakage current relay was given in Fig. 8. A toroidal transformer was used to measure leakage current. The measured current was entered to a Data Acquisition Card (DAC) and converted into a digital signal. Software of FLBLCR was written in Pascal programming language. A computer system clock was used to determine the duration of the current. Instead of a human body, a resistance bank was used to obtain various current values. A switch of the resistance bank was controlled by using digital output of DAC for selecting resistance bus. A timer was started when the switch control signal was sent. A +5 V DC voltage was used as a trip signal and sent to the circuit breaker from analog output of DAC. When a trip signal was produced, a relay was used as a circuit breaker to isolate the system from power entrance. Five discrete lines were used to obtain phases, neutral and ground connections. All of them were connected to appropriate places in the mother-panel. FLBLCR was applied to both single and three phases systems. One of the phase connections was used for a single-phase system. A digital watch, a tape-recorder and a lamp were used as loads for each of the lines.

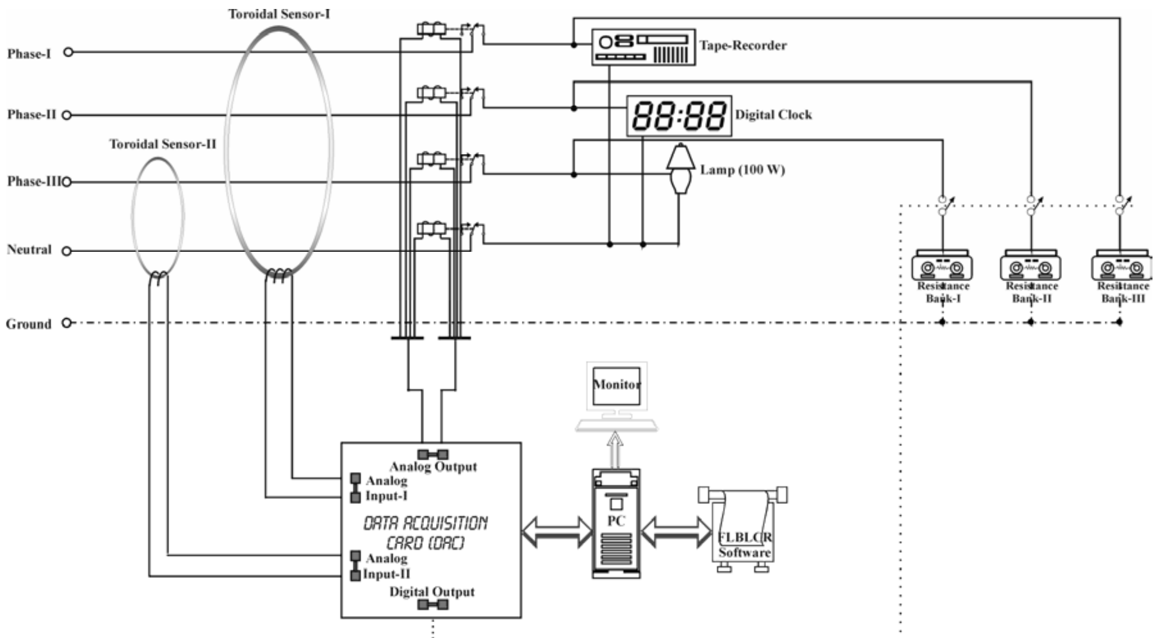

Fig. 8. Structure of complete system

Considering the previously mentioned boundary conditions, a fuzzy logic based controller and its membership functions were created to make control action more intelligent related to magnitude and duration of current as described in Fig. 2 and Fig. 3. As given in Table 1, to see and compare the effects of fuzzy logic on the output of leakage current relay more efficiently, the magnitude of leakage current and its duration was changed to various values as shown in Fig. 9-12. Results were obtained for the different conditions changed.

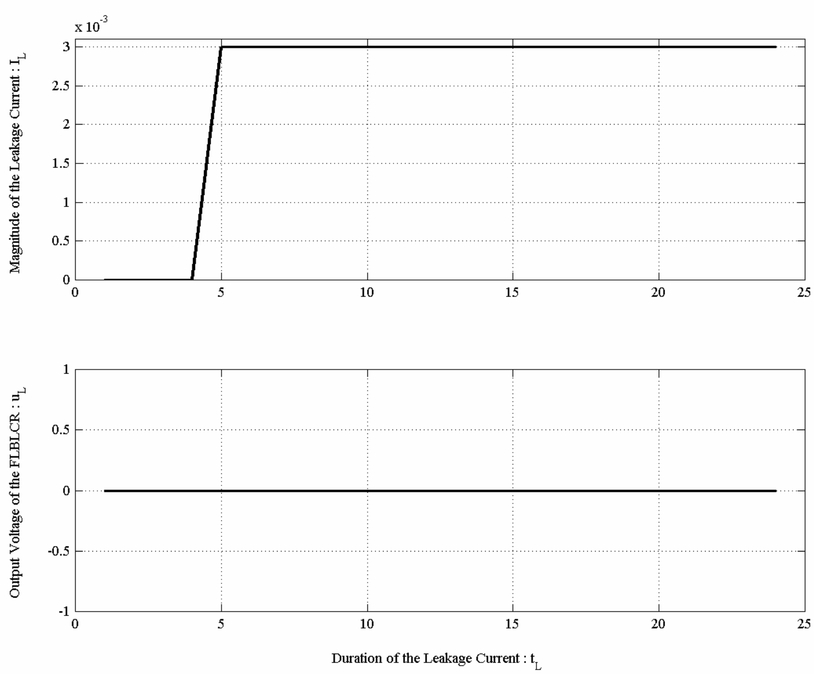

Fig. 9. Controlled system output for 3 mA

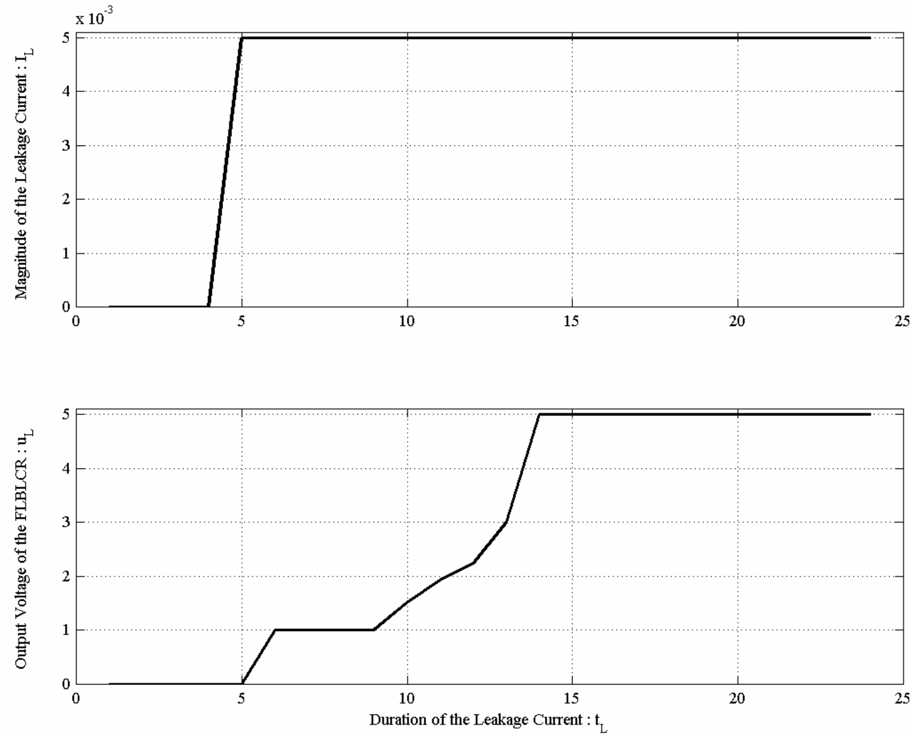

Fig. 10. Controlled system output for 5 mA

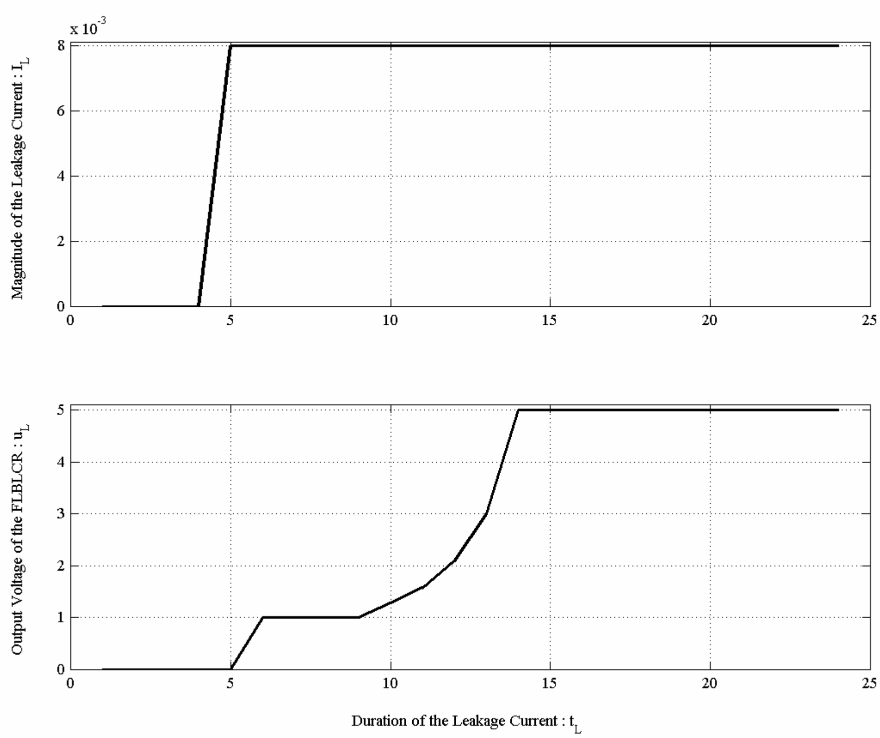

Fig. 11. Controlled system output for 8 mA

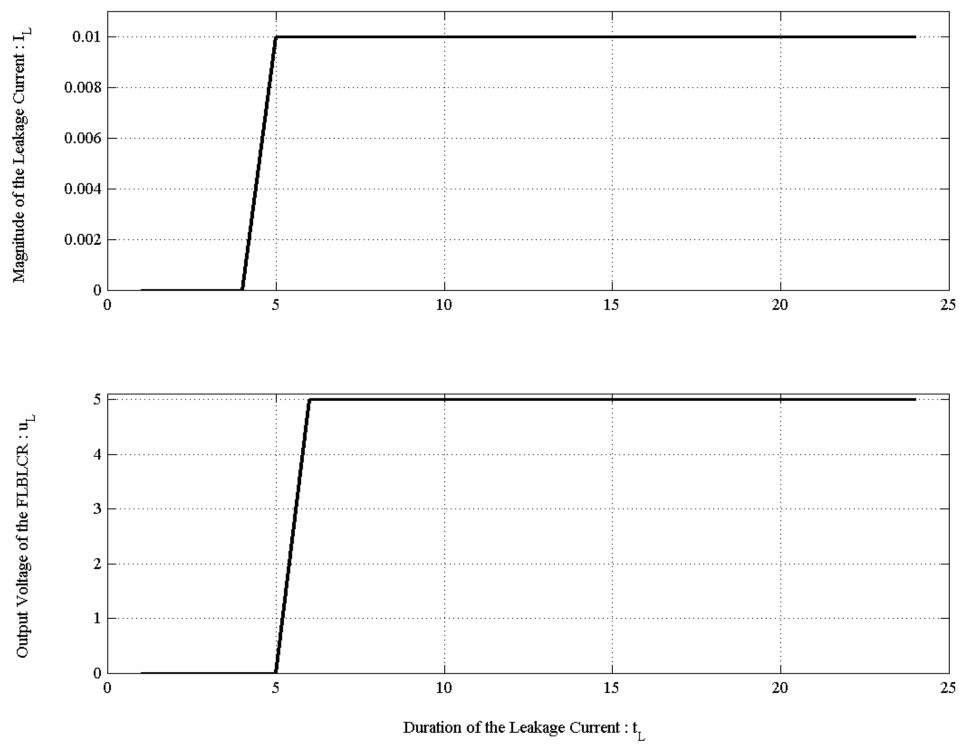

Fig. 12. Controlled system output for 10 mA

4. RESULTS OF FUZZY LOGIC BASED LEAKAGE CURRENT RELAY

An application of a fuzzy logic based controller to a leakage current and its results were given in Fig. 9-12. Different current magnitudes and durations of the leakage current were used for testing FLBLCR. A magnitude of the leakage current equal or less than 3 mA was selected as the minimum boundary condition for a warning alert. Duration of the leakage current equal or less than 3 mA had no effect on the control of warning alert or trip signal. Magnitudes of the current between 5 and 10 mA were tracked very carefully. Although the current had medium magnitude, its duration was important for human safety. If magnitude of the current was between 5 and 10 mA and its duration was long, a harmful physiological effect might occur for humans. Magnitude of the current equal or bigger than 10 mA was the upper boundary condition and threshold value as shown in Fig. 7. Duration of the current equal or bigger than 10 mA was not important for FLBLCR. If there is any leakage current equal or bigger than 10 mA, a trip signal had to be produced and the system had to be isolated from the power supply immediately.

Magnitude of leakage current was changed from 0 to 3 mA using a resistance bank as illustrated in Fig. 9. Output of the FLBLCR was shown in Fig. 10 for the changed magnitude of leakage current from 0 to 5 mA. Duration of the current was increased from 5 to 12 ms to observe the change in output of FLBLCR. A warning alert was produced if the duration of the current was 7 ms as given in Fig. 10. For a longer duration of the current, for instance 12 ms, a trip signal was sent and a prototype system was isolated from the power supply. Both warning message "THIS IS A WARNING MESSAGE" and trip signal "TRIP SIGNAL IS SENT" were monitored in MS-DOS environment.

For non-faulty cases a message "THERE IS NO PROBLEM" was also monitored. These messages were produced related to the output of the FLBLCR. For example, if output of the FLBLCR was equal to 0 then "THERE IS NO PROBLEM" message was monitored. On the other hand, "THIS IS A WARNING MESSAGE" and "TRIP SIGNAL IS SENT" were monitored if the output of the FLBLCR was equal to 1 and 5, respectively. A transient or permanent decision was made depending on magnitude and duration of the current. The current, which had a longer duration but had a medium magnitude, was classified as permanent. If the current had a shorter duration and a medium magnitude, it was defined as transient. Similar to the previous approach, magnitude of the current was increased from 0 to 8 mA, and its duration was changed from 5 ms to 10 ms as shown in Fig. 11. Although 5 ms was enough for transient classification for the current, 10 ms was recognized as permanent and the trip signal was sent. 10 mA was a critical boundary for human health and safety as drawn in Fig. 7. The currents equal to or larger than 10 mA were classified as permanent and no attention was paid to its duration (this condition was illustrated in Fig. 12).

5. CONCLUSIONS

Fuzzy logic based leakage current relay has been designed to control the tripping signal of a leakage current relay for various magnitude and duration of current values in this study. A prototype system has been designed and a fuzzy logic based control system has been applied to the system. A novel approach have been given to determine the rule-base. Not only the magnitude of leakage current, but also its duration has been used as input variables for fuzzy logic based leakage current relay. The relay proposed here was a more developed relay than conventional leakage current relays. Some abilities have been added to the studied leakage current relay such as improvement in human safety and system reliability, distinguishing whether the leakage is transient or permanent, and determining the correct action. Both single and three phases have been investigated and satisfactory results have been obtained. The proposed relay software is going to be converted to a suitable form for a micro controller in the future. Despite an increment in the cost, the proposed architecture is more suitable than classical leakage current relay.

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