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Mathematical Modeling of Time Response Analysis of Residual Current Devices with Electronic Switches

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Abstract

Today, relay contact and electronic residual current relays are used in order to protect human life against electrical shocks and machinery and equipment from malfunctions caused by excessive current. These residual current relays step in at 30 mA level and cut the current from the system. With the developed electronic switch and residual current device hybrid system, the human body residual current value and current cut-off response time were calculated using Monte Carlo Simulation frequency / intensity distributions. In the field of application, data sets were created in this study, which can be realized using physical and ambient data related to the human body resistance value. In this study, the reaction time of the system developed according to the amount of electric current, temperature of the human body, skin and moisture properties, shoes worn, decking, material type characteristics was modeled mathematically by using Monte Carlo simulation.

Keywords: Circuit breaker, electronics switches, monte carlo simulation, residual current devices, time response analysis

1. INTRODUCTION

The time from the residual current detection of the residual current relays until they completely cut off the electricity from the system is called the response time. The average response times of the residual current relays are given as 30 ms in residual current device (RCD) type residual current relays when the current is directly in contact, and 3-5 ms in electronically type residual current relays.

Mooney defined the Monte Carlo simulation method as a method of evaluating important hypotheses and statistical estimates by developing an algorithm to simulate a data set, creating a large number of samples in

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this estimated data set, and evaluating estimates obtained from these samples [1]. In their study, Papadopoulos and Yeung stated that they evaluated the reliability of parametric inference by testing hypotheses under various reasonable conditions in social and behavioral studies using mathematical theory and statistical calculations with Monte Carlo simulation [2].

The electrical conduction of the human body depends on varying body values with different ambient conditions. These values can have different results under different conditions according to ambient conditions, body characteristics and exposed electrical current values. In his study, Dalziel determined the effect of human skin thickness and humidity on body electrical resistance [3]. In his study, Nuran examined the resistance of the type of material used in shoes and floor coverings against electric current. Human skin has a resistance of 100-300 kΩ under normal conditions, while moist skin reduces to 1% of these values to 1-3 kΩ. At the same time, the resistance value of calluses and thick skin is up to 1-3 MΩ levels. It is stated that the electrical resistance can vary between 1-1.000 kΩ according to the floor covering of the shoes that the person is wearing [4].

Monte Carlo simulation has a wide range of uses. Cobanoglu et al. Monte Carlo simulation method was used to determine the state of charge of electric vehicle batteries in the design of a solar powered charging station for electric land vehicles [5]. Genç and Varan used Monte Carlo simulation method in the implementation of numerical techniques in electromagnetic field theory with visual programming methods in their studies [6]. Periyasamy and Pramanik made a model by examining the propagation of light in the tissue [7]. Baležentis and Streimikiene have sequenced power generation scenarios with Monte Carlo simulation [8]. In his study, Silva proposed a new method to calculate overload probability and risk indices in transmission equipment based on Monte Carlo simulation by using significance sampling techniques with the cross entropy method [9]. In their study, Marmidis et al. used the monte carlo simulation method in order to estimate the most suitable location for the placement of wind turbines in the field of renewable energy [10].

In direct contact of the human body with the electric current, the path followed by the current passing through the body determines the intensity of the current passing and the damage to the body during the time the human body is exposed to the current. The intensity of the current flowing also varies according to the resistance value created by the body resistance and environmental conditions, which vary from person to person. The time required for residual current relays, which will protect people from this current, to detect the current and completely disconnect the electric current, is the response time. The shorter this period, the less damage to the body will be [11].

Residual current was created using the human body model (HBM), created from capacitors and resistors, to simulate human contact to the electronic switch and residual current device developed as a hybrid [12].

In this study, the effect of the system on the reaction time was investigated using Monte Carlo Simulation with parameters such as body temperature, skin and moisture properties, shoes worn, floor covering, material type and properties. Mathematical formulation of the system was obtained by creating Probability Density Function (PDF) and Cumulative Density Function (CDF) graphs based on this time.

2. MATERIALS AND METHODS

In Figure 1, human body model is shown. It consists of 10 kΩ parallel resistance and 0.25μF capacitance. Although this HBM was developed for high current effects, it can be used at low current levels [13].

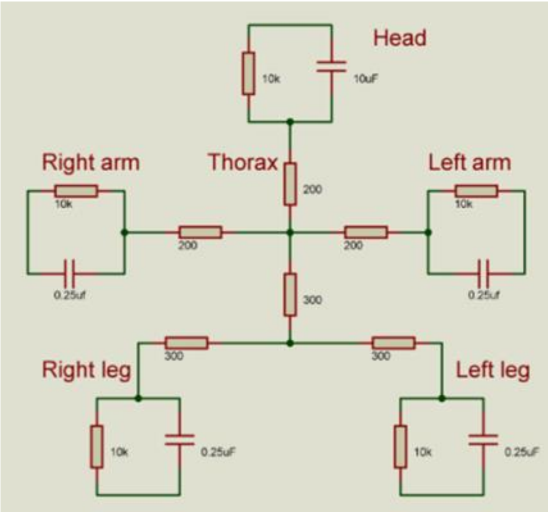

Figure 1 Human body model

It is known that electric current is the correlation between body passage, current intensity and electrical resistance. According to the body passage;

1st current path; according to the right arm-body-left arm current flow path, the human body resistance increases Z_B=10%, the heart flow coefficient becomes k=0.4.

2nd current path; according to the right arm-body-feet current flow path, the human body resistance increases Z_B=75%, the heart flow coefficient becomes k=0.8.

3rd current path; according to the hands-body-feet current flow path, the human body resistance increases Z_B=50%, the heart flow coefficient becomes k=1.

4th current path; according to the right and left hand-chest flow path, human body resistance increases Z_B=50%, the heart flow coefficient is k_{right}=1.3, k_{left}=1.5.

5th current path; according to the hands-chest flow path, the human body resistance increases Z_B=25%, the heart flow coefficient becomes k=1.1 [14].

According to the given current pathways, the residual current intensity passing through the body can be calculated with the equation;

$$\text{Ib} = \frac{U}{\text{Rg+Zb}}.k \tag{1}$$

In this equation;

I_b=The current passing over the human body (A),

U=Exposed electrical voltage (V),

Rg=Human body resistance value (Ohm),

Zb=Human body relative resistance value (Ohm),

k=Heart rate coefficient.

In this study, the voltage value in simulations was taken as 380 V, since the designed system was produced for industrial environments operating with 380 V. In addition, body residual current intensity was calculated by taking into account the resistance values varying according to the conditions given the reaction time. The response time of the system, which is designed according to the calculated body residual current intensity, also changes in direct proportion. When the designed system is operated as a residual current relay, the residual current interrupt value of the system is determined by a software value of 5 mA on the microcontroller. As a result of 200 previous experiments, the average response time of the system was determined as 1.32 ms according to the current value of 5 mA [15, 16]. In the simulations to be created, the response time was calculated and simulated according to the Ib current value calculated based on this average value.

The R_g resistance value used in formula 1 above varies depending on conditions such as body temperature, skin thickness, body humidity, shoes worn and floor covering material properties that may differ for each person and situation [3, 4]. In the simulations performed, the R_g value was added to the human body resistance value (Z_b) by providing a random value in the range of different resistance values of the specified conditions. Thus, different scenarios have been produced for calculating the I_b value, which is the current passing through the human body.

3. RESULTS

In order to test the response time of the designed system according to different conditions, 5000 different resistance values were produced by taking into account the variable resistance values in the ranges given according to the above-mentioned conditions. With these values, 5000 different scenarios were produced using Monte Carlo simulation method and PDF and CDF graphics were created to determine the efficiency of the system according to these situations.

According to the determined simulation theory, the graphs created show the distribution of the response time required for the system to completely cut off the electrical energy in the system from the moment the residual current is detected, depending on the intensity of the current passing through the body, according to the environment and body conditions.

Formula used for creating PDF graphics [17];

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (2)$$

In the formula;

μ=Average value for response time (ms),
σ=Shows the standard deviation value for the response time (ms).

The generated PDF graph polynomial equation is;

$y = -0{,}0003x^5 + 0{,}0049x^4 - 0{,}0134x^3 - 0{,}0758x^2 + 0{,}29x + 0{,}0653$

In the PDF graph given in Figure 2, the distribution of the "X" axis, which is the resistance values that differ according to the variable conditions, and the "Y" axis, which is the response time of the system developed according to the current passing through the body, can be seen. A random variable resistance value given on the X axis indicates the probability of the response time value occurring in a single simulation on the Y axis. According to the graph, the probability of distribution of response time is especially concentrated under 2ms. This situation shows that the response time probability of the designed system for the percent density of the current values passing through the human body calculated according to the body resistance value determined depending on the body temperature, skin thickness, body humidity, worn shoes and floor covering material conditions is 2ms and below.

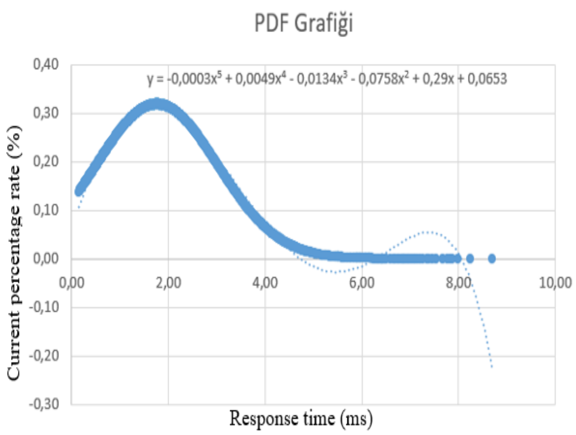

Figure 2 PDF chart generated as a result of monte carlo simulation

The Integral of the PDF chart gives the CDF chart. The formula used to create a CDF chart;

$$F(x) = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \quad (3)$$

In the formula;

μ= Average value for response time (ms),

σ= Shows the standard deviation value for the response time (ms).

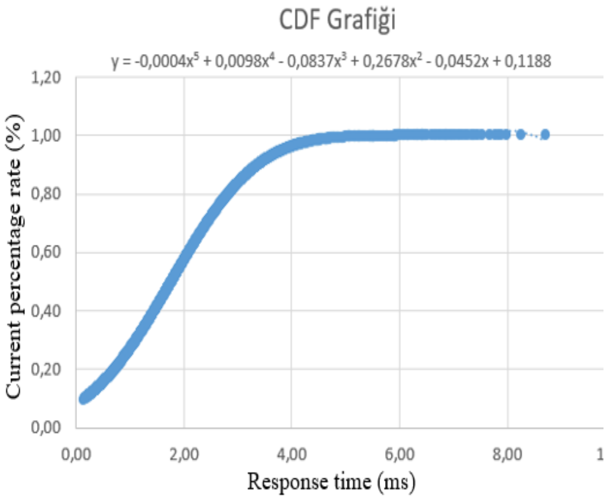

Figure 3 CDF chart generated as a result of monte carlo simulation

The generated CDF graph polynomial equation is;

$y= -0{,}0004x^5 + 0{,}0098x^4 - 0{,}0837x^3 + 0{,}2678x^2 - 0{,}0452x + 0{,}1188$

The CDF graph given in Figure 3 shows the response time intensity distribution according to the current flowing through the body. In the graph, the Y axis shows the flow values through the body, while the X axis shows the reaction time intensities according to these values. The probability of getting a value lower than or equal to the value corresponding to variable response times is seen as cumulative density. The response time of the system developed according to this distribution was 2 ms and less with a rate of 60%. In this case, it has been seen that the response time of the system developed at 60% levels of the cumulative density of the leakage current values, which is formed as a result of the simulations performed according to the human body resistance value and the path of the leakage current in the body, will be 2ms and below.

4. CONCLUSIONS

In this study, the response time required for a hybrid system with electronic switch and residual current relay to cut the electrical current as a result of direct contact of the human body with the electrical current has been investigated. Monte Carlo simulation method was used in this study. The path followed by the current passing through the body in the contact of the human body with electricity, the intensity of this current and the duration of the human body being exposed to this current play an important role in terms of health problems that may occur in the person. The intensity of this current also varies according to the resistance value created by the body resistance and environmental conditions, which vary from person to person. Under normal conditions, the human body resistance value is 100 - 300 Kohm, while the moisture rate of the body varies according to variable conditions such as perspiration, floor covering and wearing shoes. This variable resistance value affects the current intensity passing through the body. The response time of the system developed according to this current intensity to interrupt the electrical current varies.

Using the Monte Carlo simulation method, 5000 different scenarios were produced for the current intensity and system response time that differ according to variable resistance values. Using these scenarios, PDF and CDF graphics were created according to the response time of the developed system. When these graphs are examined, it is seen that even in the worst scenario, the response time probability distribution of the developed system is 2ms and less.

The leakage current value was calculated according to the temperature, humidity, skin thickness characteristics of the human body, the resistance value created by the shoes worn, the type of floor covering material and the path of the leakage current in the human body. Response time of the developed system was obtained by applying the leakage current calculated by generating random values within the range of values given in the literature and applying the specified variable resistance values to the human body modeling. The response time of the developed system is mathematically modeled according to the leakage current value obtained by Monte Carlo simulation. PDF and CDF graphics obtained as a result of this mathematical modeling, it has been determined that the response time of the developed system is fast at the desired rate in the detection of leakage current that occurs as a result of different features and body resistance values. According to this result, the developed system has a very fast response time even in cases where the resistance value formed according to the characteristics of body temperature, humidity, skin thickness, the shoes worn and the floor covering material is high, and accordingly, the leakage current passing through the human body remains at very low levels. can be said to be.

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The Declaration of Research and Publication Ethics
The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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