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A NEW DIGITAL PROTECTIVE RELAY BASED ON FUZZY LOGIC AND VALUE ESTIMATION*

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Abstract – In this paper, design and application of a new digital protective relay based on fuzzy logic and value estimation to a radial power system protection was presented. A novel approach based on value estimation was investigated for the proposed fuzzy logic based protective relay. In addition to the theoretical aspect of fuzzy logic, mathematical definition of value estimation, detection and measurement of faulty current, determination of its duration, decision mechanism and detailed system architecture were also introduced. The examined technique based on fuzzy logic and value estimation to control the protection action of the protective relay was intended to improve the performance of a conventional protective relay control for human safety and system reliability with the use of a fuzzy logic controller. The difference between estimated and sampled values was used to form the rule base. Proposed relay architecture was used as a detector and was developed to predict faults and to protect particular sections of a designed prototype radial power system at an early stage. Performance analysis was made, and related results and discussion were given.

Keywords – Value estimation, fuzzy control, AC transmission, fault detection, digital protective relay

1. INTRODUCTION

Research in the field of protection and protective relaying techniques of power systems have increased rapidly 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, relay position, where fault is determined to be either internal or external. To achieve fast and reliable distance protection many techniques have been developed [1, 2].

Substantial research towards better algorithms was carried out for protective and distance relaying. Among these algorithms, different techniques were proposed to estimate the phasor quantities of 60 Hz information based on discrete Fourier transform, batch processing least square estimates, Walsh functions, adaptive Kalman filtering, etc. [1-5]. As a result of increasing digital computers and micro controllers, a new application area came out to protective relays [3-5]. Afterwards, digital relaying algorithms were developed, simulated and then results were observed in the PC environment [6-11].

Traveling wave relays based on a magnetic field constituted by electrical current were proposed as another developed technique to classify fault type and to determine fault location [4, 12]. A case based reasoning method was enhanced for computers and digital relaying algorithm usage, and then

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expert systems were applied to power system protection [13-17]. Adaptive protective relay applications were developed and used, owing to the insufficiencies of reasoning theory [2, 18].

With the improvement of the techniques, new and intelligent protecting methods were developed. Among these, fuzzy logic based systems that have human-like operating properties were started to be used on power systems similar to other application areas. Fuzzy logic based systems differ from conventional logical systems. The fuzzy logic systems are shown to give better results than the classical methods. Recently, the research has moved to the intelligent systems in power systems applications [19-23].

In this study, a novel approach based on fuzzy logic and value estimation was investigated in order to protect the power system against faulty conditions and to control the protective relay. A prototype radial power system was designed and the proposed approach was applied to the prototype system. In addition to the theoretical aspect of fuzzy logic, mathematical definition of value estimation, detection and measurement of faulty current, determination of its duration, decision mechanism, detailed system architecture and rule base forming were also introduced. The proposed relay was developed using conventional protective relay characteristics by adding some abilities such as improved human safety and system reliability, distinguishing whether the fault was transient or permanent, and determining correct action. The prototype experimental setup consisting of a single phase was developed as a radial system and was tested for the proposed method, and satisfactory results were obtained.

2. SYSTEM MODEL AND PROPOSED METHOD

Relaying is a subdivision of power system protection engineering that is interested in determining abnormal operating conditions and obtaining corrective events for power system protection. Since human interference to the power system is not possible when a fault occurs, a fast response has the most important role in protective relay systems. The produced response has to be in a form that will cause the minimum damage to the power system. To accomplish this, a prototype power system was designed and the proposed method was applied to the developed radial power system model. System structure of the prototype power system model was shown in Fig. 1.

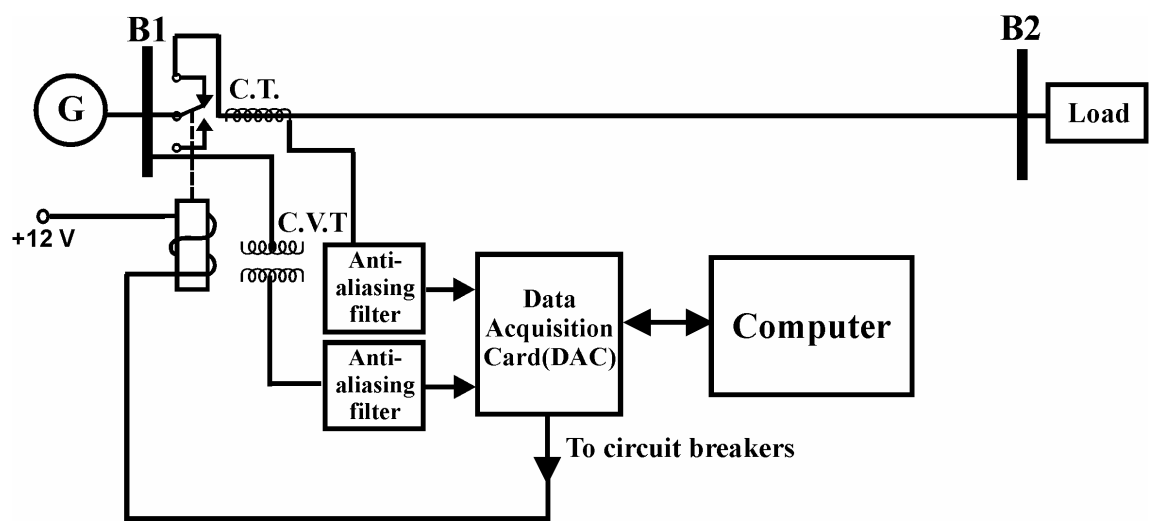


Fig. 1. Experimental setup

Current and voltage data was sampled from the designed power system by using CT and CVT. An anti-aliasing filter was used to remove noises and swings from the sampled current and voltage data. The filtered data was entered into a computer containing fuzzy logic based protective relay software, by using a Data Acquisition Card (DAC). Based on the processed current and voltage data in the software, a relay was used as a circuit breaker to isolate the power supply from the system when a fault occurred. During all these processes, a decision was made as to whether the fault was transient or permanent, and classical relay characteristics were used. If a fault characteristic was classified as transient, then the operator was alerted with a warning sound. Otherwise a trip signal was produced and relay was activated. Fuzzy logic based protective relay software was created in Pascal programming language.

In the proposed and designed relay architecture, a novel value estimation method was used as opposed to previous works. It is essential in this method to estimate the voltage value at (t+2) sampling instant. The estimated voltage value was formed by using the previously sampled values, which belong to the values at (t+1) and (t) sampling instant. The proposed method had no dependency on sampling interval and sampling frequency. To establish a relationship between estimated and previously sampled values, a mathematical expression was defined as in Eq.1.

$$x_{\text{Estimated}}(t+2) = A.\sin(2.\arcsin(\frac{x_{\text{Sampled}}(t+1)}{A}) - \arcsin(\frac{x_{\text{Sampled}}(t)}{A})) \tag{1}$$

where A is the magnitude of sampled value and x(.) is the sampled value related to sampling instant. Using the above algorithm, the expected value was estimated before the (t+2) sampling was done. A closed loop was constructed for all values to obtain continuous operation. Error and change of error between sampled and estimated value were used as input values for the fuzzy logic controller. Mathematical expressions of the error and change of error were given in Eq.2 and Eq.3.

$$e(t+2) = x_{\text{Sampled}}(t+2) - x_{\text{Estimated}}(t+2) \tag{2}$$

$$ce(t+2) = e(t+2) - e(t+1) \tag{3}$$

For the pre-fault conditions, the following assumptions were made:

1. The pre-fault conditions were normal steady-state ones.
2. The source impedances were omitted.
3. Fault impedance and neutral impedance were omitted for all faulted cases.

3. FUZZY CONTROL

The operation principle of fuzzy logic controller is similar to a human operator. It performs the same actions as a human operator does by adjusting the input signal looking at only the system output.
Fuzzy logic has three steps as shown in Fig. 2:

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).

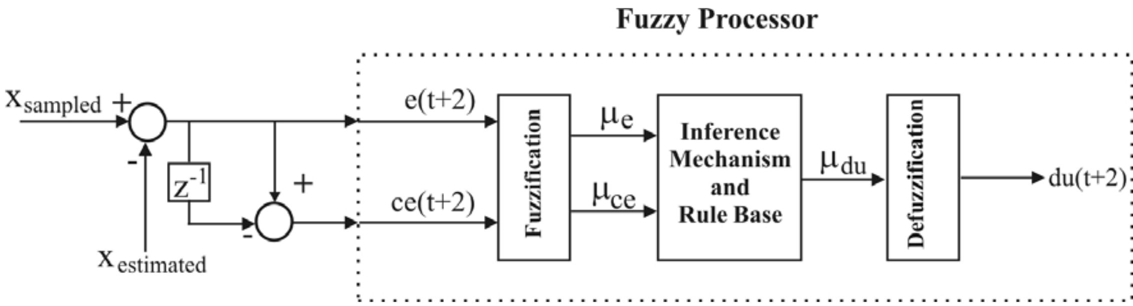


Fig. 2. Steps of a fuzzy logic based controller

Fuzzification is the first step of fuzzy logic, where the actual measured input values are mapped into fuzzy values through membership functions. To create a fuzzy control system, membership functions were first developed for the input variables "error" and "change of error". These membership functions could be defined by triangular, sigmoid, gauss, bell-shaped, etc. functions. In fuzzy logic, it is important for a variable to belong to a membership function with a relative membership degree. This gives the variables a "weighted" membership in a membership function. A variable can have a weighted membership in several membership functions at the same time. The triangular type membership functions for "error" and "change of error" were drawn as shown in Fig. 3. Mathematical expression and a graphical illustration of the membership function were given in Appendix B.

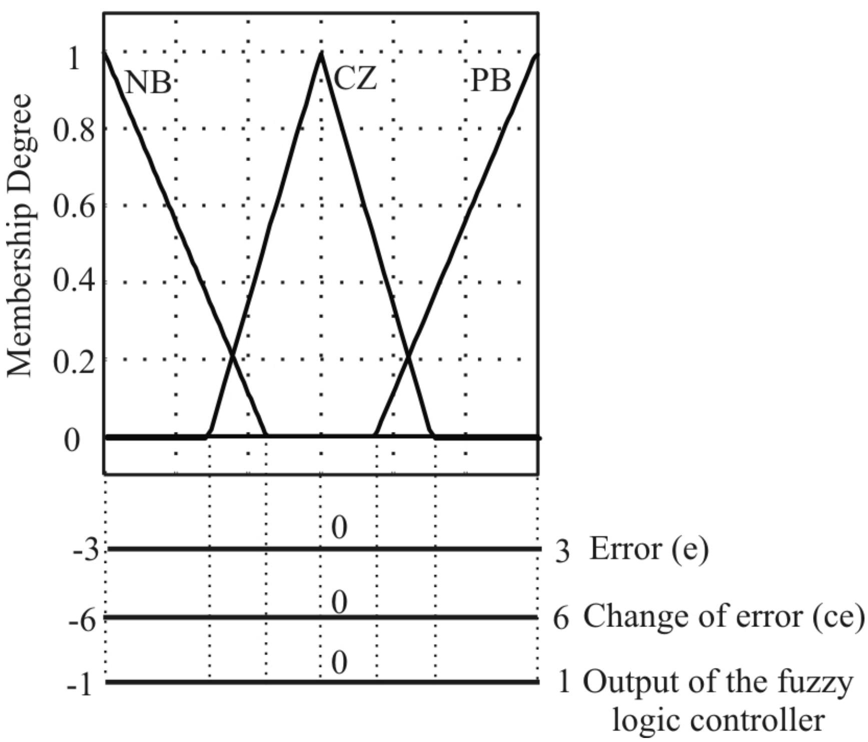


Fig. 3. Membership functions for error (e), change of error (ce), and control signal (du)

Secondly, fuzzified values were processed in the fuzzy inference system to define appropriate control action. Output of the fuzzy inference step is also fuzzy. Finally, the resultant fuzzy numbers representing the controller output were converted into crisp values. This was the last step of the fuzzy control, which is called defuzzification.

Linguistic fuzzy variables of the designed fuzzy logic controller for digital protective relay were represented by three different fuzzy sets; negative big (NB), closure to zero (CZ), and positive big (PB). Triangular type membership functions given in Fig. 3 were chosen to represent shapes of these fuzzy sets.

Although the shapes of the fuzzy subsets NB, CZ, and PB were all the same for error (e), change of error (ce), and change of control signal (du), the maximum and the minimum intervals of the universes of discourses differed from each other. The maximum and the minimum limits of the universe of discourse for error, e, were chosen as –3 and 3, respectively. In order to make changes of error more effective in terms of controller, the maximum and the minimum limits of the universe of discourse for change of error, ce, were chosen as –6 and 6, respectively. The maximum and the minimum limit values of the universe of discourse for the control signal, du, were chosen as –1 and 1, respectively, as shown in Fig. 3.

The difference between the sampled and estimated value was used to obtain the error, e, and the change of error, ce. The error and the change of error values were entered into a fuzzy logic controller. In order to determine membership degrees of these values, the fuzzification process was used and the crisp values were fuzzified by using the membership functions shown in Fig. 3. A rule assignment table was used to get correct output value using fuzzified values and its membership degrees. The rule assignment table for the proposed protection relay was given in Table 1. Obtained values from overall fired rules were entered to the defuzzification process and the output crisp value was determined.

Table 1. Rule assignment Table

	$\mathbf{NB_{ce}}$	$\mathbf{CZ_{ce}}$	$\mathbf{PB_{ce}}$
$\mathbf{NB_e}$	NB_{du}^{1}	NB_{du}^{2}	CZ_{du}^{3}
$\mathbf{CZ_e}$	NB_{du}^{4}	CZ_{du}^{5}	PB_{du}^{6}
$\mathbf{PB_e}$	CZ_{du}^{7}	PB_{du}^{8}	PB_{du}^{9}

The change in control signal was found in linguistic form by the assist with this table. These linguistic forms were defined with If-Then type rules. In the table, the left side includes linguistic terms for error, e, while the upper side of the table features linguistic terms for change of error, ce. Their cartesian form defines the linguistic form of the change in control signal, du. One of these rules can be expressed by a linguistic term as below:

IF e is NB AND ce is PB THEN du is CZ.

This expression can be rewritten in a shorter form by eliminating e, de, and du.

IF NB_e AND PB_{ce} THEN CZ_{du}.

Multiple rules are connected to each other by the term ELSE. Linguistic representation of Table 1 can be expressed as follows:

Rule 1 $\rightarrow$ IF NB_e AND NB_{ce} THEN NB_{du} ELSE

Rule 2 $\rightarrow$ IF NB_e AND CZ_{ce} THEN NB_{du} ELSE

………….. ……….. ……….

………….. ……….. ……….

Rule 9 $\rightarrow$ IF PB_e AND PB_{ce} THEN PB_{du}

In terms of membership degrees, the result can be written as:

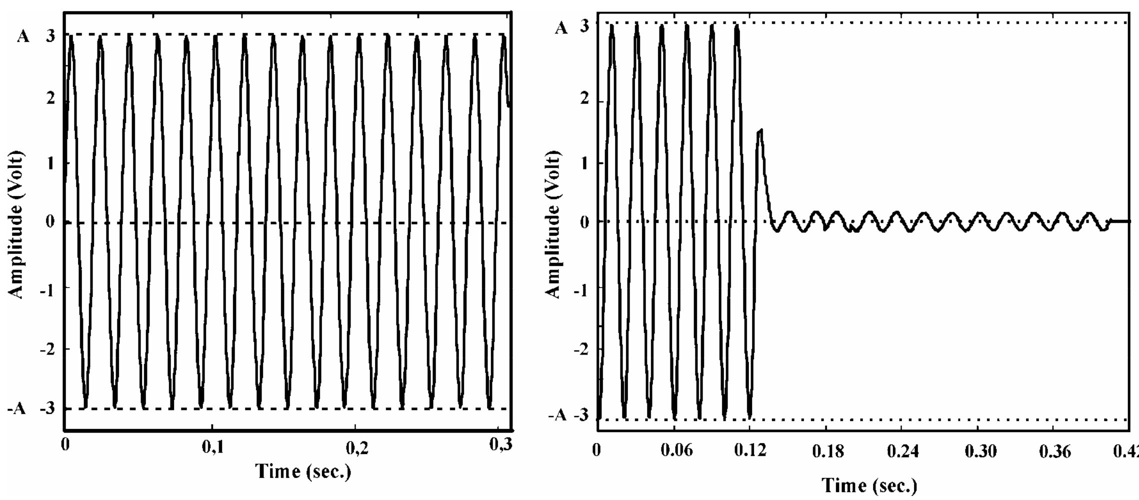
$$\mu(du)=\max[\min(\mu(e), \mu(ce))]$$

This process is the second step in fuzzy logic, which is called inference mechanism. To obtain the final value of du(k), Eq.4 can be used:

$$du(k) = \frac{\sum_{i=1}^{9} \mu_i(du)du_i}{\sum_{i=1}^{9} \mu_i(du)} \tag{4}$$

This operation is called the center of the area (COA) method, and is the last process of fuzzy logic. Since the output of this process is a crisp value, this process is called defuzzification.

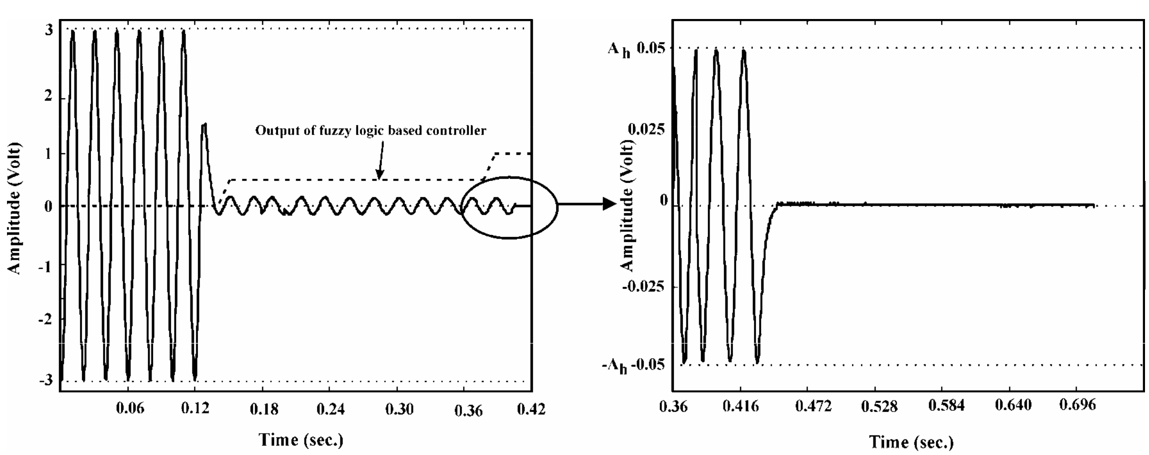
In the application of the designed fuzzy logic controller for the digital protective relay, the time variation of the sampled voltage of the prototype system for the non-faulted and faulted case were given in Fig. 4 (a) and (b).



(a) (b)

Fig. 4. Sampled voltage value of prototype system: (a) non-faulted case, (b) faulted case

In the case of fault occurred, the detailed voltage variation of the system was shown in Fig. 5.



(a) (b)

Fig. 5. (a) Change of voltage for faulted case, (b) Zoomed change of voltage for faulted case

The change of system voltage was obtained for a phase-ground fault and illustrated by the dashed line in Fig. 5 (a). This change was sensed for all cases by the fuzzy control based digital protective relay and the appropriate operations are started. Using standard relay characteristics and short circuit response of synchronous generator [24], a decision has been made whether the faulted case duration is less than or greater than 10 periods. If the duration was less than 10 periods, then the fault was classified as temporary and a warning sound was produced for the operator. If it was greater than 10 periods, then the fault was classified as permanent and the necessary control output signal was produced for the circuit breaker.

In Fig. 5 (b), A_h is the amplitude for faulted case and the zoomed drawing is used to show the change of system voltage at the faulted bus. In Fig. 5, the fuzzy controller output was illustrated for faulty cases by using a dotted line. The fuzzy controller output was equal to 0 for the non-faulted case and the output value was increased to 0.5 for the transient fault. When the resultant of the classification of the fault was considered as permanent, the fuzzy controller output was assigned to 1. The duration of the fault was determined by using a counter. To determine the 10 periods, a system clock was used.

4. CONCLUSIONS

In this study, experimental results of a new digital protective relay based on fuzzy logic and value estimation were presented. In addition to the theoretical aspect of fuzzy logic, mathematical definition of the value estimation, detection and measurement of faulty current, determination of its duration, decision mechanism and detailed system architecture were also introduced. The proposed controller and digital relay were applied to the prototype power system. A new fault estimation algorithm which differs from the cited references was used for the proposed relay. The algorithm was independent from sampling time and signal period. A fuzzy logic based digital protective relay was built and successfully applied to the prototype power system model. The proposed relay was developed by using conventional protective relay characteristics by adding some abilities such as improved human safety and system reliability, distinguishing whether the fault was transient or permanent, and determining correct action. Additionally, voltage falling did not affect the proposed relay and no control signal was produced to isolate the system from power supply.

NOMENCLATURE

ω	Angular velocity
τ	Period
μ	Membership degree
A	Magnitude of sampled value
a, b, and c	Parameters of triangle
A_h	Magnitude of sampled value for faulty case
ce	Change of error
du	Change of control signal
e	Error
NB, CZ, and PB	Membership functions and their labels
t	Sampling instant
x(.)	Sampled value related to sampling instant
z^{-1}	Zero order holder

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APPENDIX A

It is clear that for a system which shows sinusoidal changing behavior, sampled value at (t) sampling instant is as below:

$$x_{\text{Sampled}}(t) = A.\sin(\omega t) \tag{5}$$

$$\omega t = \arcsin(x_{\text{Sampled}}(t)/A) \tag{6}$$

Similar to this, for (t+1) sampling instant

$$x_{\text{Sampled}}(t+1) = A.\sin(\omega t + \tau) \tag{7}$$

$$\omega t + \tau = \arcsin(x_{\text{Sampled}}(t+1)/A) \tag{8}$$

Replacing Eq.6 with in Eq.8,

$$\arcsin(x_{\text{Sampled}}(t)/A) + \tau = \arcsin(x_{\text{Sampled}}(t+1)/A) \tag{9}$$

$$\tau = \arcsin(x_{\text{Sampled}}(t+1)/A) - \arcsin(x_{\text{Sampled}}(t)/A) \tag{10}$$

In order to determine value, which will be sampled at (t+2) sampling instant, Eq.11 can be used.

$$x_{\text{Estimated}}(t+2) = A.\sin(\omega t + 2\tau) \tag{11}$$

$$2\tau = \arcsin(x_{\text{Estimated}}(t+2)/A) - \arcsin(x_{\text{Sampled}}(t)/A) \tag{12}$$

Using equality of Eq.12 and Eq.10, Eq.13 can be obtained.

$$\begin{aligned} 2\tau = \arcsin(x_{\text{Estimated}}(t+2)/A) - \arcsin(x_{\text{Sampled}}(t)/A) = \\ 2(\arcsin(x_{\text{Sampled}}(t+1)/A) - \arcsin(x_{\text{Sampled}}(t)/A)) \end{aligned} \tag{13}$$

If $x_{\text{Estimated}}(t+2)$ is left alone in one side of equality, then Eq.14 is exposed. Obtained, this equation is equal to Eq.1.

$$x_{\text{Estimated}}(t+2) = A.\sin(2.\arcsin(x_{\text{Sampled}}(t+1)/A) - \arcsin(x_{\text{Sampled}}(t)/A)) \tag{14}$$

APPENDIX B

Graphical illustration of a triangular type membership function is shown in Fig. App. B-1.

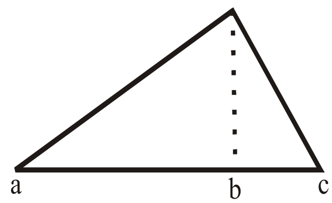

Fig. App. B-1. Graphical illustration of a triangular type membership function

where a is starting point of triangle, b is top point of triangle and c is ending point of triangle.
Mathematical expression of the triangular type membership functions for the error, e, regarding the above Fig. can be given as in Eq. 15:

$$\mu(e) = \begin{cases} 0 & e < a \\ (e-a)/(b-a) & a \le e \le b \\ (c-e)/(c-b) & b \le e \le c \\ 0 & e > c \end{cases} \tag{15}$$