บทความวิจัย

การออกแบบระบบป้องกันสำหรับมอเตอร์เหนี่ยวนำ: กรณีศึกษา ความผิดพร่องโรเตอร์เยื้องศูนย์แบบขนาน โดยใช้ฟัซซีลอจิก

บุญเติม อุ่นวิเศษ กาญจน์ กันปัญญา สิทธิพงศ์ อินทรายุทธ และ ศุภชัย ปลายเนตร*
สาขาวิชาเทคโนโลยีไฟฟ้าอุตสาหกรรม คณะเทคโนโลยีอุตสาหกรรม มหาวิทยาลัยนครพนม

* ผู้นิพนธ์ประสานงาน โทรศัพท์ 08 1117 8358 อีเมล: prainetr@npu.ac.th
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รับเมื่อ 17 ธันวาคม 2564 แก้ไขเมื่อ 5 เมษายน 2565 ตอบรับเมื่อ 19 พฤษภาคม 2565 เผยแพร่ออนไลน์ 7 ตุลาคม 2565

บทคัดย่อ

การป้องกันความผิดพร่องของมอเตอร์เหนี่ยวนำมีความจำเป็นและสำคัญสำหรับอุตสาหกรรมสมัยใหม่ ซึ่งสามารถลดต้นทุนการบำรุงรักษาเครื่องจักรกล งานวิจัยนี้นำเสนอการออกแบบระบบตรวจจับและป้องกันมอเตอร์เหนี่ยวนำ โดยใช้เทคนิคฟัซซีลอจิกร่วมกับโปรแกรมเมเบิลลอจิกคอลโทรล (PLC) โดยเริ่มจากการออกแบบโดยการกำหนด 2 อินพุต คือ ข้อมูลสัญญาณการสั่นสะเทือนและข้อมูลสัญญาณกระแส เพื่อสร้างฟังก์ชันสมาชิก และสร้างกฎของฟัซซีจำนวน 9 กฎ ด้วยโปรแกรม MATLAB จากนั้นนำไปใช้ออกแบบและเขียนโปรแกรมร่วมกับ PLC ส่วนอินพุตรับสัญญาณแอนะล็อกจากเซนเซอร์ตรวจจับการสั่นสะเทือน และกระแสมอเตอร์เมื่อเกิดการผิดพร่องจากการเยื้องศูนย์ของมอเตอร์ ระบบเซนเซอร์ตรวจจับแปลงสัญญาณแอนะล็อกเป็นสัญญาณดิจิทัล (A to D) 4-20 มิลลิแอมแปร์ เชื่อมโยงกับอินพุตของ PLC การเขียนโปรแกรมแลดเดอร์ใช้หลักการตัดสินใจจากกฎฟัซซีสร้างอัลกอริทึมเพื่อป้องกันความผิดพร่องจากการเยื้องศูนย์ของโรเตอร์ ผลการจำลองและทดลองแสดงให้เห็นประสิทธิภาพของการตรวจจับมีความถูกต้องเฉลี่ยร้อยละ 85 และการป้องกันมีประสิทธิภาพน่าพอใจ การวิจัยนี้จึงเป็นพัฒนาอัลกอริทึมระบบตรวจจับ ระบบตัดสินใจ ระบบควบคุมและระบบป้องกัน ซึ่งสามารถนำไปประยุกต์ใช้งานสำหรับเครื่องจักรกลไฟฟ้าในอุตสาหกรรม

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Research Article

Design Protection System for Induction Motor: A Case Study Parallel Misalignment Rotor Fault Using Fuzzy Logic

Boonterm Ounviset, Kan Kanpany, Sittpong Intrayut and Supachai Prainetr*
Department of Industrial Electrical Technology, Faculty of Industrial Technology, Nakhonphanom University, Nakhon Phanom, Thailand

* Corresponding Author, Tel. 08 1117 8358, E–mail: prainetr@npu.ac.th DOI: 10.14416/j.kmutnb.2022.10.005
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Abstract

Fault protection system of induction motors is important for modern industry and cost maintenance of machine. The propose of this work is to design the detection and protection system of induction motor with using Fuzzy logic technique with Programmable Logic Control (PLC). Firstly, Fuzzy rule is designed by configure 2 input for create the membership function and create 9 fuzzy rule with Matlab and apply to create program PLC with the input used analog motor current by vibration and current sensors to convert digital input (A to D) 4-20 mA. to PLC. Secondly, protection system algorithm is designed and then this system is applied with PLC. The simulation and experimental results show that the efficiency of detection fault can be decided accuracy mean is 85% and protection have been satisfied. This study develops algorithm such as detection, decision, control and protection the application for maintenance and prevention which can be applied to the realization for electrical machine in the industry.

Keywords: Design Protection, Induction motor, Parallel Misalignment Rotor Fault, Fuzzy Logic, PLC

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1. Introduction

Induction motor is an important power source for the equipment in production process. It has been long time to continuously operate with load variation and high temperature. Moreover, it causes deterioration, energy consumption, shutdown of machinery and loss in the production. Therefore, the monitoring and protection are important roles to prevent, maintain and forecast the equipment life which are necessary to be considered [1]. Analysis fault can be divided into two methods including stopping motor operation and non-stopping motor operation. The faults can be determined by measuring the line current, vibration and noise. In addition, the airgap torque, magnetic force lines, acoustic signal and temperature signals are determined. In the case of eccentricity, it can be performed by analysis of the stator current signal in the side band of frequency and application of infrared thermography technique to indicate efficiency for detect fault of motor [2]–[4]. The model analysis of air gap magnetic field used finite-element method is able to predict type of misalignment [5].The application diagnosis of vehicle engine is operated by using wavelet transform and fuzzy intelligent for classifying the situation of vehicle engine fault [6]. The reliability of the motor current can be analyzed and interpreted the faults by current signals. These current signals can measure by the induction motors which considers from air gap asymmetry, stator coil short circuit. The case of the rotor misalignment is one of the groups of mechanical faults which has been reported that can be analyzed by using analysis techniques such as current signal, vibration signal and sound signal [7]. Then, this signal is processed via Fast Fourier Transform (FFT) technique which is suitable for analysis mechanical faults of the induction motors and providing a good level of effective analysis [8]. However, the interference of other signals is resulted in not to analyze the resolution by FFT technique. Therefore, wavelet transform is proposed for solving this problem. This technique is used for decomposing of the signal resulting in providing feature extraction which is a satisfied result [9]. Moreover, Motor current (MC) has well efficient method to use as protected faults [10]. Industrial application of the Programmable Logic Controller (PLC) is a device for controlling speed and monitoring condition of electric drives [11]. Furthermore, PLC is used to detect and isolate fault in the manufacturing system [12]. The several specific analog and digital I/O signal are handled for protection trip faults signal which is a control unit involving a PLC. Therefore, the concept of this paper is proposed to design and apply Fuzzy logic technique for protection of motor faults and improvement algorithm performed by PLC.

2. Materials and Methods

The materials and methods for design protection and fault analysis of induction motor are demonstrated in this section. These are various types of faults while this study was focused on the parallel misalignment fault. In this research, Fuzzy Logic techniques is proposed with using rule base algorithm which is one of AI techniques for diagnosis and protection fault. Firstly, MATLAB is used to design and simulate of Fuzzy model. Secondly, Fuzzy Rule is converted to LADDER program for using with PLC by the IF or THEN base function command which was implement program

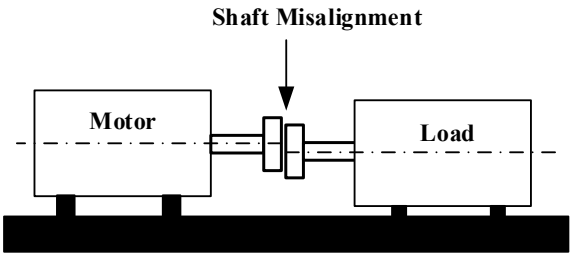


Figure 1: Type of misalignment: (a) Parallel misalignment.

algorithm to prevent fault of the motor.

2.1 Shaft misalignment

Shaft misalignment is a main factor damage of induction motor in machine. It consists of parallel, angular, and the combine action between parallel and angular as shown in Figure 1. Moreover, the impaction result of the vibration and acoustic noise is related to the degree of eccentricity. This study focuses on parallel type base on which is the most effective in industrial sector [5].

2.2 Fuzzy system with PLC

The fuzzy algorithm was designed for applying with PLC. It can be created ladder diagram by code text, block diagram and sequential diagram. Designing fuzzy from ladder logic consisted of three contents for designing the fuzzy system as follow:

- Fuzzification is the first process which involves a domain transformation where crisp inputs are transformed into fuzzy inputs.
- Inference mechanism is based on IF THEN rules by using known MIN, MAX methods while each rule set is used for defuzzification process.
- Defuzzification is the process for producing a quantifiable result in fuzzy logic, given fuzzy sets and corresponded to membership degrees. The advantage of defuzzification technique is center of gravity (centroid).

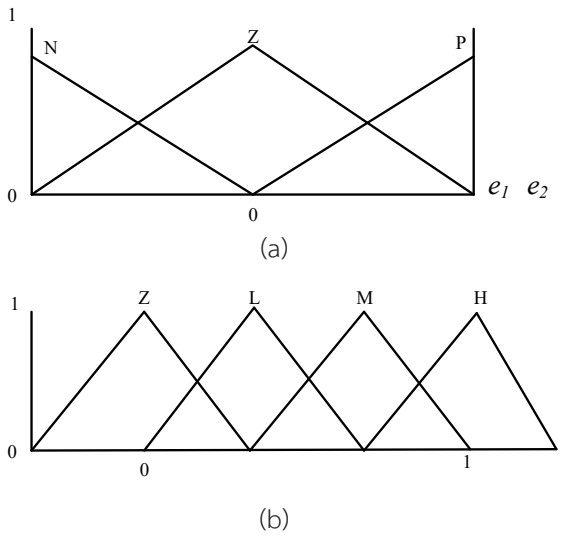


Figure 2: Pattern of membership function. (a) Fuzzy input, (b) Fuzzy output.

2.3 Methods

In this section, the methods process is divided into two parts: 1) the detection current signal of case study parallel misalignment and 2) the prevention vibration signal and design fuzzy logic for protection system and using PLC.

2.3.1 Design Fuzzy rule

Designing concept of Fuzzy method used Matlab Simulink to process and performance and calculate Fuzzy inference system (FIS) input variable used Equation (1), (2), and concept of membership function as shown in Figure 2.

Table 1 showed the configuration an input and output variable of the Fuzzy algorithm which will used designing with goal condition. Designing and calculation FIS can be calculated by following equation.

Table 1: Design Fuzzy rule

Input 2 (e_2)	Input 1 (e_1)		
	Positive	Zero	Negative
Positive	Danger	Caution	Danger
Zero	warning	Accept or Normal	Danger
Negative	warning	Caution	warning

$$e_1(k) = \frac{P_n(k) - P_f(k)}{P_n(k)} \quad (1)$$

$$e_2(k) = \frac{e_1(k) - e_1(k-1)}{e_1(k)} \quad (2)$$

where P_n is the current variable of the normal condition, P_f is the current variable of fault condition and e_1, e_2 are input variable to Fuzzy system.

In Figure 3(a), Figure 3(b), we design the membership function and set rule containing the knowledge of predictive fault condition (four rules) following;

2.3.2 Defuzzification process

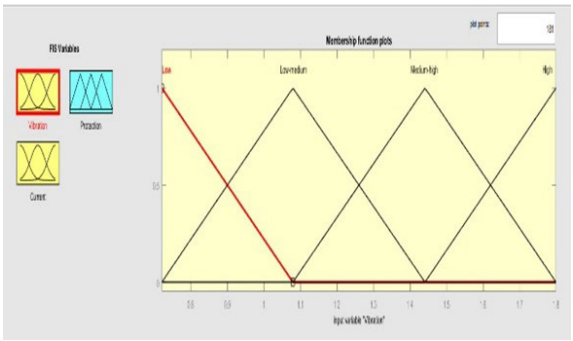
Defuzzification is a process of providing the output of Fuzzy system which must be converted to signal forms including current signal, voltage signal and control signal. The calculation defuzzification value with center of gravity method can be calculated as following Equation (3)

$$COG = \frac{\sum_{x=a}^{b} \mu_A(x)x}{\sum_{x=a}^{b} \mu_A(x)} \quad (3)$$

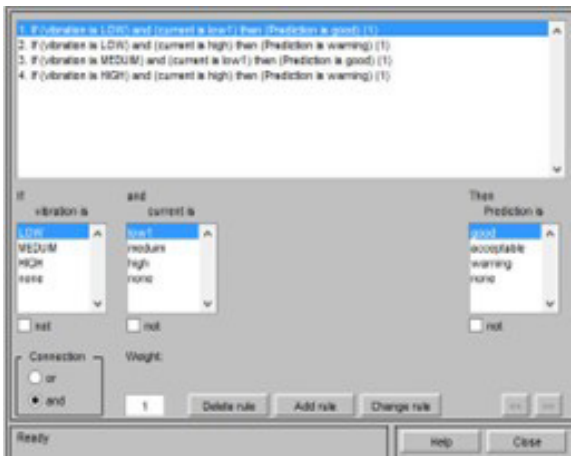
where COG is center of gravity and μ_A is element of membership function.

2.3.3 Experimental setup

The experimental setup consisted of three parts: Firstly, misalignment setup was an induction motor with condition of 11 kW, 380 V, 50 Hz, 4 pole, 1450 rpm with starting by star connection and fix



(a)



(b)

Figure 3: Designing concept of Fuzzy method.

speed and constant load. The parallel misalignment was used to adjust the different level misalignment of 0.01 mm, 0.02 mm and 0.03 mm which was measured calibration by the dial gauge. Secondly, the detection current signal used hall effect sensor LEN-HX-10NP, accuracy 1%, linearity 1, DC to 50 kHz Frequency bandwidth, input current Ip 20 A and low pass filter cut off high frequency used LPF 4 order and Data Acquisition (DAQ) NI 32 bit. Finally, design protection system consisted of the vibration sensor with frequency range 10 Hz-1 kHz and converted to analog signal 4–20 mA to PLC OMRON model CP1H to

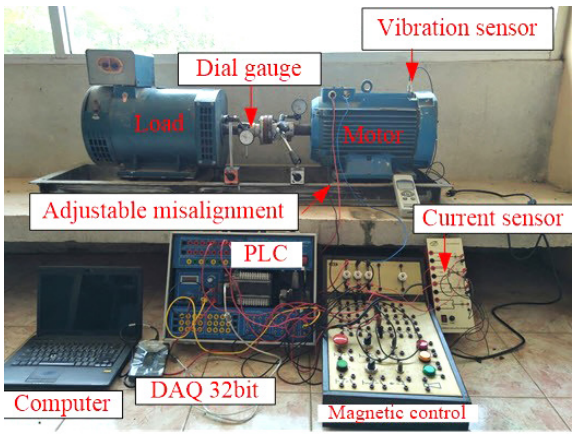


Figure 4: Equipment of experimental setup.

investigate protection when vibration misalignment occurred more than the standard criterial. The diagram of experimental setup and laboratory are displayed in Figure 4. The parameters of motor which is used in the experiment is displayed in Table 2.

Table 2: Induction motor parameter

Item	Value
Power	11 kW
Number of phase	3 Phase, 380V
Pole	4 Pole
Rated frequency	50 Hz
Rated speed	1450 rpm

Figure 5 shows flowchart of designed Fuzzy with PLC. Beginning with setting variable (input), data from signals of vibration and current from sensor were converted from the analog to the digital and connected with input system of PLC. Then, Ledder program of PLC which was designed from Fuzzy will formulate the conditions in the terms of IF-Then function. From the Fuzzy rule (9^{th}), program will estimate and resolve the signal from the detection and fault of motor which is performed as level of

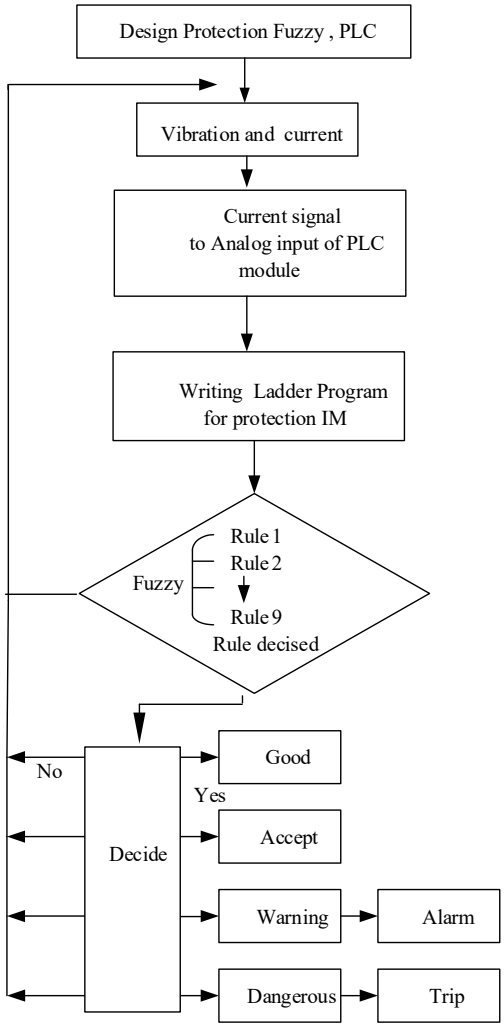


Figure 5: Flowchart design Fuzzy with PLC and apply protection fault of induction motor.

fault. If there is too fault from the standard designing, the circuit protection will operate to prevent from damage.

2.3.4 Detection and protection system

In this study, an implementation algorithm of a hybrid system for detection and protection use multi techniques by both signal analysis and artificial intelligence. It can be divided into two parts. First part is the detection with sampling rate signal at 2 kHz

to separate the spectrum current which was enough for the case of misalignment fault through wavelet transform resulting in classify the high frequency components into four scales, analysis signal and interpretation indicator in time and frequency domains [6]. Second part is the protection which operated the vibration signal from sensor with 4–20 mA, analog signal to input module of the PLC, then processing used the designing a training rule base knowledge by standard of vibration machinery according to ISO 2372 [12].

Table 3: Design Fuzzy rule for protection system

Vibration Range (mm/s)	Prediction	Protect Mode
0 to 0.71	Good	save
0.72 to 1.80	Accept	save
1.82 to 4.5	Warning	alarm
> 4.5	Dangerous	Trip

Table 4: Design Fuzzy rule used stator current

Current Range (mA)	Prediction	Protect Mode
0 to 4 mA	Good	save
4.1 to 10 mA	Accept	save
10.1 to 20 mA	Warning	alarm
> 20mA	Dangerous	Trip

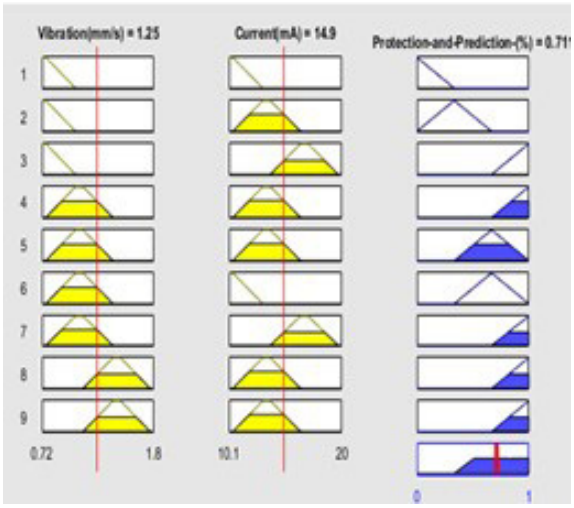


Figure 6: Rule viewer for normal condition.

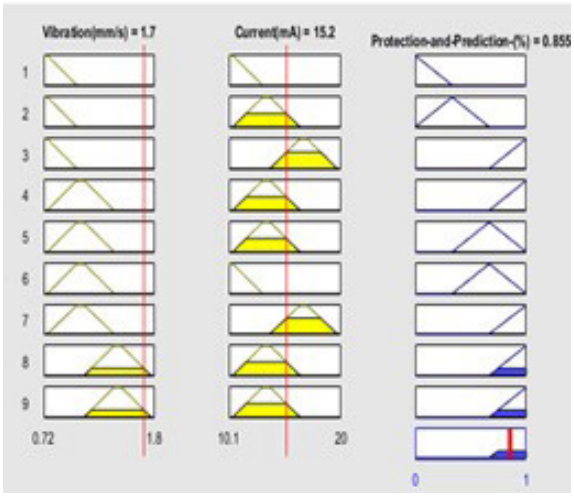


Figure 7: Rule viewer for fault condition.

3. Results and Discussion

The objective of this study is to propose an implementation of protection fault in case parallel misalignment of a three-phase induction motor with apply PLC.

3.1 Simulation results

In this research, the MATLAB program and Fuzzy Logic Toolbox function are applied for defuzzification process with using rule viewer function for analyzing the output and then, display condition of the system. This rule should be considered to effect of the input which can select the input to observe the output results rule viewer and surface view as shown in Figure 6 and Figure 7

Figure 6 and Figure 7 shows the simulation results of the fuzzy rule which the input data is

vibration and current Fuzzy rule can be decided normal condition accuracy mean is 71% (0.71) and fault condition mean is 85% (0.85).

3.2 Experiment of vibration results

The result of real work application by PLC and rule base knowledge method has designed by four rule bases. The designing algorithm is considered between healthy condition and misalignment fault as shown in Table 5.

Table 5: Result of different misalignment test

Normal (mm/s)	Fault 1 (mm/s)	Fault 2 (mm/s)	Fault 3 (mm/s)
0.2	0.5	0.5	0.5
0.3	0.6	0.6	0.6
0.4	0.5	0.5	0.5
0.3	0.4	2.5	4.9
0.4	0.5	4.2	5.6
0.3	2	4.8	5.8
0.4	4.1	4.9	5.9
0.3	4.5	5	5.9
0.4	4.6	5.1	5.9

Note: Fault 1, Fault 2, Fault 3, were setting misalignment level at 0.01 mm, 0.02 mm and 0.03 mm.

Figure 8 displays the graph of the relation between the vibration signal and time which compared the signal between normal and misalignment faults. From the experimental shaft misalignment fault of the motor, testing level at aliment and misalignment at 0.01 mm, 0.02 mm, and 0.03 mm plotted as black, red, green and blue line, respectively. It was found that the misalignment increased with increasing vibration. This led to mechanical faults and caused deterioration bearings of the motor. The induction motor on alignment condition obtained maximum

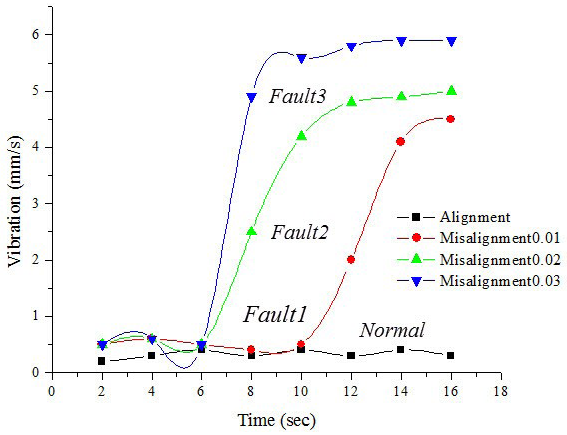


Figure 8: Vibration of different level faults.

vibration value at 0.04 mm/s according to ISO 2372. Therefore, experimental result data was used to create the rule base algorithm and reference. Table 3 and Table 4 shows designing the rule base knowledge representation for decision with PLC. Algorithm was designed from the four rules base. The rule base knowledge should be consisted of the motor healthy condition. The motor was able to operate and the motor is permissible allowed. However, the preparation for maintenance and prevent danger is vibration of exceeding standards with PLC which decided to trip and prevent damage of motor fault.

4. Conclusions

In this paper, the proposed development dual system for designing fuzzy and protection was validated by PLC of induction motor fault. This study used motor vibration, current sensors and Fuzzy logic configure 9 rule with PLC. Simulation from Fuzzy rule can be decided normal condition accuracy mean is 71% (0.71) and fault condition mean is 85% (0.85). Experimental results show that a Fuzzy method can be applied with PLC in

real work and high protection sensitivity. Therefore, the Fuzzy rules from vibration signals was applied according to the ISO 2372 and IEEE std.112 criterial standard [12], [13] for PLC decision and protection fault automatically. Moreover, this study has been supported and developed on fault protection in electrical machine [14]. For the further work, multi signal parameters and decision technique systems will be investigated.

5. Acknowledgement

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