Comparison between a Mamdani and Sugeno Controllers Based Power Theft Detection

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Abstract

In this paper a proposed system is set to identify the illegal power theft on electrical grids by utilizing a wired control system based on microcontrollers. The proposed system allows easy access to the information with the combination of a traditional power grid and a new technology (Arduino kits). A novel automated control system was proposed in this paper, which makes use of Arduino based fuzzy logic Toolbox in MATLAB. Arduino has been used in the proposed system to monitor and record the meter readings while fuzzy logic controllers have been used to act as a relay. Simulations have been implemented through this work based on a fuzzy inference systems using Toolbox/ MATLAB. The paper shows a comparison between two inference types, namely, Mamdani-type and Sugeno-type. Although both of these two types are varying slightly in terms of their design's steps, results of the Sugeno-type inference system indicated that it is able to prevent any value of stealing electricity even less than Nano amperes comparing with another type due to its output membership functions are crisp. By using the Sugeno controller, the controller's response is more accurate and better than the Mamdani controller's output. The results obtained from the simulation show that immediately the illegal load is connected to the utility system. Whereas, the results obtained from the hardware show that any unexpected usage is instantaneously being sent to the utility. This project is significantly useful to prevent instantly power theft

when it has been discovered, consequently illegal users won't be able to use.

Keywords: Arduino, MATLAB, FIS, FL, MFs, GECOL.

1. Introduction

The proposed system is an attempt to prevent the power theft. The system could bring benefits of enhanced organizational productivity and cost effectiveness by automating the monitoring, gathering and analysis of data. The prevention of power theft for residential consumers has been simulated by Toolbox/MATLAB. Simulation can be used in a wide variety of applications. Fuzzy logic software is used to build intelligent systems in order to solve complex problems. It acts as a standalone process and execute action without human intervention. The most common two types of fuzzy inference system are used in this project which are Mamdani and Sugeno- inference. Mamdani-controller based FIS is executed in four steps: Fuzzification of the input variables, Rule evaluation; Aggregation of the rule outputs, and finally Defuzzification [1]. The goal of the Sugeno controller is generation of fuzzy rules from a given input-output data set. Differences between Mamdani and Sugeno are [2]. The actuation of weather the Mamdani controller or Sugeno controller is the prevention of this illegal use. In order to process the input to get the output reasoning there are six [3] steps involved in the creation of a rule based fuzzy system which are: Identify the inputs and their ranges and name them. Then, identify the outputs and their ranges and name them. Consequently, create the degree of fuzzy membership function for each input and output. And construct the rule base that the system will operate under. Accordingly, decide how the action will be executed by assigning strengths to the rules. Finally, combine the rules and defuzzify the output. As there are many types of fuzzy logic controllers, the most commonly types have been used in this project.

In this work, the control logic was used to checks the system continuously and perform the electricity-cutoff operation whenever power theft detected by comparison between the Master and Slave boards

In 2018, in India, researchers [4] projected a system on identify electricity theft using the data mining technique. This project mainly focuses on an encoding technique that simplifies the received customer energy consumption readings (patterns) and maps them on corresponding irregularities in consumption. The author showed that there are four phases: first, data preprocessing that represents data cleaning, data transformation, and data reduction. Second, artificial neural networks. There are many advantages of their system. The project explains the operation of classification techniques on customer energy consumption and illegal use of electricity showing how the electricity theft can be detected by fuzzy techniques based data mining method. Through their system, they could avoid electricity theft by end-user and reducing detection costs manually. However, using of K-Means clustering algorithm and artificial neural networks need to find unseen frauds. Therefore, implementing this system with artificial intelligence needs to the high experience of using these techniques to overcome any inadequacies.

Researchers in 2018 [5] provided an innovative scheme for the detection and monitoring of electrical power theft in the distribution system based on the principle of power line communication. Any illegal utilization of electricity will be detected with the differential change in the amplitude of the narrowband carrier signal, which can be detected with precision. Simulation results using MATLAB are provided showing that the scheme is simple and efficient. The system has many advantages while it has also disadvantages. The advantages are the following things like If the system output is interfaced with monitoring techniques, it will be easy to interpret the data regarding the theft from a remote location. The loss of electricity due to theft can be minimized. The system can be easily implemented to either developed or developing countries as it consists of simple and cheap components. The theft of electricity can be located within a range of 25-50m. During the real-time implementation of the scheme, certain factors such as the loading effect on the oscillator and rating of the components should be considered. I think the drawback of the system is the proper isolation from the power frequency signal is needed, otherwise, the oscillator could be damaged and consequently, the entire detection circuit could also damage.

Another design [6] has been proposed in 2019 in India for detecting the quantity and the exact location of theft power. The proposed system based on the Neuro-Fuzzy logic consists of two parts namely the load side and substation side. Both sides consist of PIC Microcontroller, MAX232, loads, relays, and Neuro-Fuzzy logic algorithm. It is well planned at the verdict out of theft information exhibited by the PC. The fuzzy logic algorithm contains the number of units programmed and identify the theft from load side and report to the utility through display units. The PIC microcontroller is used to transfer the data (include power with respect to time) to the electricity board from each home. The utility has a Neuro Fuzzy Technique to analysis the readings from a group of different substations. If any power theft occur, It will give the exact location of theft. It is not only stretch the theft location, it will produce how much of energy theft and corresponding penalty amount are calculated and displayed on the screen of computer.

A group of researchers [9] in India in 2012 have provided a system using fuzzy logic based power theft prevention and power quality improvement. The concept of their proposed system is depending on the difference between the total current supplied by the distribution transformer and the total current consumed by the consumer and this difference is used to detect the power theft. Current and voltage are fed as input to the fuzzy logic controller and the corresponding change in output voltage is provided by the fuzzy controller to improve the power quality and to prevent the power theft. It has two drawbacks. One is related to the surface rule view of the proposed rules of the fuzzy inference. As it is known that the surface rule view should be smooth in its ascent and descent. The other drawback of their project is: by using the fuzzy logic, they could control and change the tap changer of the transformer in order to cut off the power to the homes that the transformer feeds. The electricity, thus, will cut off from the thief once their system realizes that there has been a theft. However, cutting off the electricity will be executed, by their system, from all homes that are connected to that transformer. As a result, electricity will be disconnected from legal users too. While our system, the electricity will be disconnected only from illegal users and leave the rest of the users with no electricity interruption.

2. Identification of the System for Theft Problem

This work proposes two control systems that provide a solution of power theft problems by placing the system which will be constructed utilizing the Arduino UNO with smart devices. Arduino UNO with current sensors will be formed as a number of Master and Slave boards. The system was modeled by a fuzzy logic Toolbox/MATLAB. The system has three circuits which are the Master, Slave, and fuzzy inference system.

The Master circuit in which to be connected to the substation's energy meter is shown in figure 1.

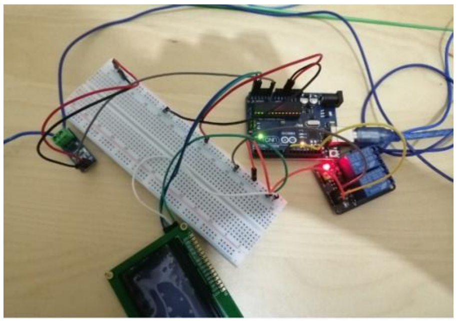

Figure 1. shows the Master Circuit.

The Slave circuit in which to be connected to a home's energy meter is shown in figure 2.

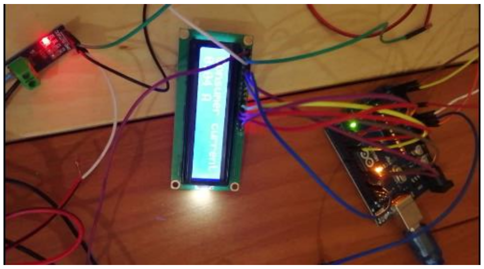

Figure 2. shows the Slave Circuit.

The fuzzy logic circuit in which to be connected to the Master circuit, as shown in the block diagram below.

The theft signal will be sent from the Master to the fuzzy logic controller in case there is a difference in the compared values between the Master and Slave boards. The controller's response depending on its inputs will then be fed to an illegal user to prevent stealing the power.

These two control methods were introduced and implemented in order to warn thecustomer and then if necessary cut-off the electricity when the power theft has occurred.

The first control method is connecting a Mamdani controller to the ATmega328P microcontroller. The second control method is connecting a Sugeno controller to the.

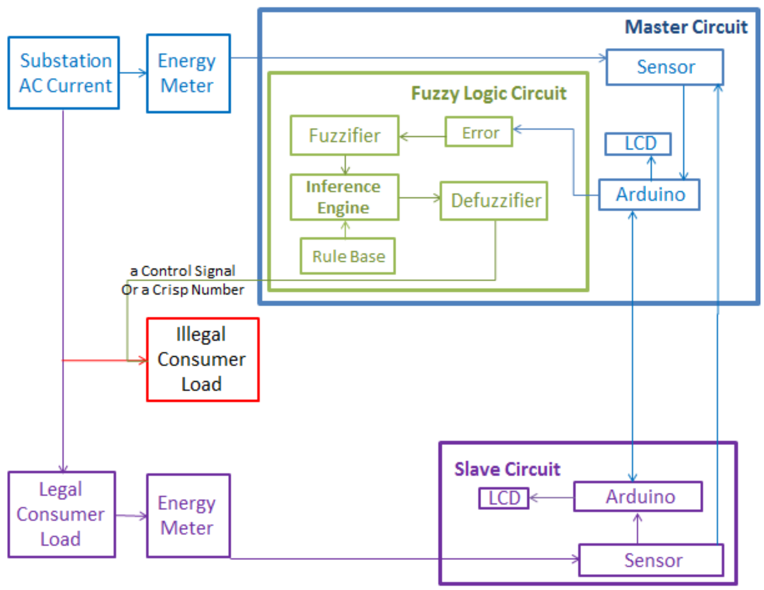

Figure 3. the System Block Diagram

same type of microcontroller stealing the power.

These two control methods were introduced and implemented in order to warn the customer and then if necessary cut-off the electricity when the power theft has occurred. The first control method is connecting a Mamdani controller to the ATmega328P microcontroller. The second control method is connecting a Sugeno controller to the same type of microcontroller.

3. Design and Implementation of the Automatic Power Theft

This work proposes a system designed to identify illegal power usages by utilizing wired control system based on intelligent system. The system employed allows easy access to the consumption data obtained from a traditional power grid (Libyan grid) and a noval technology (Arduino kits).

A novel automated control system was introduced to make use of Arduino based fuzzy logic Toolbox in MATLAB. The Arduino system was used to monitor the power system, control the energy consumption data and display it through LCDs. The electricity power theft is prevented by the employed fuzzy logic utility wherever it has happened. When power theft is detected, a message will be sent out as an alert to the employed utility system via wiring mechanism.

The fuzzification and the defuzzification process are performed using command line functions. The system behaves depending on membership values that were assigned to find out optimal solutions using simple logic rules, and then implement these rules in a FIS. Crisp inputs for both the Mamdani and Sugeno controllers are resulted from membership functions depending on linguistic terms and their ranges [7].

A). Fuzzy Inputs

In fuzzy logic toolbox software, the input is always a crisp numerical value limited to the universe of discourse of the input variable (in this case, the interval from 0 through 1).

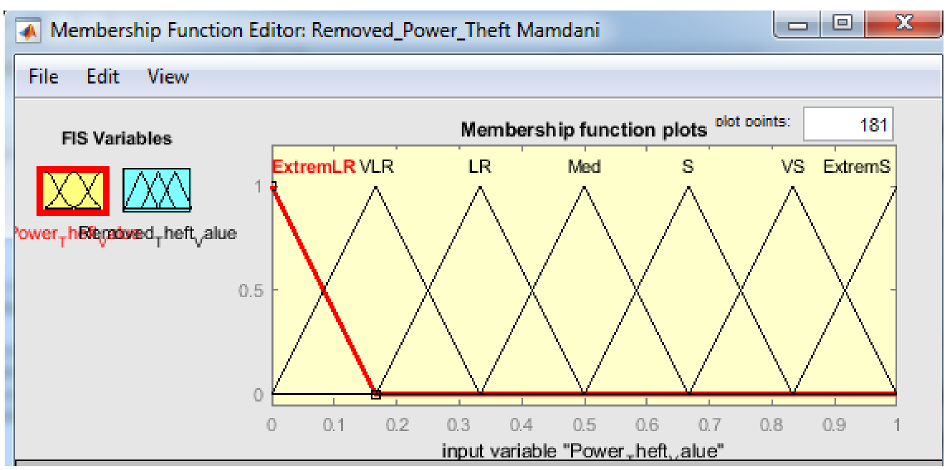

Figure 4. MFs for Fuzzy Mamdani Inputs for Prevention Power Theft.

In the proposed model, linguistic terms and their ranges and fuzzy inputs for Mamdani's inputs and Sugeno's inputs are exactly the same magnitudes and quantities as shown in figure 4. Membership functions are triangular and symmetrical for both inference types. The output is a fuzzy degree of membership in the qualifying linguistic set (always the interval from 0 through 1).

B). Fuzzy Outputs

As the membership functions (MFs) of the fuzzy output are related to the input. Then, they are output changes of the fuzzy logic. If the error (input) is not zero, then changes (output) will be that value we need to eliminate this error. Thus, ranges of the output will be same as input. The MFS for fuzzy outputs in the Mamdani- type are shown in figure 5.

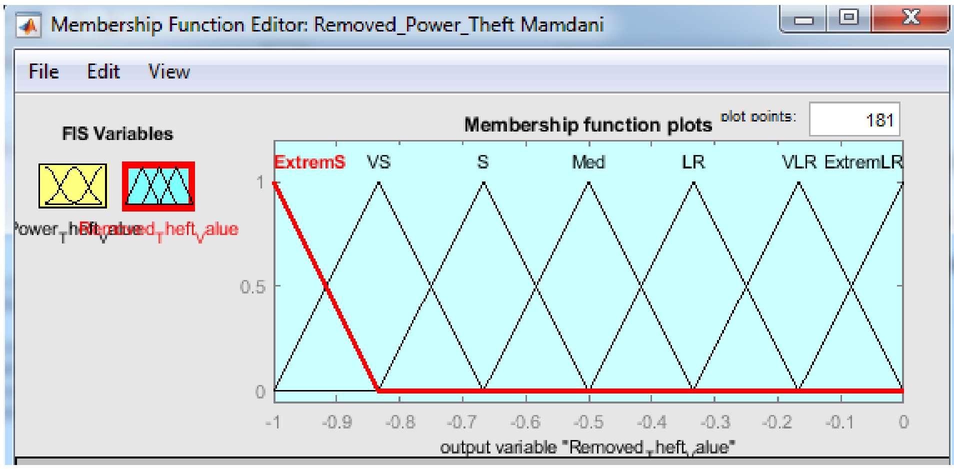

Figure 5. MFs for Fuzzy Mamdani's Outputs for Prevention Power Theft.

On the other side, seven output variables for fuzzy Sugeno's outputs have been introduced to characterize each crisp input according to their linguistic terms and ranges as shown in figure 6.

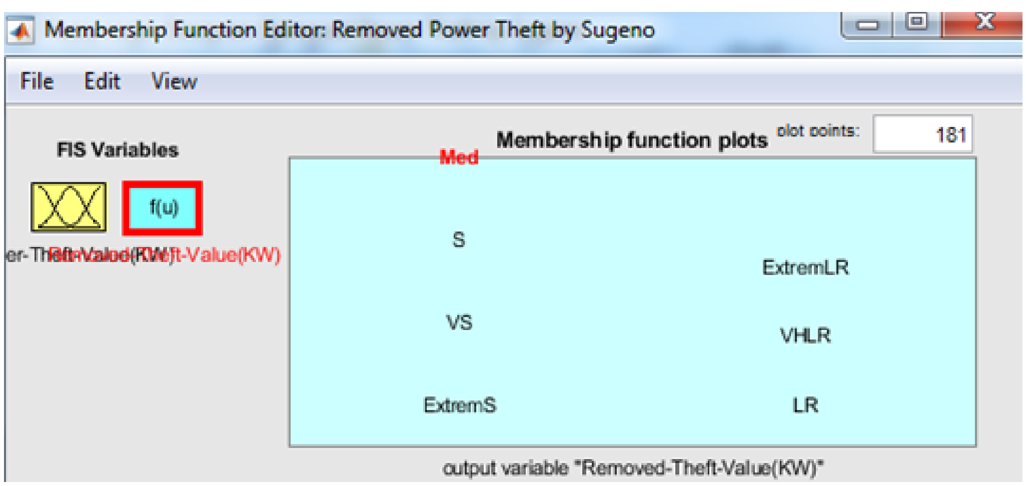

Figure 6. MFs for Fuzzy Sugeno's Outputs to Prevent the Power Theft.

The control logic has been used to checks the system continuously and execute the electricity-cut off operation whenever power theft has identified by comparison between Master readings and Slave readings. The actuation of the fuzzy controller was used to prevent this illegal use. If there is an error in readings between Master and Slave boards, then this error is fed as input to the fuzzy logic controller and the corresponding change in output load provided by the controller will be given to an illegal user to prevent stealing the power. The fuzzy logic in this operation acts as a relay in order to cut-off the electricity and stop the theft depending on control rules.

The Mamdani-controller based FIS is executed in four steps: Fuzzification of the input variables, Rule evaluation, Aggregation of the rule outputs, and finally Defuzzification. While, the Sugeno-controller is executed in only two steps instead of four: Fuzzification process and Rule evaluation. That is the main difference between the Sugeno and Mamdani methods. There are other differences such as instead of a fuzzy set, Sugeno uses a mathematical function of the input. Mamdani-style inference, requires to find the centroid of the two-dimensional shape. In the proposed system, the Mamdani method is not computationally efficient. Sugeno method uses a fuzzy singleton which is a fuzzy set with a membership function that is unity at a single particular point. Using the Sugeno controller the results of the process are more accurate and fuzzy outputs are better than the Mamdani controller's outputs [8].

3.1 Fuzzification method

The Fuzzification of the input variable is the first step to build up the FIS. The Fuzzifier is a process responsible for changing crisp values into fuzzy values. Fuzziness assists us to evaluate the rules.

3.2 Control Rules

Creating control rules is the second step to build up the FIS. Figure 7 shows that if there is no error, then there is no theft has occurred and no need to eliminate any value from the electricity cable that connected to an electricity pole. If there is any error even extremely small, then the power theft has occurred. Thus there is no electricity will be fed to that illegal user.

Depending on these rules the system will act as a relay switching mechanism and instantly cutoff the electricity from an illegal user. In the proposed system, the generated rules for both of the Mamdani method and Sugeno method are exactly the same

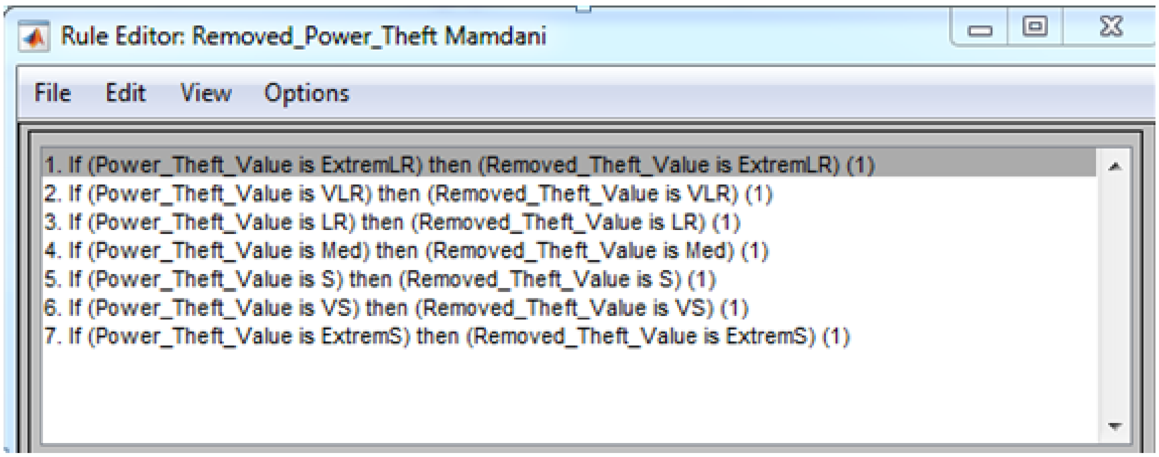

Figure 7. Control Rules for Prevention of Power Theft.

3.3 Aggregation method

In order to get only a single fuzzy set, all rules are aggregated to combine them into a particular fuzzy set. This process is called Aggregation of the rule outputs which is the process of unification of the outputs of all rules which are extracted from membership functions. In the proposed system, the output of the Sugeno style is always crisp value due to no aggregation.

3.4 Defuzzification method

The aggregated output fuzzy set is the decision but in form of fuzzy output sets. The aggregated output fuzzy is fed as the input to the Mamdani defuzzifier. As a result, the decision will be converted from fuzzy output sets to a crisp output which represents a controller's response. The defuzzifier is a process responsible for changing fuzzy set into a crisp value. The Sugeno method is very similar to the Mamdani method without defuzzification.

4. System Flowchart

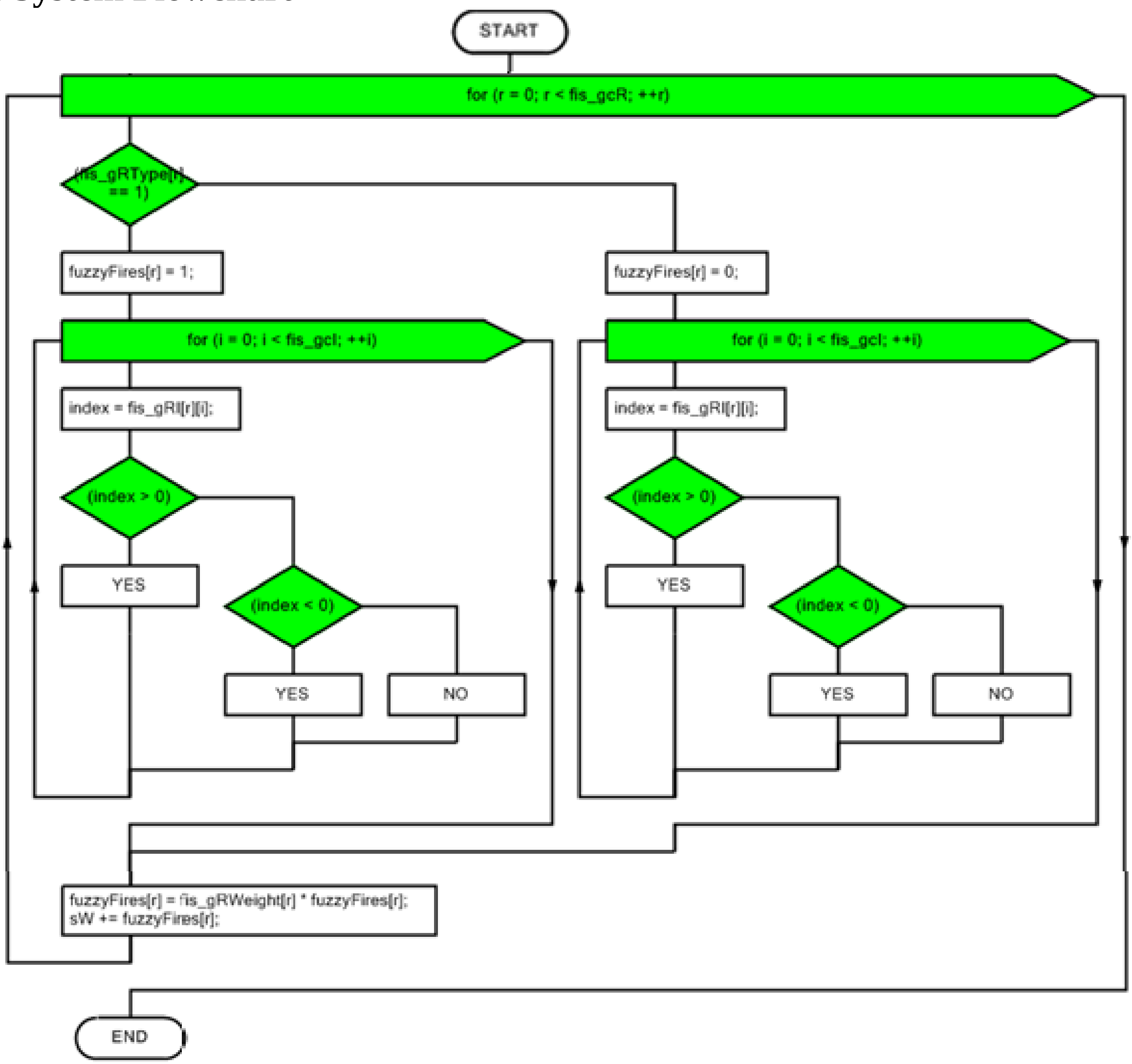

Figure 8. the Sugeno System Flowchart

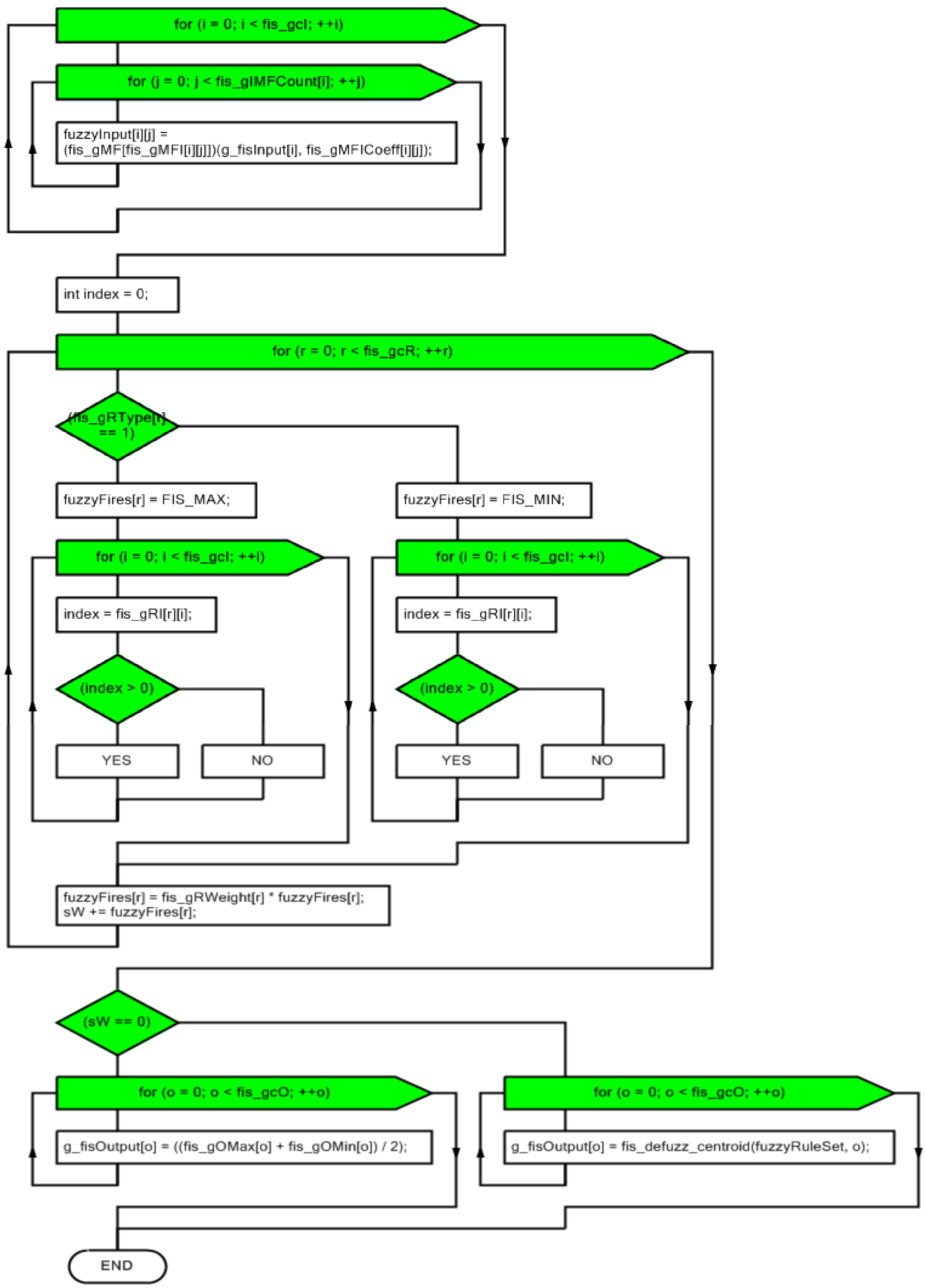

Figure 9. the Mamdani System Flowchart

5. Simulation Results and Discussion

The results in Toolbox/MATLAB are shown in the form of the Rule Viewer and the Surface Viewer. In the Rule Viewer figures

5.1 Rule Viewer

The rule viewer interprets the entire fuzzy inference process at once and as it plots every part of every rule, it shows how the shape of certain membership functions influences the overall result [10]. Figure 8 shows that the index line (the red line) representing power theft value crosses the membership function line "Power Theft Value" in the right column determines the degree to which a rule is activated. The yellow area of color under the membership function curve is used to make the fuzzy membership value clearer.

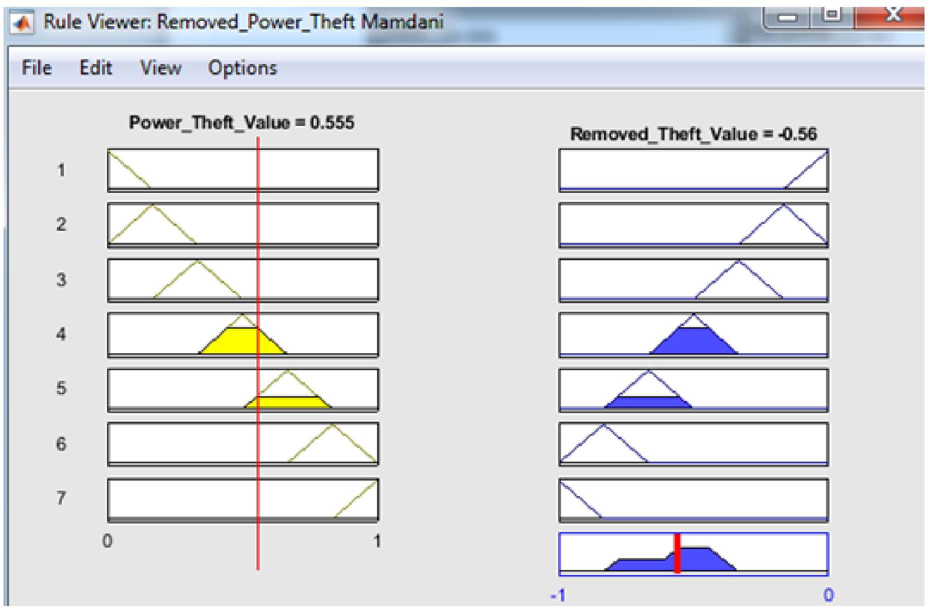

Figure 8. Rule Viewer for Prevention of 0.555 KW of Theft using Mamdani Method.

If we assumed that the output range of both the Mamdani and Sugeno controllers is between 0 to 1, and 0.5 in the middle between them, then in results of the Mamdani method we find that the required value to be subtracted from the stolen current value are almost the same when they get closer to a point of 0.5 in case the controller is Mamdani as shown in figure 8, and they will be exactly the same only at point of 0.5. Whenever these two values move away from 0.5 the difference between them continues to increase until it will reach around to 5% error. While in results of the Sugeno method, that are shown in figure 9, it clear that there won't be a difference between these two values regardless how much they are far or close to a point of 0.5. The required value that will be subtracted from the stolen current value are always the same even if they get far away from 0.5.

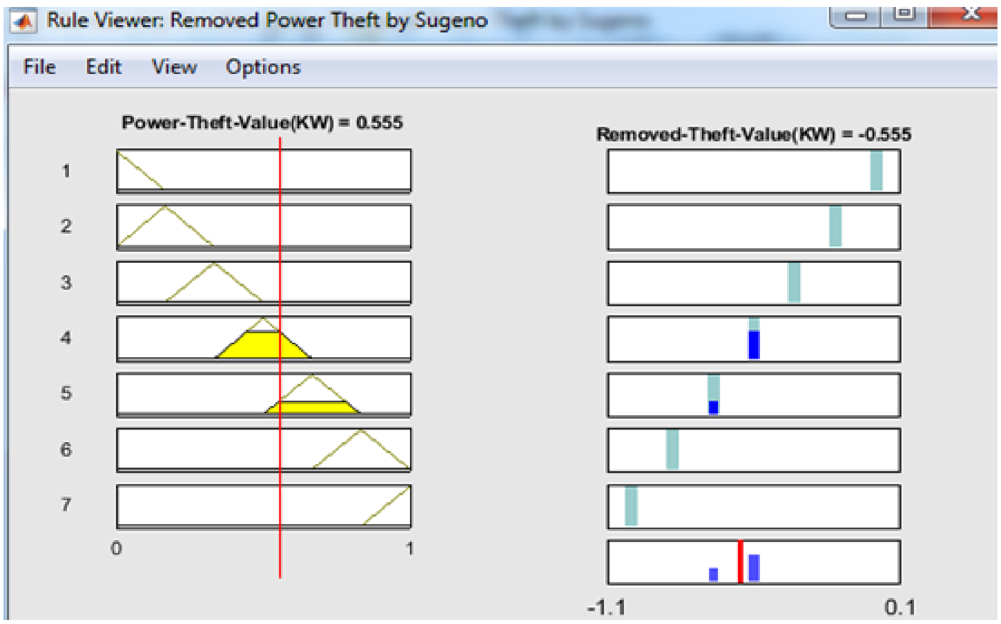

Figure 9. Rule Viewer for Prevention of 0.555 KW of Theft using Sugeno Method .

In figure 10, where the controller is Mamdani, the input (theft value = 0.451 KW) is still near than 0.5 KW, the output (removed theft value) equals to -0.445 KW which is almost the same. Accordingly, the fuzzy inference system has been successfully applied with very small error equals to 0.006 KW.

Figure 10. Rule Viewer for Prevention of 0.451 KW of Theft using Mamdani Method.

Assuming the Mamdani controller's input is 0.869 KW, then the controller's output was noticed equal to -0.838 KW which is closed to its input but not exactly the same value and the error is still small -0.031 KW as shown in figure 11.

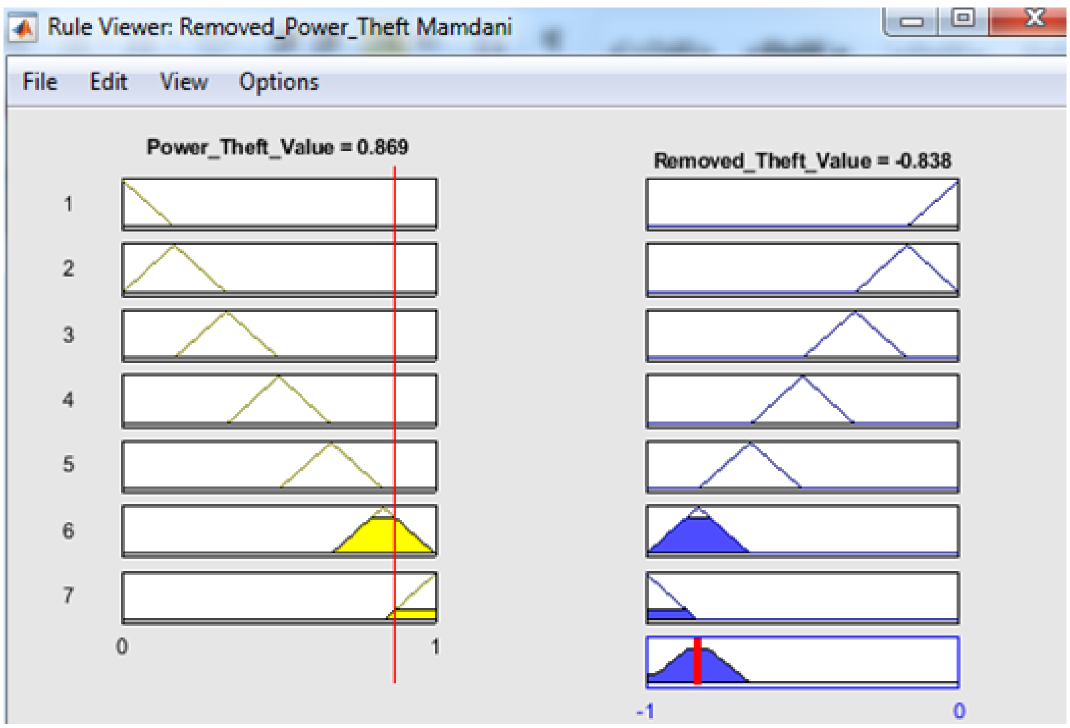

Figure 11. Rule Viewer for Prevention of 0.869 KW of Theft using Mamdani Method.

As long as the difference between the input and the output of the fuzzy controller is still small, it does not matter how much more accuracy as far as the ease of application matters. However, when the value of the difference grows as shown in figure 12 where the input is 0.0701 and accordingly the output is 0.137, it is better to use the other type which is Sugeno inference despite the difficulty of applying it.

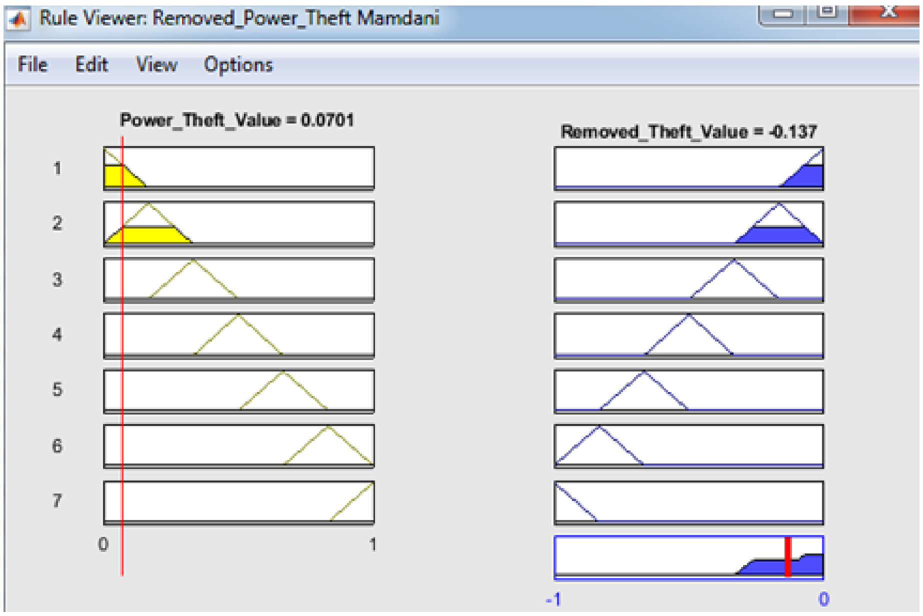

Figure 12. Rule Viewer for Prevention of 0.0701 KW of Theft using Mamdani Method.

Figure 13 shows the reaction of the Sugeno inference type in which the whole value of the theft would be removing.

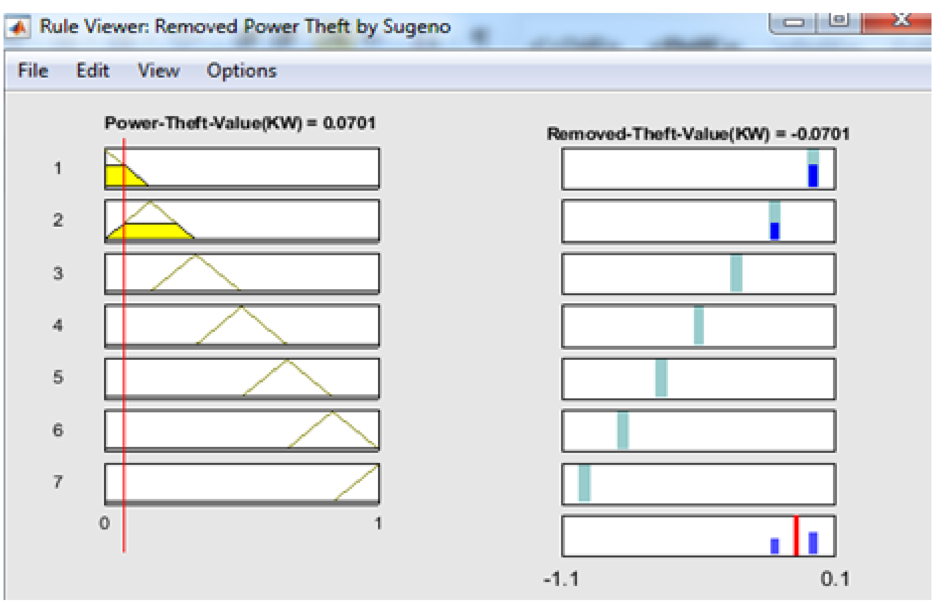

Figure 13. Rule Viewer for Prevention of 0.0701 KW of Theft using Sugeno Method.

The Mamdani-type inference is an intelligent system in which the fuzzy sets are determined from the combination of each rule are through the aggregation operator and then theses fuzzy sets are defuzzified to yield the output of the system.

Figures 14 and 15 show after the aggregation process, if a fuzzy set for (0.999) and it's corresponding output variable that has been defuzzified to be (-0.945) and (0.999) for the Mamdani and Sugeno controllers respectively. If the controller is Mamdani then the system will be able to remove only 0.945 from 0.999 and leaving a small current to be passed through the cable.

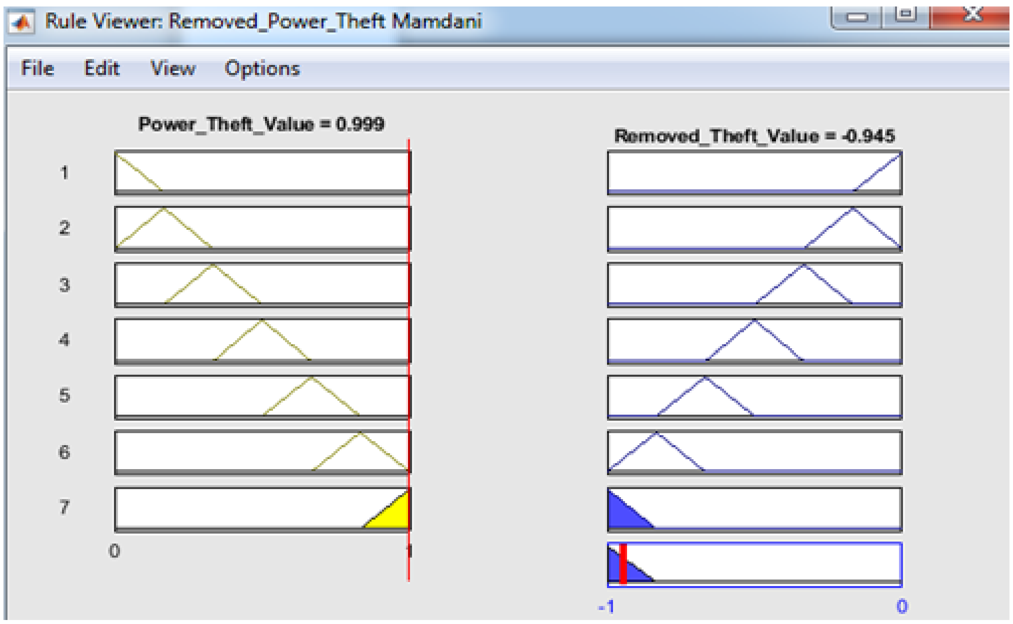

Figure 14. Rule Viewer for Prevention of 0.999 KW of Theft using Mamdani Method.

However, (0.945) is not exactly equal to (0.999). Consequently, we still have a stolen current value with an amount of 0.054 KW that has not been eliminated yet through using the Mamdani style. While resorting to using the Sugeno style, we would get much more efficient. The Sugeno-type inference is also an intelligent system in which the consequent of each rule is a linear combination of the inputs. The output is a weighted linear combination of the consequents as shown in figure 15.

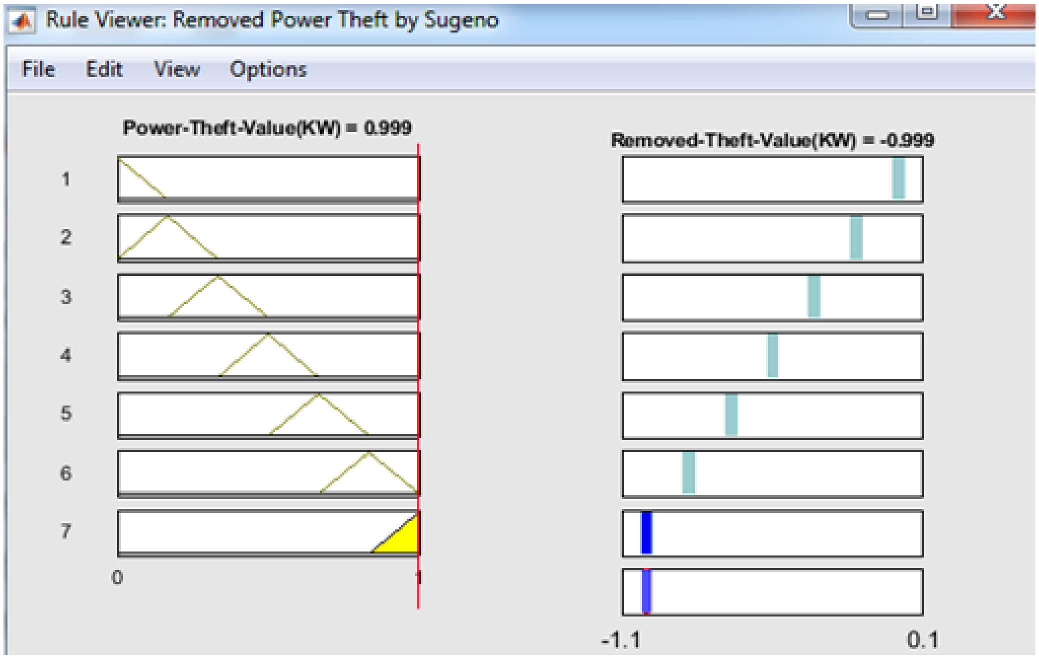

Figure 15. Rule Viewer for Prevention of 0.999 KW of Theft using Sugeno Method.

Adjusting these input values by clicking on any of these plots for each input. This will move the red index line horizontally, to the point where you have clicked. Alternatively, you can also click and drag this line in order to change the input values. Figure 16 shows the whole fuzzy inference process take place where the theft value is specified equal to 0.001KW then we note a new calculation is performed equals to 0.054KW which is far from 0.001 KW.

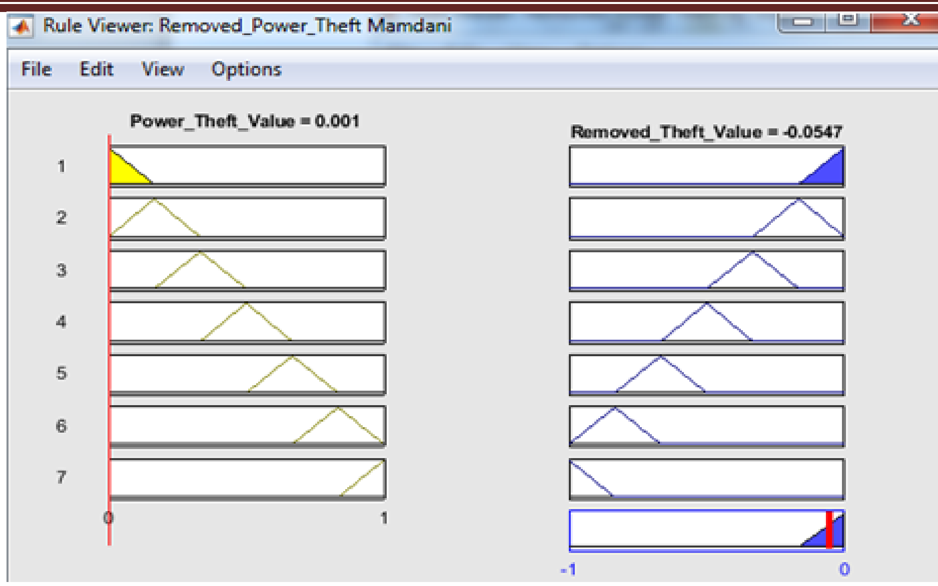

Figure 16. Rule Viewer for Prevention of 0.001 KW of Theft using Mamdani Method.

The Sugeno-type inference can be considered as a pre-defuzzified fuzzy set. Due to the output membership functions in Sugeno system are either linear or constant, the system finds the weighted average of a few data points rather than finding the centroid as shown in figure 17.

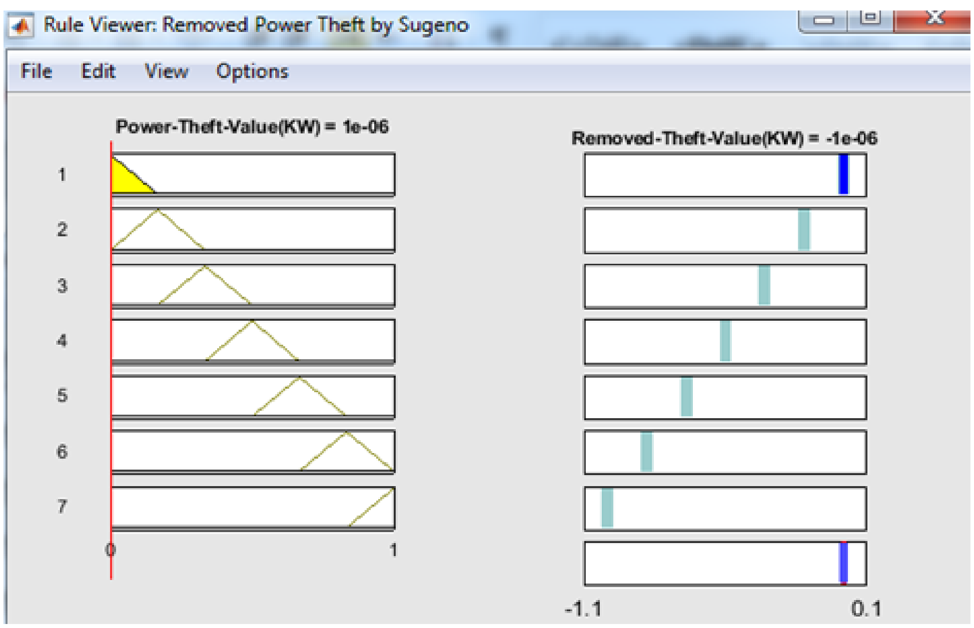

Figure 17. Rule Viewer for Prevention of $(1 * e^{-6})$ KW of Theft using Sugeno Method.

As input to the controller is the value to be reduced from the calculated value by an Arduino. Whenever the controller's input is far from 0.5 and the type of controller is Mamdani, the accuracy of the system would be very low. Accordingly, the fuzzy logic would not be successfully applied with very large error as shown in figure 18.

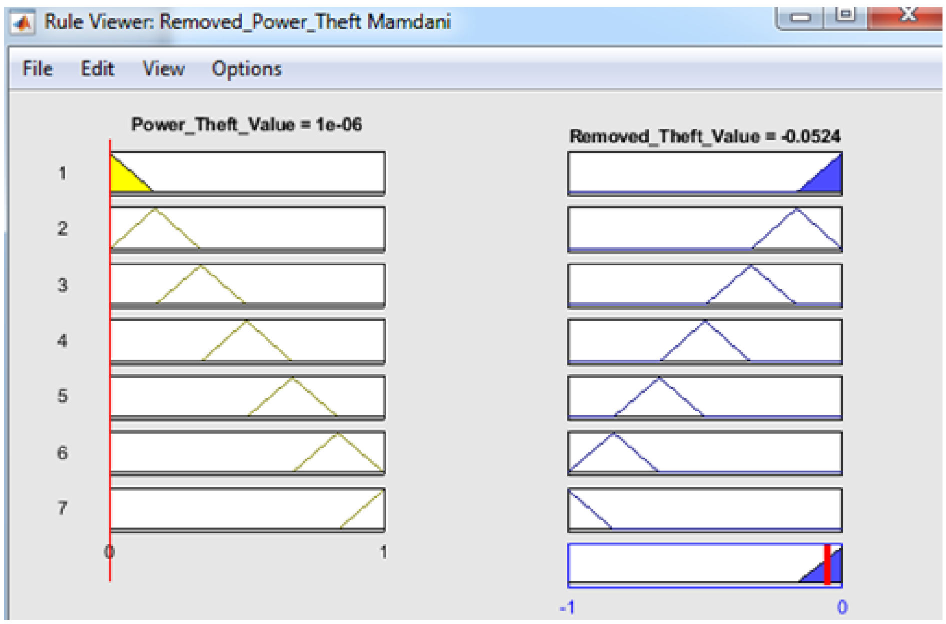

Figure 18. Rule Viewer for Prevention of $(1 * e^{-6})$ KW of Theft using Mamdani Method

In the all above figures that represent rule viewers, the aggregation occurs down the second column, and the resultant aggregate plot n the all above figures, the aggregation occurs down the second column, and the resultant aggregate plot is shown in the single plot appearing in the lower right corner of the plot field. The defuzzified output value is shown by the thick line passing through the aggregate fuzzy set.

The rule viewer displays a roadmap of the whole fuzzy inference process. It is designed to view the fuzzy inference diagram. It is used to know how individual membership function shapes influence the results. The two plots across the top of each figure represent the antecedent and consequent of each rule. Each rule is a row of plots, and each column is a variable. The rule numbers are displayed on the left of each row. By clicking on a rule number we view the rule in the status line.

To compare the dependency of one of the outputs on any inputs for two types of inference we use the surface viewer; that is, it generates and plots an output surface map for the system.

5.2 Surface Viewer

The results obtained from the comparison between surface viewers for fuzzy inference system (FIS) types show that immediately the illegal load is connected to the proposed system. Any unexpected usage is instantaneously being sent to the utility. This project is significantly useful to prevent instantly power theft when it has been discovered. Thus, illegal users won't be able to use. Figures 19 and 20 show how the result of the fuzzy Sugeno controller is more accurate than the result of the fuzzy Mamdani controller.

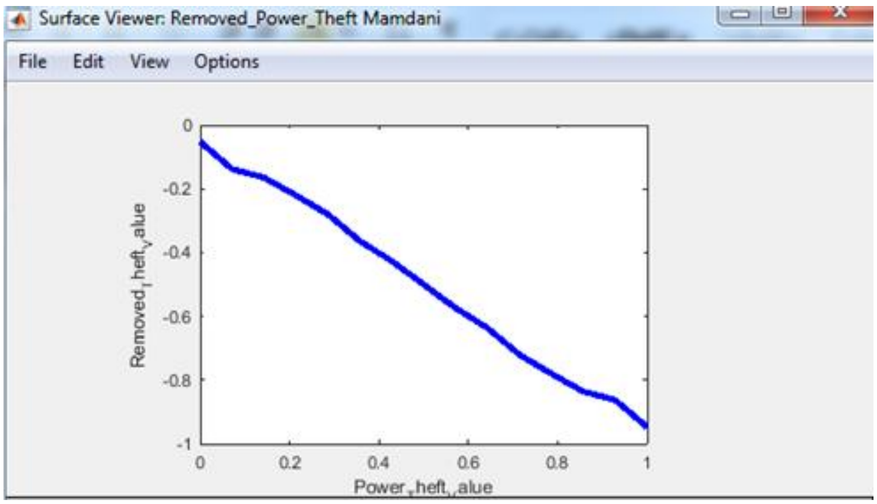

Figure 19. Surface Viewer for Prevention of Power Theft using Mamdani Controller.

The Sugeno inference system is fully responsive to all theft values that needed to be removed. Figure 20 shows the surface viewer based on the Sugeno method is more accurate to describe the model. Thus, all the data related to power theft will be removed from the mainline of electricity. The Sugeno FIS is extremely well suited to this task. The main concern in this project is to select the most accurate model with the highest degree of both confidence and accuracy, preferably with the lowest possible average cost associated.

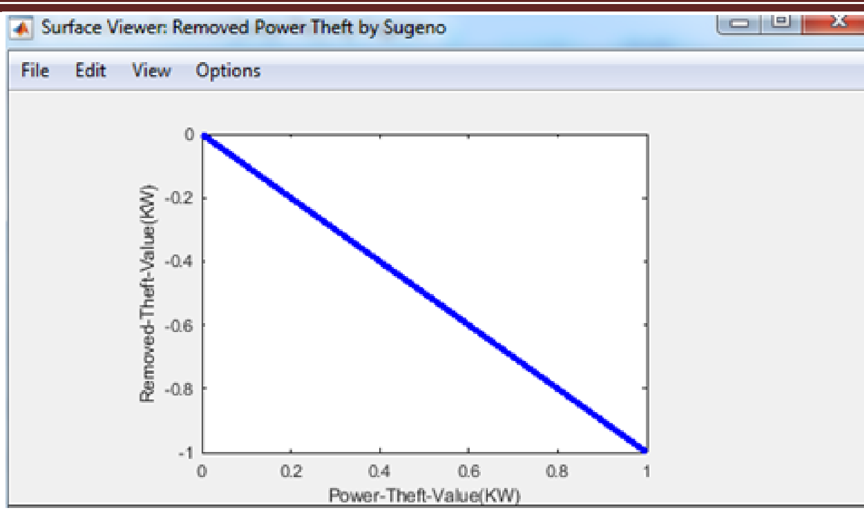

Figure 20. Surface Viewer for Prevention of Theft using Sugeno Controller.

The curve represents an one-input one-output case and shows the relationship between system's input to the system's output is linear and inverse, the value of the input is equal exactly to the value of the output by the same amount and the opposite of the trend. The negative sign that is existed in a rule viewer for both of the Mamdani and Sugeno controllers, means the subtraction operations have been executed to eliminate the theft.

From the analysis of the results above, the proposed system performed significantly well classifying the type of electricity user (legal or not). The program, that has been written in C/C++ Languages, was developed and proved a highly effective and accurate classifier on real identification of the type of data consumption. Thus, this algorithm can be relied on to be robust when used by GECOL for monitoring and users' classification purposes.

6. Conclusion

Simulation has been performed by the MATLAB for creating a model of the system that detect and monitor the power theft using a wireless technology. The consumption data is collected by the Master board from the Slave board and then is analyzed by the microcontroller. As the Slave is required to send the data for a specific user. These data contain information about the consumers' consumption behavior (e.g. legal or illegal, if legal, is it within normal or higher). The system is focused on two arguments which are: normal load case and the power theft case. The contributions of this work is a novel approach to develop a monitoring and detection system based fuzzy logic system that automatically monitors users' consumption. The theft of electricity in developed and developing countries is recently higher than years ago. Aims have been achieved by the system which are: detection of power theft using an Arduino with other devices and then cutting off electricity automatically using the fuzzy controller once the power theft has occurred. Due to prevention of power theft, there will be saving a massive amount of electricity. This will increase companies' profits and their economy. The proposed system is very accurate and displays accurate numbers with a wide range of loads. The target of the simulation is to design a system in which automatically detects and controls illegal connection of electricity. At this point, the FISs for prevention of power theft was completely defined, in that the variables, membership functions, and the rules necessary to calculate theft values and, and finally surface viewer that represents the entire mapping in one plot. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves all the pieces that are described in Membership Functions, Logical Operations, and If-Then Rules.

7. References

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