A Time-Varying Harmonic Distortion Diagnostic Methodology Using Fuzzy Logic

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***Abstract*—Harmonic distortion in power systems is an old problem which continues to grow in importance due to the proliferation of non-linear loads and of sensitive electronic devices. Thus, the need of standards to limit such distortion is required. Due to the time-varying nature of the distortion more advanced techniques are required to properly quantify their impact. This paper proposes the utilization of fuzzy logic to analyze, compare, and diagnose harmonic distortion indices in a power system.**

I. Harmonic Distortions in Power Systems

When non-linear loads are connected to an electric power system they tend to inject distortions into the system. These harmonic distortions, by Fourier analysis, are components that have frequencies that are integer multiples of the fundamental frequency. These harmonic distortions are produced by power generation and non-linear loads. The nonlinear nature of these loads change the sinusoidal shape of the AC current and consequently the AC voltage [1]. Typically the harmonics are assumed to be periodical/time-invariant. However harmonic components are continually changing with time [2]. It is important then to look at the harmonics from a time-varying perspective.

II. Intro to Fuzzy Logic

The ideas behind fuzzy logic have been around since 1965 when they were introduced by Lofti A. Zadeh. Fuzzy logic, however, has not been widely used since 1965, it has only gained popularity in the last 20 years, meaning that there are many new applications of fuzzy logic [3].

In a traditional bivalent logic system an object either is or is not a member of a set. The idea of fuzzy sets is that the members are not restricted to true or false definitions. A member in a fuzzy set has a degree of membership to the set. For example, the set of temperature values can be classified using a bivalent set as either hot or not hot. This would require some cut-off value where any temperature greater than that cut-off value is ‘hot’ and any temperature less than that value is ‘not hot’. If the cut off point is at 50^{o}C then this set does not differentiate between a temperature that is 20^{o}C and a temperature of 49^{o}C. They are both ‘not hot’ [3].

If a fuzzy set were to be used in this situation each member of the set, or each temperature, would have a degree of membership to the set of hotness. The function that determines this degree of membership is called the fuzzy membership function (Figure 1)

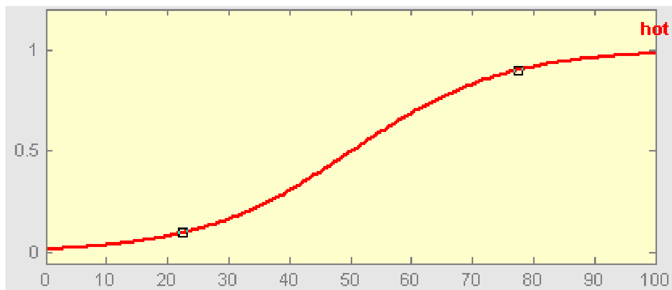

Figure 1: Fuzzy membership function for hotness

There are countless different membership function topologies that can be used; the most common are triangular, Gaussian and sigmoidal. This function is a sigmoidal function. The attributes of the membership function can be modified based on the desired input [4]. If the relevant temperature range was between 20 and 60 degrees, for example, and more weight was needed for higher temperatures then an appropriate membership function can be determined. The determination of this function is dependant on the desired weighting of the input.

III. Fuzzy Logic Control

The basic fuzzy logic control system is composed of a set of input membership functions, a rule-based controller, and a defuzzification process. The fuzzy logic input uses member functions to determine the fuzzy value of the input. There can be any number of inputs to a fuzzy system and each one of these inputs can have several membership functions. The set of membership functions for each input can be manipulated to add weight to different inputs. The output also has a set of membership functions. These membership functions define the possible responses and outputs of the system [4].

The fuzzy inference engine is the heart of the fuzzy logic control system. It is a rule based controller that uses If-Then statements to relate the input to the desired output [4]. The fuzzy inputs are combined based on these rules and the degree of membership in each function set. The output membership functions are then manipulated based on the controller for each rule. Several different rules will usually be used since the inputs will usually be in more than one membership function. All of the output member functions are then combined into one aggregate topology. The defuzzifaction process then chooses

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the desired finite output from this aggregate fuzzy set. There are several ways to do this such as weighted averages, centroids, or bisectors. This produces the desired result for the output.

IV. The Harmonic Distortion Fuzzy Model

The fuzzy model for the harmonic distortion diagnostic was implemented in MATLAB using the fuzzy logic toolbox. This toolbox allows for the creation of input membership functions, fuzzy control rules, and output membership functions [5]. To implement this system in Simulink the system will need to have two different inputs: the harmonic voltage and the temperature. These two inputs will then be processed by a fuzzy logic controller that will output a degree of caution. This degree of caution is then decoded into one of four possible outputs: No problem, Caution, Possible Problem, and Imminent Problem. A simple (two-variable example) diagnostic system was created as shown in Figure 2.

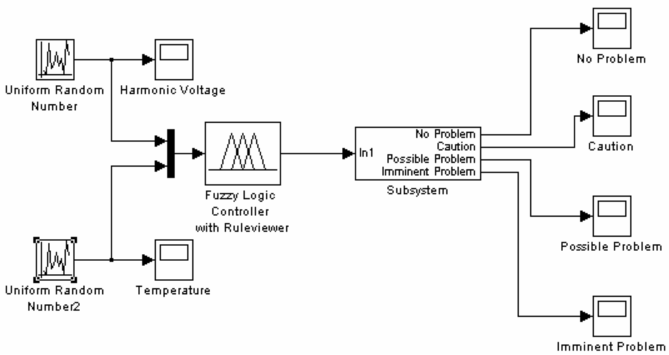

Figure 2: Harmonic Distortion Diagnostic Simulink Model

This diagnostic system uses random number inputs for the harmonic voltage and temperature inputs. The harmonic voltage input (Figure 3) is a random distribution in the range of 0 to 10. The temperature input (Figure 4) is a random distribution in the range of 30 to 100 degrees Celsius.

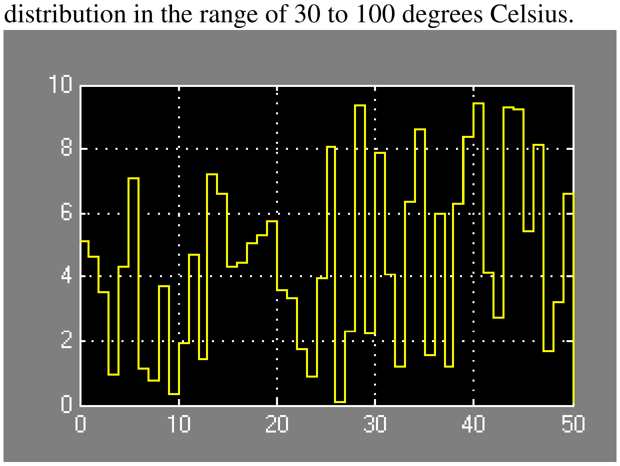

Figure 3: Harmonic Voltage Input

These input function ranges can now be used in determining the fuzzy membership sets. The fuzzy system will have these two inputs and one indicating output (Figure 5). The fuzzy system used will be a mamdani system [4], and the centroid method for defuzzification. The input membership function for harmonic voltage (Figure 6) will have five different

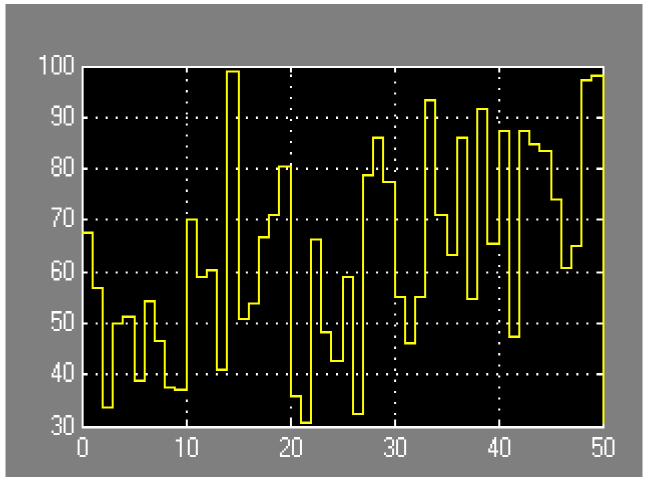

Figure 4: System Temperature Input

membership functions: very low, low, medium, high, and very high. The range of this function is 0 to 10, these are the possible input values. The very low and very high membership functions continue on to infinity in either direction to include any voltage value out of range.

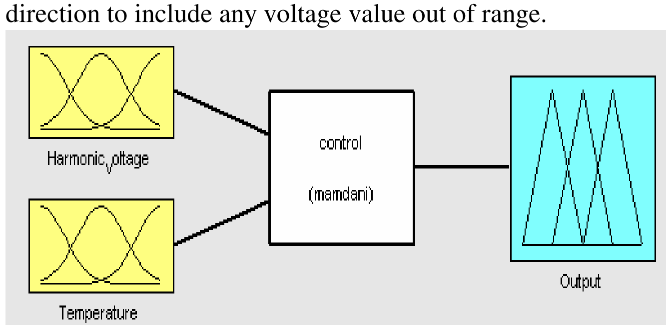

Figure 5: The Fuzzy Logic Diagnostic Controller

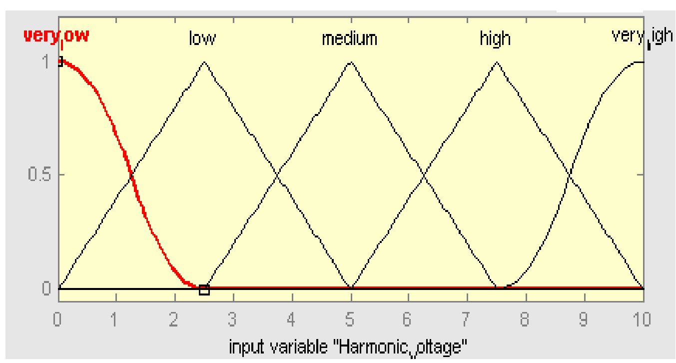

Figure 6: The Harmonic Voltage Input Membership Functions

The harmonic voltage membership functions define anything from 0 to 5 as *low*, using a triangular function. Anything from 2.5 to 7.5 is *medium*, and anything from 5 to 10 is *high*. An input with a harmonic voltage of 3 will have about an 80% membership in the *low* function and about a 20% membership in the *medium* function. The total membership in this case will add up to be 100% but this is not required in a fuzzy set.

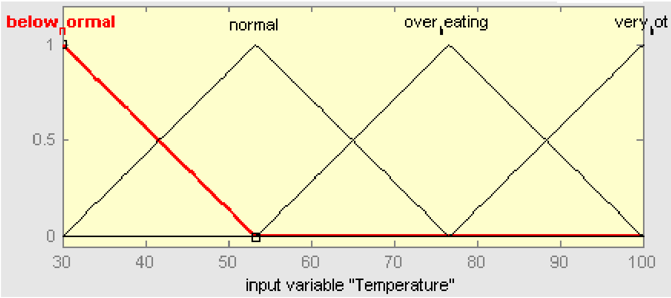

Figure 7: The System Temperature Input Membership Functions

There are four temperature input membership functions (Figure 7). The *below normal* function is a triangular function centered at 30 that extends up to 53 degrees. The *normal* triangular function is centered at 53 degrees, extending from 30 to 76 degrees at its limits. The *over heating* triangular membership function is centered at 76 degrees with the same magnitude of range as the *normal* function. The *very hot* function begins at 76 degrees and peaks at 100 where it extends on past the set max input of 100 to cover out of limit values.

The output has four membership functions, *no problem*, *caution, possible problem*, and *imminent problem* (Figure 8). These membership functions are all triangular and are spread evenly on a range of 0 to 1.

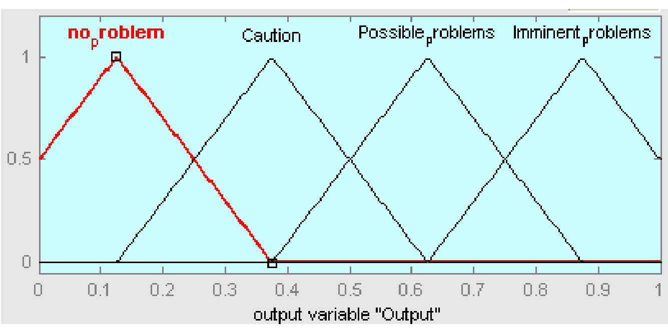

Figure 8: The Output Membership Function

Once all of the input and output membership functions have been defined the heart of the control can now be defined; the rules. The fuzzy rules are in the form of if-then statements. These statements look at both inputs and determine the desired output. In this system increasing voltage and increasing temperature will lead to an imminent problem. A low temperature with a relatively high voltage will not necessarily be an imminent problem though. The rules defined for this system are in Table 1 below:

Table 1: Membership Rules

If Harmonic Voltage is:	And the temperature is:	Then the Output is:
very_low	below_normal	no_problem
very_low	normal	no_problem
very_low	over_heating	no_problem
very_low	very_hot	Caution
low	below_normal	no_problem
low	normal	no_problem
low	over_heating	Caution
low	very_hot	Possible_problems
medium	below_normal	no_problem
medium	normal	Caution
medium	over_heating	Possible_problems
medium	very_hot	Possible_problems
high	below_normal	Caution
high	normal	Possible_problems
high	over_heating	Possible_problems
high	very_hot	Imminent_problems
very_high	below_normal	Possible_problems
very_high	normal	Possible_problems
very_high	over_heating	Imminent_problems
very_high	very_hot	Imminent_problems

These rules are the defining elements of this system. They determine the output based on the input. These rules can be looked at graphically as a rule map (Figure 9). This rule map illustrates the response of the system to different inputs. On the map the blue represents no problem and the yellow represents an imminent problem. The intermediate colors show the mix of fuzzy options in between.

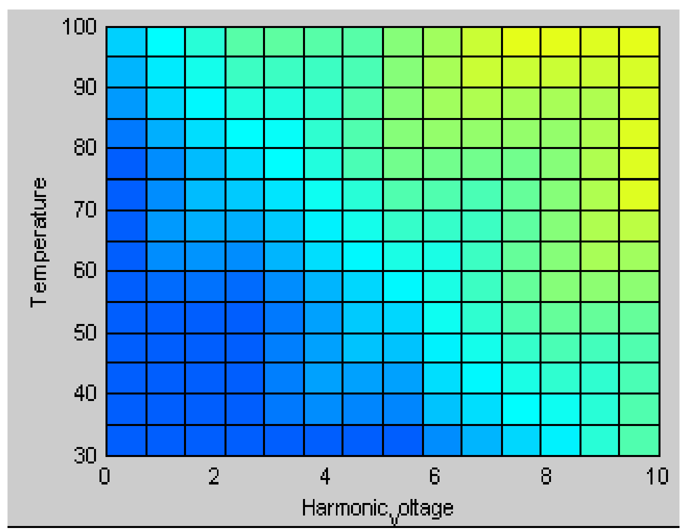

Figure 9: Fuzzy Control Rule Map

Now that the fuzzy control system has been entirely defined it is exported into the Simulink model. The model includes some decoding logic that will output different discrete levels for each of the possible outputs (Figure 2). This could serve as digital input to some other system.

V. SIMULATION

The inputs for this example system have been shown before; they are randomly generated data within a valid range. The system can be simulated using this data. The output signals generated are shown in Figure 10 through Figure 13.

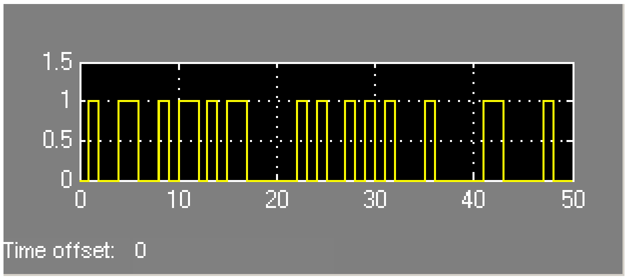

Figure 10: No Problem Output

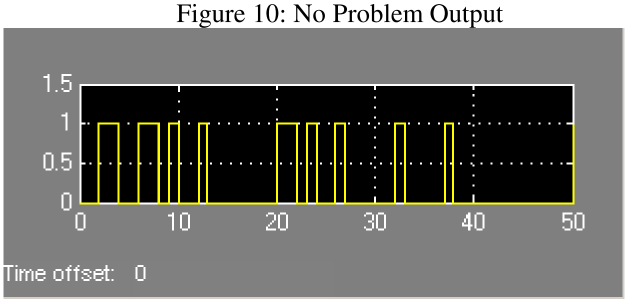

Figure 11: Caution Output

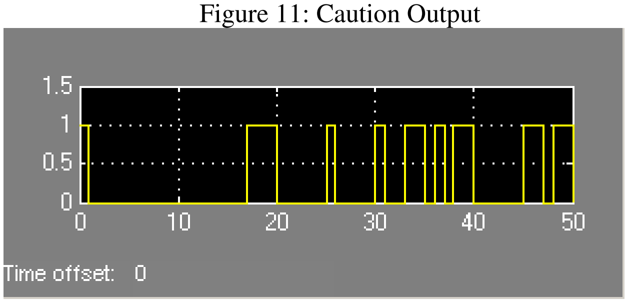

Figure 12: Possible Problem Output

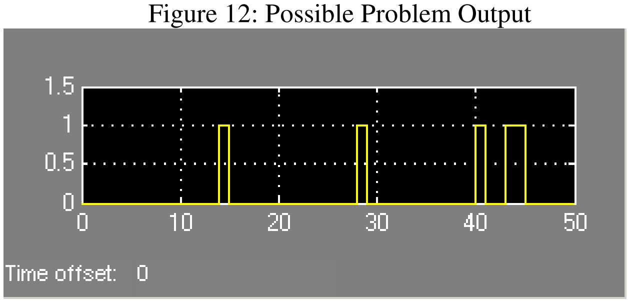

Figure 13: Imminent Problem Output

These results could be then used to compute probability distribution functions and or send alarm notes to a central controller.

VI. Harmonics Plus THD and Temperature Case

Using the model developed above a more involved case can be set up. This case will look at the fundamental voltage variation as well as the variation of the third, fifth and seventh harmonics. The following variations will be used in this case:

Table 2: Input Variations

Fundamental	+/- 10%
V3	1% – 8%
V5	1% – 8%
V7	1% – 8%
VTHD	1% – 13%
Temperature	30°C – 100°C

The Fundamental and the harmonics will have uniform random function generators as inputs. These function generators will generate a uniform distribution of inputs within the variances given in Table 2. The total harmonic distortion will be calculated depending on these inputs and so it will be in the range of 1% to 13%, these are the best and worst case scenarios. The temperature variation will remain the same as in the previous case.

Using this input data and the basic model developed in the first case a Simulink model can be developed that processes all the input data and gives an appropriate indication for each harmonic, the fundamental, and THD. These indications will remain the same as in the previous case. Each indicator will have a fuzzy logic controller that implements one of three control topologies, one for the fundamental, THD, and the harmonics. The final Simulink model can be seen in Figure 14.

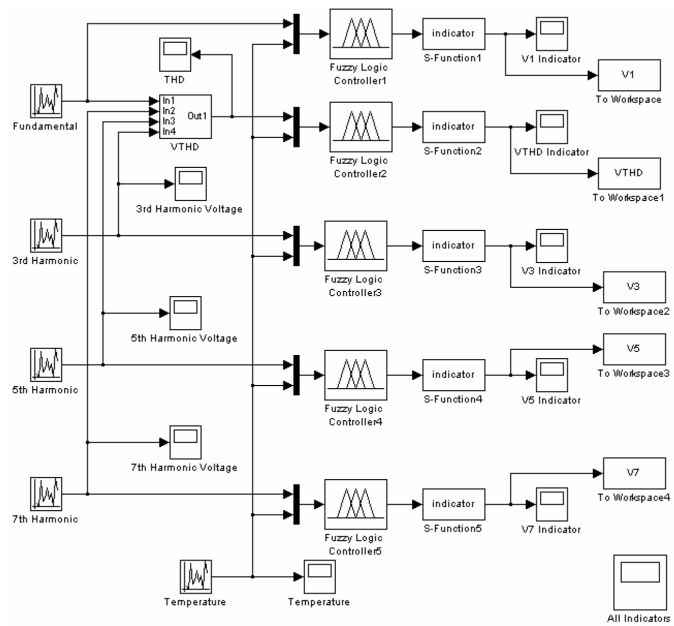

Figure 14: Final Simulink Model

The first fuzzy logic controller will use the fuzzy inference system that has the following rule surface that shows high output values in yellow and low values in blue:

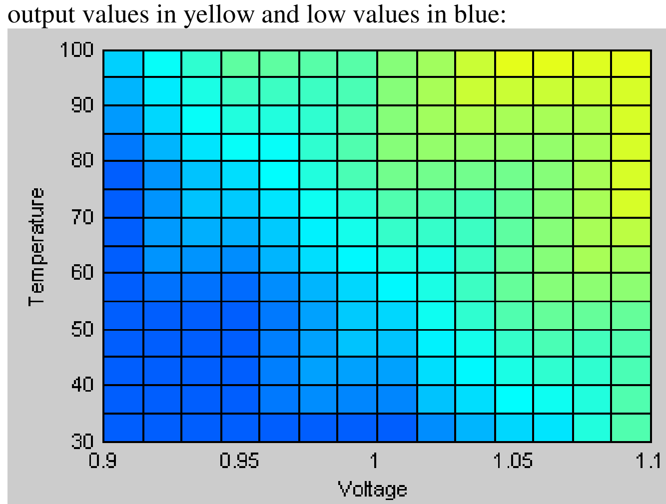

Figure 15: Fundamental Rule Surface

This rule surface shows the behavior of the fuzzy controller depending on the temperature and input voltage variation. The total harmonic distortion rule surface and the harmonic voltage rule surfaces will be essentially the same except with different scales based on the variations given in Table 2, they can be seen in Figure 16.

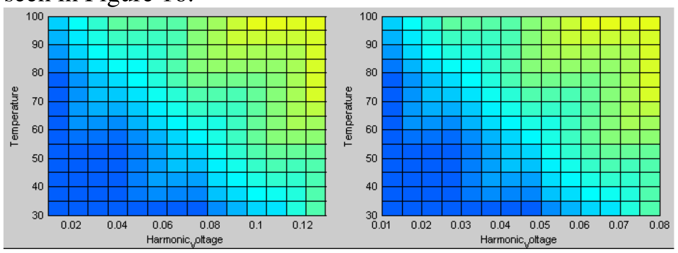

Figure 16: THD and Harmonic Rule Surfaces

The second fuzzy controller uses the THD fuzzy inference system and the remaining three fuzzy controllers use the harmonic fuzzy inference system.

The S-functions in the model are simple MATLAB files that process the fuzzy logic controller output and determine the output level using the code shown in Figure 17.

```
if u < 0.25
    sys= 0;
elseif u < 0.5
    sys= 1;
elseif u <0.75
    sys= 2;
else
    sys= 3;
end;
```

Figure 17: S-function Code

This code will split the fuzzy output into four ranges and then output either a 0,1,2, or 3 corresponding to No Problem, Caution, Possible Problems, and Imminent Problems. After this final decoding step the output is sent to scopes and also to workspace variables. These workspace variables will allow for statistical analysis after simulation.

VII. Simulation Results

The inputs for the simulation are all from uniform random number generators that will generate random numbers within the previously defined ranges. The system will be modeled for a 24 hour period with the number generators producing a new number every 2 minutes.

Each random number generator has a different seed value to produce a different set of numbers. All of the inputs can be seen in Figure 18. From top to bottom the inputs are the fundamental, third harmonic, fifth harmonic, seventh harmonic and the temperature. The harmonics and fundamental are given as percentages (0.08 = 8%).

The outputs of the system will be one of four options, 0,1,2, or 3 which represent the possible warning indicators. These outputs can be seen in Figure 19. In that figure the outputs, from top to bottom, are the fundamental, third, fifth, seventh harmonics, and finally the total harmonic distortion.

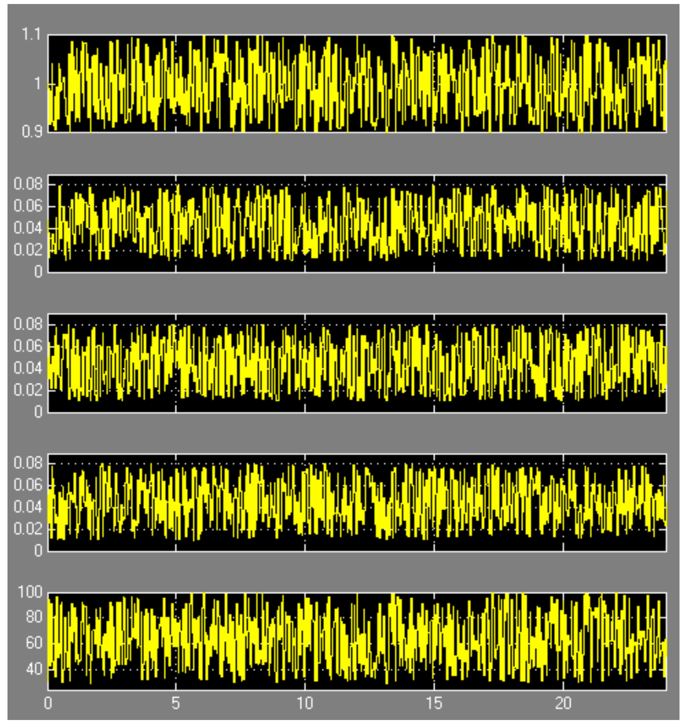

Figure 18: All System Inputs (top down): Fundamental, Third, Fifth, Seventh Harmonics and Temperature

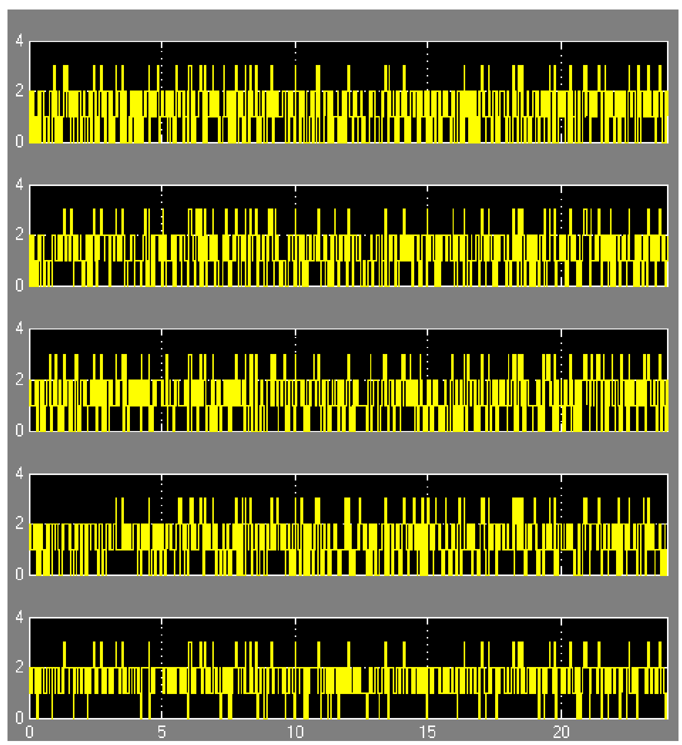

Figure 19: Output Indicators (Top down): Fundamental, Third, Fifth, Seventh Harmonics and THD

Most of the outputs appear to be in the Caution or Possible Problems state by looking at the output plot. The outputs were exported into MATLAB where they could be plotted in a histogram to so that the distribution of outputs could be easily seen. This histogram can be seen in Figure 20. From this we can tell that most of the results are the first three states, except with the total harmonic distortion where most of the results are either Caution or Imminent Problems.

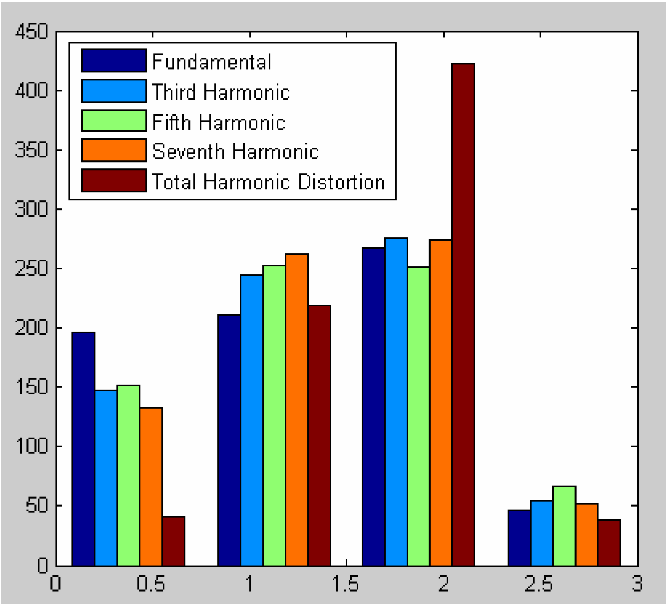

Figure 20: Output Histogram: Uniform Distribution

The simulation was repeated with different input distributions as well. Figure 21 shows the output histogram when the inputs are all Gaussian distributions. The output histograms are broken up into four sections as a result of the filtering that occurs in the S-function code, shown in Figure 17, which reduces the fuzzy controller output to only four states. The output distribution of the fuzzy controllers can be plotted with higher resolution, for an example the output of the fundamental fuzzy controller can be seen in Figure 22. That output is the unprocessed output of the fuzzy logic controller.

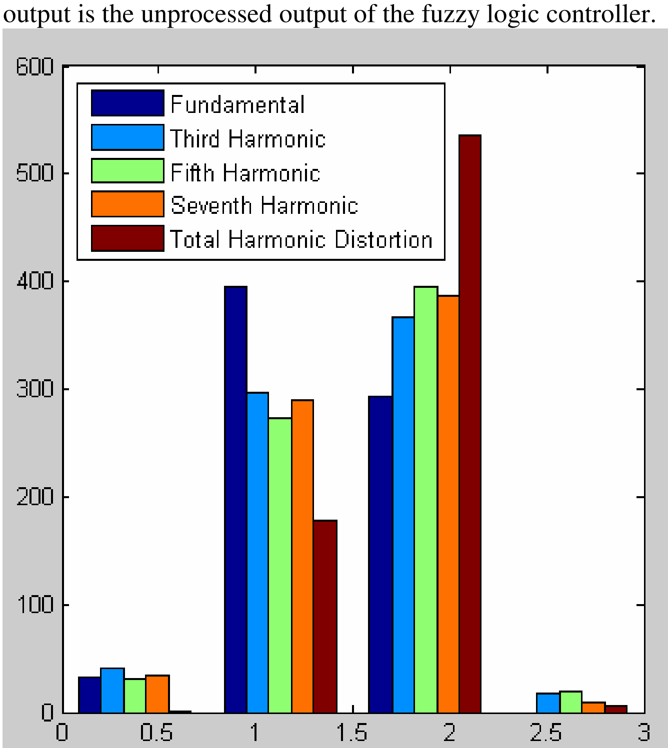

Figure 21: Output Histogram: Gaussian Distribution

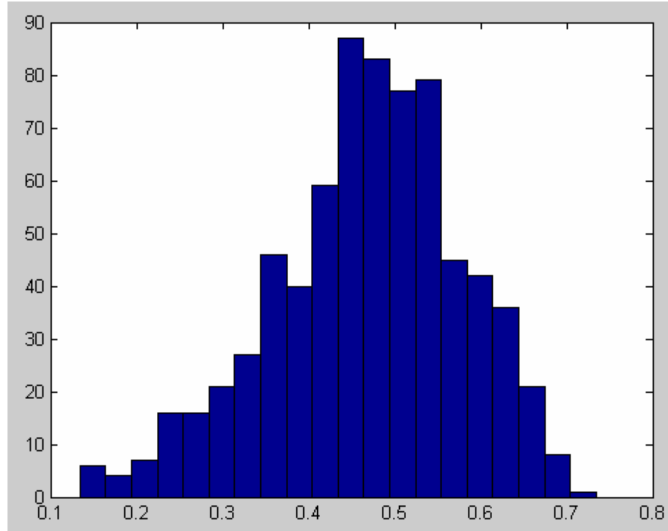

Figure 22: Fundamental Fuzzy Logic Controller Output Histogram

VIII. Conclusions

This paper presented a methodology to analyze harmonic distortion impact on system equipment using a fuzzy logic based system. The examples simulated indicate the potential for using such a procedure for studying complex systems and performing a meaningful evaluation and/or analysis of the impact of time-varying harmonic distortion on a power system.

IX. References

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X. Biography

Bryan Klingenberg is originally from London, Ontario Canada. He came to Calvin College in Grand Rapids, Michigan where he is currently finishing his undergraduate degree in electrical and computer engineering. He is also working towards his mathematics minor. Bryan has work experience at Beta Integrated Concepts where he works with industrial automation control systems. He plans to attend graduate school after he completes his undergraduate degree in May of 2006. This work was done in cooperation with Professor Paulo Ribeiro in the Engineering department at Calvin College. It was also funded through a Calvin College CIT department ALIVE grant.