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A FUZZY-EXPERT SYSTEM FOR CLASSIFICATION OF SHORT DURATION VOLTAGE DISTURBANCES

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Abstract. One of the important aspects in power quality assessment is automated detection and classification of power quality disturbances which requires the use of artificial intelligent techniques. This paper presents the application of fuzzy-expert system for classification of short duration voltage disturbances which include voltage sag, swell and interruption. To obtain unique features of the voltage disturbances, fast Fourier transform analysis and root mean square averaging technique are utilized so as to determine the disturbance parameters such as duration, maximum and minimum rms voltage magnitudes. Based on these parameters, a fuzzy-expert system has been developed to set the fuzzy rules incorporating five inputs and three outputs. The system is designed for detecting and classifying the three types of short duration voltage disturbances, so as to determine whether the disturbance is instantaneous, momentary and non sag, swell and interruption. To verify the accuracy of the proposed system, it has been tested with recorded voltage disturbances obtained from monitoring. Tests results showed that the developed fuzzy-expert system gives a correct classification rate of 98.4 %.

Key words: Power quality, fuzzy-expert system, sag, swell and interruption.

Abstrak. Satu aspek penting dalam penilaian kualiti kuasa adalah pengesanan dan pengkelasan gangguan kualiti kuasa secara automatik yang memerlukan penggunaan teknik kepintaran buatan. Kertas kerja ini membentangkan penggunaan sistem pakar-kabur untuk pengkelasan gangguan voltan jangka masa pendek yang termasuk lendut voltan, ampul dan sampukan. Untuk memperolehi sifat unik bagi gangguan voltan, analisis jelmaan Fourier pantas dan teknik purataan punca min kuasa dua digunakan untuk menentukan parameter gangguan seperti tempoh masa, magnitud voltan pmk maksimum dan minimum. Berasaskan pada parameter ini, sebuah sistem pakar-kabur telah dibangunkan dengan mengset aturan kabur yang menimbangkan lima masukan dan tiga keluaran. Sistem ini direka bentuk untuk mengesan dan mengkelaskan tiga jenis gangguan voltan tempoh masa pendek dengan menentukan sama ada gangguan adalah gangguan ketika, gangguan seketika dan bukan gangguan lendut, ampul dan sampukan. Untuk mengesahkan kejituan sistem yang dicadangkan, ia telah diuji dengan gangguan voltan yang diperolehi dari pengawasan. Keputusan ujian menunjukkan bahawa sistem pakar-kabur yang dibangunkan telah memberikan kadar pengkelasan yang betul sebanyak 98.4 %.

Kata kunci: Kualiti kuasa, sistem pakar-kabur, lendut, ampul dan sampukan

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1.0 INTRODUCTION

Power quality (PQ) has been a research area of increasing interest particularly in the past decade. The interest in PQ involves all three parties, namely, utility companies, equipment manufacturers and electric power customers. It is a term often used today for describing an important aspect of the electricity supply and utilization. A PQ problem is any occurrence manifested in voltage, current, or frequency deviation that results in failure or misoperation of end-use equipment [1]. Voltage sag, swell, interruption, transient and waveform distortion are examples of disturbances related to PQ problems. Short duration voltage variations are a group of disturbances categorized by IEC which comprise of voltage sag, swell and short interruptions. Table 1 shows the types and characteristics of short duration voltage variation. Each type of voltage variation can be designated as instantaneous and momentary disturbance, depending on its duration [2]. The short duration voltage variations are usually caused by faults in a system, energization of large loads that require high starting currents and intermittent loose connections in power wiring. Depending on fault location and system conditions, faults can cause voltage sag, voltage swell and a complete loss of voltage or interruption.

Table 1 Types and characteristics of short duration voltage variation

Type	Disturbance	Duration	Voltage magnitude
Instantaneous	Sag	0.5-30 cycles	0.1-0.9 p.u
	Swell	0.5-30 cycles	1.1-1.8 p.u
	Interruption	0.5-30 cycles	$<$ 0.1 p.u
Momentary	Sag	30 cycles-3 s	0.1-0.9 p.u
	Swell	30 cycles-3 s	1.1-1.4 p.u
	Interruption	30 cycles-3 s	$<$ 0.1 p.u

An important aspect in PQ studies is the ability to perform automated detection and classification of disturbances obtained from monitoring. Efforts for automating the detection and classification process have been addressed for many years. Such an automated PQ assessment requires a high level of engineering expertise and powerful tools. The new and powerful tool of interest for PQ assessment is by using signal processing techniques such as wavelets [3] and artificial intelligent (AI) techniques such as neural network [4], expert system [5] and fuzzy logic [6-8]. Fuzzy logic has been applied to determine whether computer-based loads are sensitive to voltage sag [6]. A fuzzy reasoning process was developed to decide the reliability of these loads when subjected to voltage sag disturbances. A hybrid scheme using fuzzy-expert system and Fourier linear combiner has been developed for identification of transient disturbances [7]. Other applications of fuzzy logic for PQ assessment have been developed for classification of oscillatory and impulsive transients [8], detection of harmonic sources [9] and classification of various PQ disturbances such as voltage sag, swell, interruption, transient and voltage notching [10-11]. The above-mentioned fuzzy logic methods differ in the signal processing techniques used for extracting the features of various disturbances. The techniques that have been employed for feature extraction are wavelet transform analysis [9,11] and time-frequency analysis based on the S-transform [10]. Such signal processing techniques usually involve elaborate processing of signals and take longer time in extracting disturbance features and therefore may not be suitable for real time disturbance detection.

This paper presents a simple signal processing technique based on the fast Fourier transform (FFT) analysis and root mean square (rms) averaging technique for extracting the features of PQ disturbances and providing inputs to the classification system. For classification of short duration voltage disturbances comprising of voltage sag, swell and interruption, a fuzzy-expert system is developed. The inputs to the fuzzy-expert system that have been considered are the maximum and minimum rms voltage magnitudes in per unit and disturbance duration in seconds. The outputs of the system consider instantaneous sag, non-sag, momentary sag, instantaneous swell, non-swell, momentary swell, instantaneous interruption, non-interruption and momentary interruption.

2.0 FUZZY LOGIC AND FUZZY-EXPERT SYSTEM

Fuzzy logic (FL) refers to a logic system which represents knowledge and reasons in an imprecise or fuzzy manner for reasoning under uncertainty. Unlike the classical logical systems, it aims at modeling the imprecise modes of reasoning that play an essential role in the human ability to infer an approximate answer to a question based on a store of knowledge that is inexact, incomplete, or not totally reliable [12]. It is usually appropriate to use FL systems when a mathematical model of a process does not exist, or does exist but is too difficult to encode and too complex to be evaluated fast enough for real time operation.

A fundamental element of FL is the membership function which describes the degree of a certain variable "*x*", belonging to a fuzzy set "A". This degree of membership is expressed by a number between 0 and 1 in which a membership value of 1 means that the variable is completely satisfactory for the fuzzy set "A", whereas a value of 0 means that it is completely unacceptable in that fuzzy set, and it does not belong to the set "A" at all. Any deviation is acceptable with an intermediate degree of satisfaction between 0 and 1. A fuzzy set can be defined by a function called the membership function in which the most widely used membership functions are the triangular and trapezoidal functions.

A fuzzy-expert system is an expert system that uses a collection of fuzzy sets and rules for reasoning of data. The set of rules in a fuzzy-expert system is known as the rule base or knowledge base. When fuzzy-expert system is used to solve real problems, the following steps are generally followed [12]:

(i) Describe the original problem in a linguistic or mathematical form.
(ii) Define the input and output variable for the fuzzy inference system, whose range and thresholds can be based on empirical knowledge.
(iii) Define appropriately the number and shape of membership functions for each input and output variables. The membership functions express the degree of satisfaction of a certain variable value into a defined fuzzy set. This step is called fuzzy matching which calculated the degree that the input data match the condition of the fuzzy rules.
(iv) Define the If-Then inference rules that represent the practical behavior being modeled by an expert.
(v) Select the fuzzy operators for the defuzzification process in order to ensure that fuzzy set of the output variables are converted to the crisp numbers.

3.0 THE PROPOSED FUZZY EXPERT SYSTEM FOR CLASSIFICATION OF SHORT DURATION VOLTAGE DISTURBANCES

The proposed fuzzy-expert system is designed to classify short duration voltage disturbances defined as instantaneous and momentary sag, swell and interruption, as shown in Figure 1. In the study, the disturbance data are obtained from PQ monitoring in which the monitoring software by default has three different sampling frequencies of 0.4 kHz (128 cycle), 1.6 kHz (32 cycle) and 6.4 kHz (8 cycle) and each frame has 1024 samples.

3.1 Preprocessing and Extraction of Features

To process the raw disturbance data so as to extract features of the various disturbances, preprocessing of the disturbance signals is required. Initially, fast Fourier transform analysis is used to separate the 8, 32 and 128 cycle waveforms. Then root mean square (rms) method is applied by first approximating the fundamental frequency profile of actual voltage waveform and determining the maximum and minimum voltage magnitudes. An advantage of this method is its simplicity, fast calculation and less requirement of memory because rms voltage can be stored periodically instead of per sample.

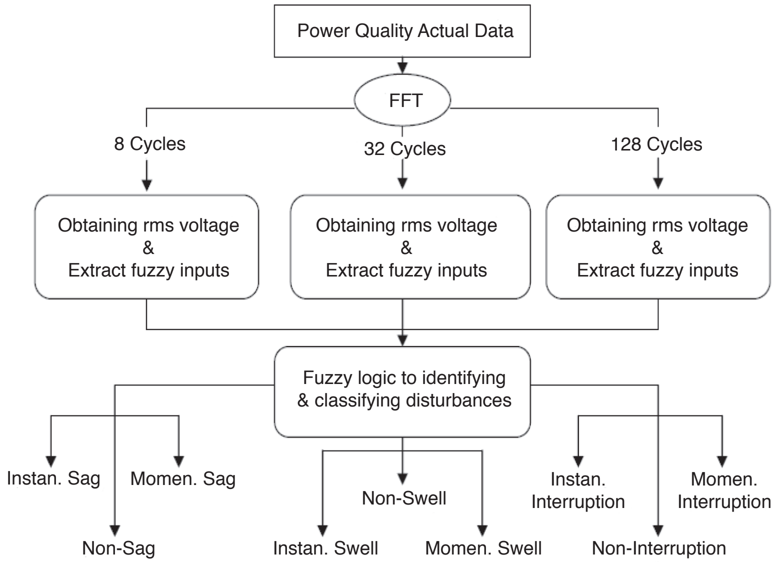


Figure 1 Design of the proposed fuzzy-expert system

In determining the maximum and minimum voltages in each half cycle waveform, in the case of 8, 32, and 128 cycle waveforms, there are 16, 64, and 256 maximum and minimum voltage samples. Figure 2 (a) shows the maximum and minimum voltage values for a 32 cycle disturbance. To obtain an accurate rms voltage waveform, the maximum and absolute of minimum voltage samples are recorded in a matrix with 1024 array size as shown in Figure 2 (b) in which the size is equal to the number of samples in an actual voltage waveform. The averaging technique is then applied by taking the average value of the maximum and absolute of minimum voltage values. The 8, 32 and 128 cycle disturbance waveforms which have 16, 64 and 256 voltage samples are then changed to 1024 samples using the 6, 4 and 2 times averaging, respectively. In this way, all the zero values between the maximum and minimum voltage values in the matrix are replaced with the average values.

The rms voltage values are then converted to per unit (p.u) voltage by dividing the voltage values with its nominal voltage value. The nominal voltage value can be determined, for example, by calculating the average of the first fifteen voltage samples. Figure 3 shows the results of the averaging process by plotting the rms voltage magnitude in per unit.

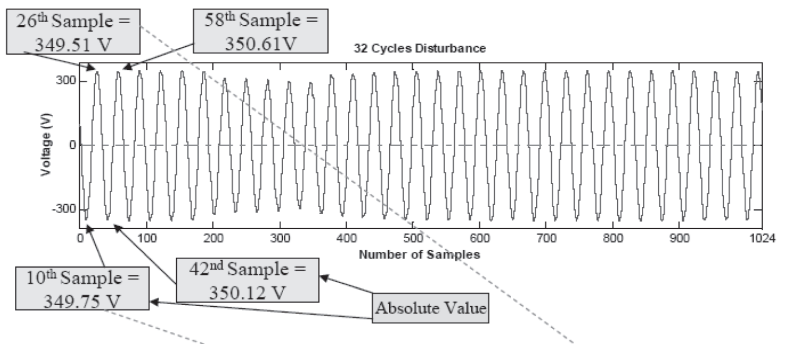
3.2 Fuzzy Logic Inputs and Outputs

The Mamdani-type fuzzy inference system with five inputs and three outputs has been considered in the proposed fuzzy-expert system. The five inputs include maximum voltage in p.u (Max-V), sag duration in second (SagDurat), swell duration in second (SwelDurat), transient duration in second (TranDurat) and minimum voltage in p.u (Min-V). The maximum voltage has been chosen as a fuzzy input variable so as to classify instantaneous and momentary swell whereas the minimum voltage is for differentiating between interruption and voltage sag. The sag duration is used as an input variable for classifying instantaneous and momentary sag whereas the swell duration is used to classify swell disturbance to instantaneous and momentary swell. The transient duration is chosen as a fuzzy input for distinguishing between instantaneous swell and impulsive transient disturbance. The three FL outputs are Output1, Output2 and Output3 in which Output1 is designated for classifying instantaneous sag, non-sag and momentary sag, Output2 for classifying instantaneous swell, non-swell and momentary swell, and Output3 for classifying instantaneous interruption, non-interruption and momentary interruption.

3.3 Membership Functions

The input and output variables are represented by some membership functions which are either in trapezoidal or triangular forms. The range of input variables and thresholds are chosen in accordance with the respective disturbance definition as defined in the IEEE Std 1159-1995. The membership functions defined for the five input variables are as shown in Figures 4 to 8. The output variables are defined by three membership functions as shown in Figures 9 to 11. The meaning of each defined fuzzy sets for each of the input and output variables are explained in Table 2 and Table 3, respectively.

a)



b)

[0 0 0 0 0 0 0 0 0 349.75 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 349.51 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 350.12 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 350.61 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 351.34 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 352.32 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
352.5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 352.68 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 352.2
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 351.6 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 350.7 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 350.48 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 323.3 0 0 0 0 0 ...]

Figure 2 (a) Maximum and absolute of minimum voltage values (b) Replacing voltage values with zeros in the matrix

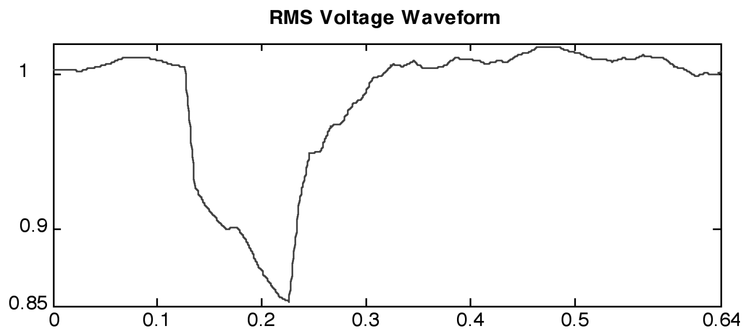


Figure 3 RMS voltage magnitude in per unit

To determine the disturbance duration, it is needed to change the horizontal axis unit from number of samples as shown in Figure 2(a) to time. As one cycle of voltage waveform in 50 Hz network has period of 0.02 second, the duration for the 8, 32, and 128 cycle waveforms are calculated as ($8 \times 0.02 = 0.16$ s), ($32 \times 0.02 = 0.64$ s), and ($128 \times 0.02 = 2.56$ s), respectively. Figure 3 shows the plot of the 32 cycle voltage sag waveform with its 1024 samples converted to time in 0.64 second.

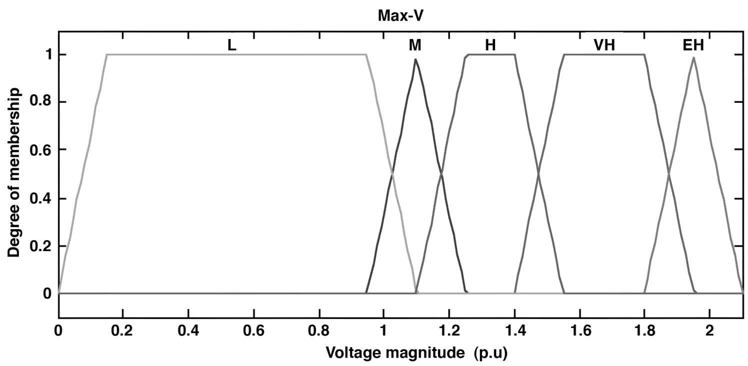


Figure 4 Maximum voltage input membership function

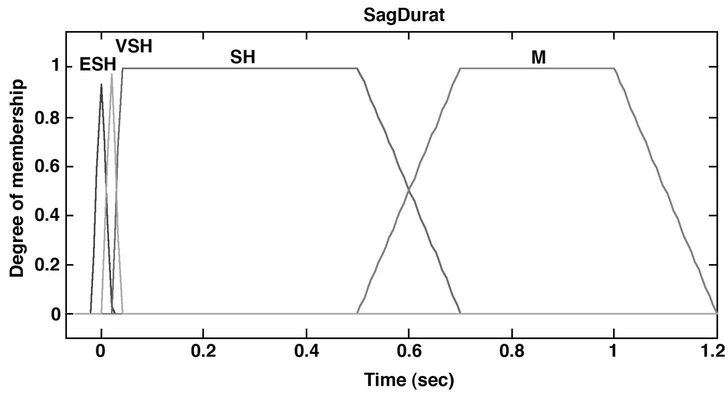


Figure 5 Sag duration input membership function

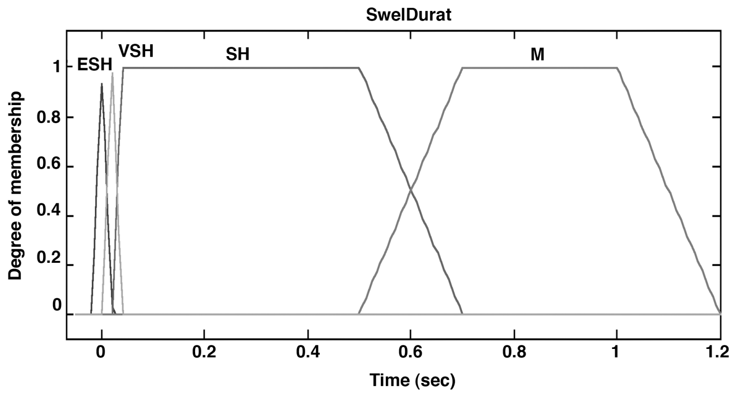


Figure 6 Swell duration input membership functions

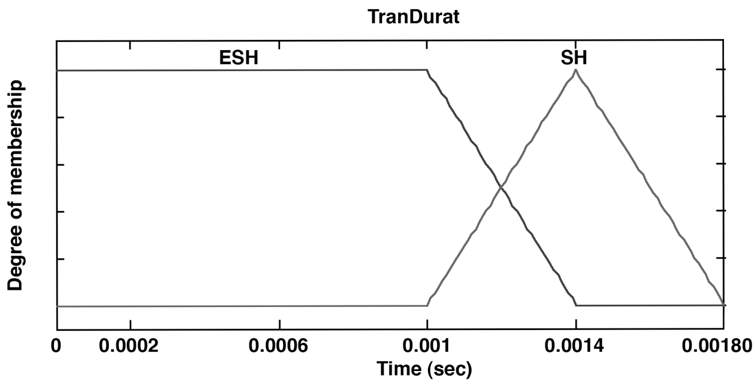


Figure 7 Transient duration input membership functions

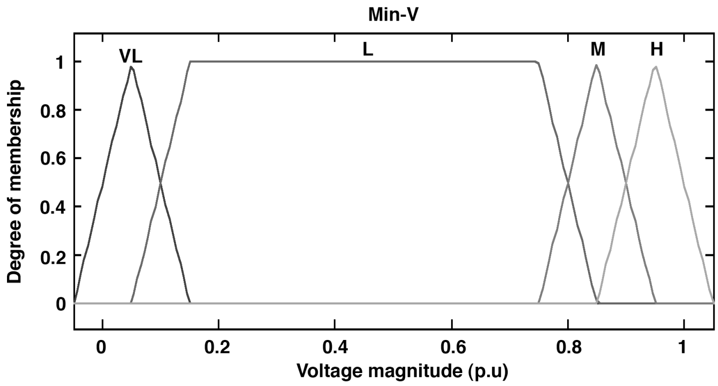


Figure 8 Absolute minimum voltage input membership function

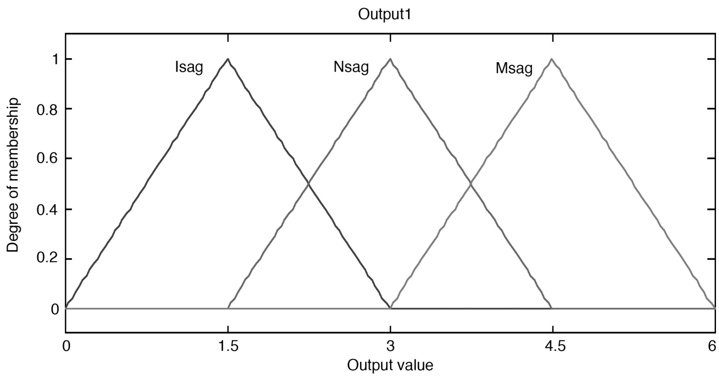


Figure 9 Output1 membership function

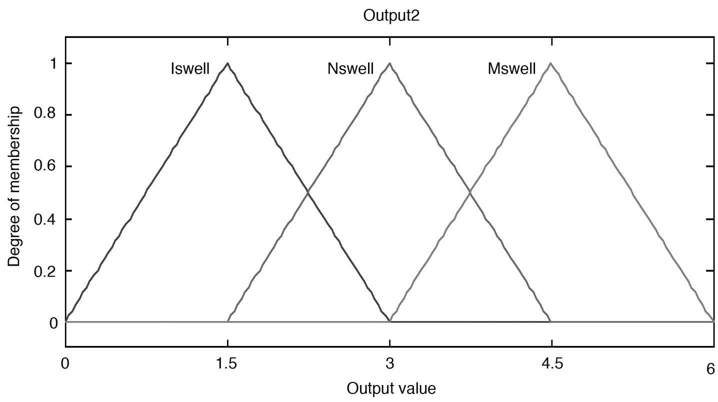


Figure 10 Output2 membership function

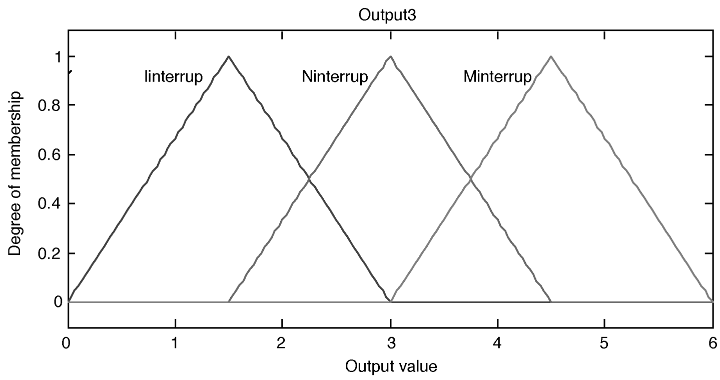


Figure 11 Output3 membership function

3.4 Generation of Rules

Based on the nineteen fuzzy sets defined for the five input variables and nine fuzzy sets defined for the three output variables, 139 If-Then rules have been generated for classifying sag, swell and interruption disturbances. The fuzzy If-Then rules are generated from the rule editor window of the Matlab fuzzy logic toolbox as shown in Figure 12. The fuzzy operators and defuzzification method selected for this application is as shown in Table 4.

Examples of the generated rules for identifying sag, swell and interruption and classifying them to instantaneous, momentary and non sag, swell and interruption are given as follows:

(1) If (Max-V is L) and (SagDurat is SH) and (SwelDurat is ESH) and (TranDurat is ESH) and (Min-V is L) then (Output1 is Isag)(Output2 is Nswell)(Output3 is Ninterrup).

(2) If (Max-V is M) and (SagDurat is SH) and (SwelDurat is ESH) and (TranDurat is ESH) and (Min-V is VL) then (Output1 is Nsag)(Output2 is Nswell)(Output3 is Iinterrup).

(3) If (Max-V is VH) and (SagDurat is M) and (SwelDurat is SH) and (TranDurat is SH) and (Min-V is M) then (Output1 is Msag)(Output2 is Iswell)(Output3 is Ninterrup).

(4) If (Max-V is L) and (SagDurat is ESH) and (SwelDurat is ESH) and (TranDurat is ESH) and (Min-V is VL) then (Output1 is Nsag)(Output2 is Nswell)(Output3 is Ninterrup).

(5) If (Max-V is H) and (SagDurat is SH) and (SwelDurat is SH) and (TranDurat is SH) and (Min-V is VL) then (Output1 is Nsag)(Output2 is Iswell)(Output3 is Iinterrup).

Table 2 Fuzzy sets defined for the input variables

Membership function	Input 1: Maximum voltage (p.u)	Input 2: Sag duration (sec)	Input 3: Swell duration (sec)	Input 4: Transient duration (sec)	Input 5: Absolute minimum voltage (p.u)
1	L Low	ESH Extremely short	ESH Extremely short	ESH Extremely short	VL Very low
2	M Medium	VSH Very short	VSH Very short	SH Short	L Low
3	H High	SH Short	SH	Short	M Medium
4	VH Very high	M Medium	M Medium		H High
5	EH Extremely high				

Table 3 Fuzzy sets defined for the output variables

Membership function	Output 1	Output 2	Output 3
1	Isag Instantaneous sag	Iswell Instantaneous swell	Iinterrup Instantaneous interruption
2	Nsag Non sag	Nswell Non swell	Ninterrup Non interruption
3	Msag Momentary sag	Mswell Momentary swell	Minterrup Momentaryinterruption

Table 4 Fuzzy operators and defuzzification method

AND	Min
OR	Max
Implication	Min
Aggregation	Max
Defuzzification	Mom

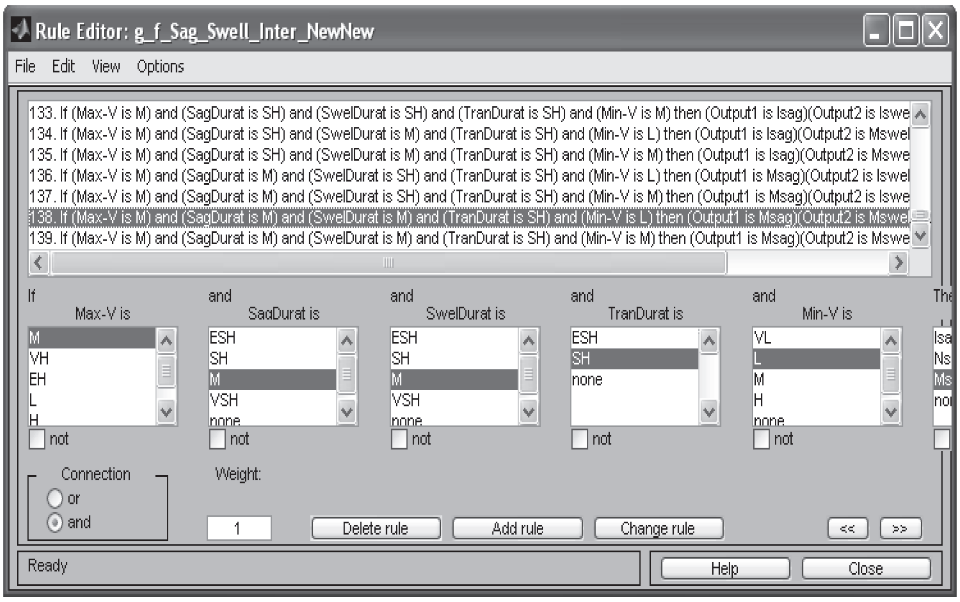


Figure 12 Generated rules in fuzzy rule editor window

4.0 RESULTS

The developed fuzzy-expert system has been verified with real PQ disturbances obtained from monitoring in which the number of different types of disturbances are shown in Table 5. For easy use of the fuzzy-expert system in classifying short duration voltage disturbances, a graphical user interface program (GUI) has been developed. The GUI window as shown in Figure 13 displays the identified disturbance in terms of the type of disturbance, characteristics of the disturbance and graphical plot of the actual and rms voltage waveforms.

The fuzzy-expert system has classified correctly 999 disturbances from the total number of 1015 tested disturbances, thus giving a classification accuracy of 98.42 %. In order to analyze the effectiveness and accuracy of the proposed

Table 5 The number of different types of disturbances for testing the fuzzy-expert system

Type of Disturbances	Sag	Swell	Inter-ruption	Transient	Voltage notching	Multiple disturbances waveform	Pure sinusoidal waveform (non-disturbances)
No. of Disturbances	544	88	2	183	177	16	5

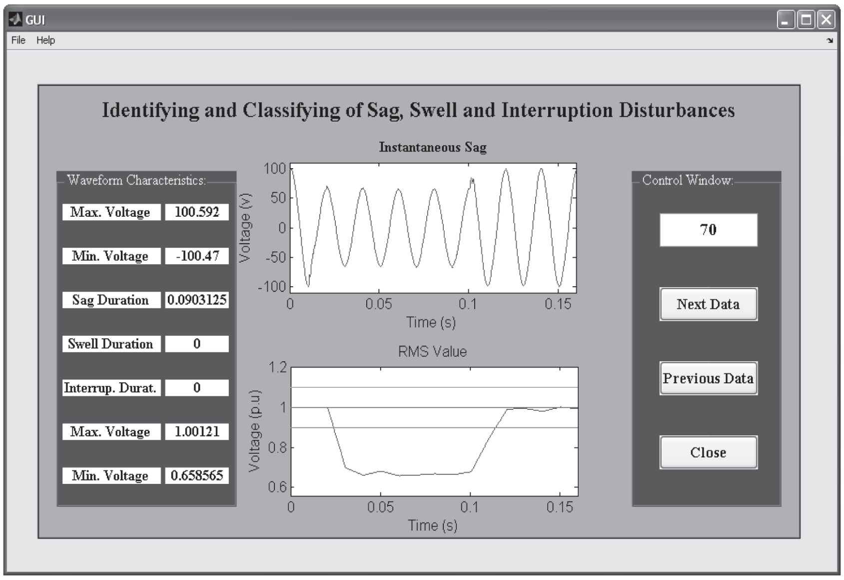


Figure 13 GUI window for classifying short duration voltage disturbances

Table 6 Examples of the fuzzy-expert system testing results

Case	Input1: Max-V (p.u)	Input2: SagDurat (sec)	Input3: SwelDurat (sec)	Input4: TranDurat (sec)	Input5: Min-V (p.u)	Output 1	Output 2	Output 3	Fuzzy output	Expected output
1	1.013	0.895	0	0	0.8114	4.5	3	3	Momentary sag	Momentary sag
2	1.3145	0	0.0139	0.0003	1	3	3	3	Non sag, non swell & non interruption	Oscillatory transient
3	1.0054	0	0	0	0.9024	3	3	3	Non sag, non swell & non interruption	Non-disturbance
4	1.0832	1.535	0	0	0.0239	3	3	4.5	Momentary interruption	Momentary interruption
5	1.298	0	0.205	0.0525	0.9581	3	1.5	3	Instantaneous swell	Instantaneous swell
6	1.3316	0	0.0142	0.0003	0.9993	3	3	3	Non sag, non swell & non interruption	Oscillatory transient
7	1.1717	0	0.0464	0.0019	1	3	1.5	3	Instantaneous swell	Repetition oscillatory transient
8	1.0108	0.0125	0	0	0.8978	1.5	3	3	Instantaneous sag	Instantaneous sag
9	1.461	0.0025	1.615	0.5375	0.8976	3	4.5	3	Momentary swell	Momentary swell
10	1.2411	0.9125	1.005	0.2375	0.8242	4.5	4.5	3	Momentary sag & swell	Momentary sag & swell
11	1.6904	0	1.5675	0.75	0.959	3	3	3	Non sag, non swell & non interruption	High voltage
12	1.0195	1.6975	0	0	0.022	3	3	4.5	Momentary interruption	Momentary interruption

cont.

Table 6 (continued)

Case	Input1: Max-V (p.u)	Input2: SagDurat (sec)	Input3: SwelDurat (sec)	Input4: TranDurat (sec)	Input5: Min-V (p.u)	Output 1	Output 2	Output 3	Fuzzy output	Expected output
13	1.3045	0	0.0737	0.025	0.9722	3	1.5	3	Instantaneous swel	Instantaneous swell
14	1	0	0	0	0.989	3	3	3	Non sag, non swell & non interruption	Impulsive transient
15	1.51	0	0.0334	0.0073	0.9602	3	1.5	3	Instantaneous swell	Instantaneous swell
16	1.0011	0.3088	0	0	0.4797	1.5	3	3	Instantaneous sag	Instantaneous sag
17	1.1352	0	0.0063	0.0019	0.9633	3	3	3	Non sag, non swell & non interruption	Repetition voltage notching
18	1	0.1411	0	0	0.6737	1.5	3	3	Instantaneous sag	Instantaneous sag
19	1.3465	0	0.0172	0.005	0.9049	3	1.5	3	Instantaneous swel	Instantaneous swel
20	1.5325	0	0.075	0.0255	0.9675	3	1.5	3	Instantaneous swell	Instantaneous swell
21	1.0689	0	0	0	0.954	3	3	3	Non sag, non swell & non interruption	Non-disturbance
22	1.2887	0	0.1366	0.0386	1	3	1.5	3	Instantaneous swell	Instantaneous swell
23	1.0165	0.63	0	0	0.7877	4.5	3	3	Momentary sag sag	Multi instantaneous
24	1.0015	0.1681	0	0	0.8923	1.5	3	3	Instantaneous sag	Instantaneous sag
25	1.1222	0.09	0.0075	0.005	0.4963	1.5	3	3	Instantaneous sag	Instantaneous sag
26	1.204	0.0197	0.007	0.0011	0.6834	1.5	3	3	Instantaneous sag	Instantaneous sag
27	1.0409	1.4	0	0	0.5674	4.5	3	3	Momentary sag	Momentary sag
28	1.4568	0	0.1606	0.0631	0.9774	3	1.5	3	Instantaneous swell	Instantaneous swell
29	1.1593	0.0144	0.05	0.0056	0.8549	3	1.5	3	Instantaneous swell	Instantaneous swell
30	1.2757	0.26	0.0938	0.0244	0.8826	1.5	1.5	3	Instantaneous sag & Swell	Instantaneous sag & Swell

method in classifying PQ disturbances, a comparison in terms of percentage of classification accuracy is made with the fuzzy-expert system proposed by [11] which gives correct classification rate of 99 %. Based on the classification results, the performance of the proposed fuzzy-expert system is comparable to the method proposed by [11]. The proposed approach is computationally simple compared to the wavelet based fuzzy-expert system [11], because it uses a simpler and faster signal processing technique for the extraction of input features. In addition, real voltage disturbances obtained from monitoring have been used to validate the proposed fuzzy-expert system.

To illustrate the classification results of the proposed fuzzy-expert system, 30 case examples are presented as shown in Table 6. The results show that the fuzzy-expert system is able to classify not only single disturbance such as instantaneous or momentary sag, swell and interruption but can also classify multiple disturbances of different types as in cases 10 and 30. For disturbances not classified under sag, swell and interruption, the fuzzy-expert system gives an output of non-sag, non-swell and non-interruption disturbance such as that shown in cases 2, 3, 6 and 21. There are also some cases in which the system is not able to correctly classify the disturbances as in cases 7 and 23.

5.0 CONCLUSION

A fuzzy-expert system has been developed for detecting and classifying short duration voltage disturbances, namely, instantaneous, momentary and non sag, swell and interruption from the 8, 32 and 128 cycles waveforms. For the fuzzy inference system, one hundred and thirty nine fuzzy If-Then rules has been created based on five fuzzy inputs and three fuzzy outputs. Prior to the fuzzy implementation, a simple signal processing technique based on FFT and rms averaging technique have been used to derive the features of various disturbances. The proposed fuzzy-expert system has been tested with various types of real voltage disturbances so as to verify its accuracy in classifying sag, swell and interruption. The test results reveal that the proposed system has accurately identified and classified 98.42% of the tested voltage disturbances. For disturbances other than sag, swell and interruption, the developed fuzzy-expert system classifies such disturbances as non-sag, non-swell and non-interruption. The system is also capable of identifying multiple disturbances such as instantaneous sag and swell. Based on the testing results, the fuzzy-expert system can be considered to be accurate in classifying short duration voltage disturbances.

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