Classifying Short Duration Voltage Disturbances Using Fuzzy Expert System

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***Abstract*—In this paper, fuzzy logic is applied for identifying and classifying the short duration voltage variations of 8, 32 and 128 cycles waveforms. A program is written in Matlab to determine the parameters such as duration, maximum and minimum root mean square voltages of a disturbance by using the fast Fourier transform analysis. Based on these parameters, a fuzzy inference system has been developed with five fuzzy inputs, three fuzzy outputs and 139 fuzzy rules. The inputs are the maximum and minimum voltage magnitudes in per unit and disturbance duration in seconds. On the other hand, the outputs are namely output1, output2 and output3 in which output1 is for classifying instantaneous sag, non sag and momentary sag, output2 is for classifying instantaneous swell, non swell and momentary swell and output3 for classifying instantaneous interruption, non interruption and momentary interruption. The proposed fuzzy expert system has been tested with 1015 recorded voltage disturbances consisting of sags, swells, interruptions, transients, voltage notching and multiple disturbance waveforms. The results have proved that the developed fuzzy system has accurately identified and classified 98.42% of the tested voltage disturbances.**

Keywords*—Power quality, fuzzy expert system, sag, swell and interruption.

I. INTRODUCTION

Power quality (PQ) has become an issue of increasing interest since the late 1980s [1]. With the increased use of power electronic devices, customers have become more concerned on electric PQ. In power systems, faults, dynamic operations and nonlinear loads often cause various types of power quality disturbances such as voltage sag, voltage swell, switching transient, notches, flicker, harmonics, etc. [3, 11, 12]. Short duration variation in distribution systems is defined as a change in the root mean square (RMS) of voltage or current at the power frequency for duration from 0.5 cycles to 1 minute. These variations include power interruption, sag and swell [2-4]. It is also one of the most important PQ phenomena in present days due to their frequency of occurrence and the extent of the consequences caused to customers [2, 5, 6].

Proper diagnosing and classifying of PQ disturbances requires a high level of engineering expertise and powerful tools. The new and powerful tool of interest for PQ diagnosis is by using artificial intelligent (AI) techniques which has received extensive attention from researches in the area of electric power [13]. From the AI tools of interest in electric power community, fuzzy logic is a tool that has emerged in the mid sixties and has been used in the past decade for many applications especially in PQ diagnosis such as harmonic source detection [7], classification of transient disturbances [8] and the investigation on computer-based load sensitivity to voltage sag [14].

Fuzzy logic (FL) has rapidly become one of the most successful of today's technologies for developing sophisticated control systems [9]. It is a powerful variation of crisp logic based on the experience and knowledge of human operation. In more specific terms, what is central about fuzzy logic is that, unlike classical logical systems, it aims at modeling the imprecise modes of reasoning that play an essential role in the remarkable human ability to make rational decisions in an environment of uncertainty and imprecision. This ability depends, in turn, on human ability to infer an approximate answer to a question based on a store of knowledge that is inexact, incomplete, or not totally reliable [10]. 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, expressed in an interval of [0, 1], is a measure of proximity to this set. A membership value of 1 for a particular value "x_0" 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, that is, it does not belong to the set "A" at all. Any deviation is acceptable with an intermediate degree of satisfaction between 0 and 1. This is a special property that is very useful to model some real word uncertainties, which are linguistically expressed by experts [15]. The If-Then logic rules can be used to combine membership values for fuzzy variables, trying to mimic the human reasoning process. All the consequences for each defined rule are aggregated to give a result which is expected to be a real value, and is supposed to be the closest to the real knowledge being modeled [9]. Fuzzy logic has been successfully implemented in control applications where system models do not exist, or where the models are too complex mathematically and computationally intense [1].

In this application a fuzzy expert system has been developed to classify short duration voltage disturbances. For this purpose, the FL expert system is designed with five inputs, three outputs and 139 rules. The FL logic inputs consider the maximum and minimum voltage magnitudes in per unit and the disturbance duration in seconds. The fuzzy outputs are named as Output1, Output2 and Output3 in which Output1 gives an output which classifies avoltage sag to three categories, namely, instantaneous sag, momentary sag and non-sag. The Output2 gives an output which classifies a voltage swell to instantaneous swell, momentary swell and non-swell. Finally, the Output3 gives an output which classifies a voltage interruption to instantaneous, momentary and non-interruption categories.

II. METHODOLOGY

The main purpose of the study is to identify sag, swell and interruption disturbances and to classify them to instantaneous or momentary categories as shown in the flowchart of the system of Fig. 1. The sag, swell and interruption disturbances were identified by also considering and analyzing other disturbances such as transient, voltage notching, multiple disturbances and pure sinusoidal waveforms. The disturbance data were obtained from real-time power quality monitoring in distribution systems by using the remote power monitors. The data downloaded from the PQ monitoring software by default has three different sampling frequencies captured per frame that are at 0.4kHz (128 cycle), 1.6kHz (32 cycle) and 6.4kHz (8 cycle) in which each frame has 1024 samples.

From the flowchart of the fuzzy expert system shown in Fig. 1, initially, the fast Fourier transform is used to distinguish the 8, 32 and 128 cycle disturbances by evaluating the time duration of one cycle for each disturbance. The RMS voltage is obtained from actual disturbance voltage waveform by extracting the maximum and absolute of minimum sample voltages. A program is written in Matlab to determine the parameters such as time duration of disturbances, maximum and minimum RMS voltages of the disturbances which are then used as FL input data. Based on these parameters, the Mamdani-type fuzzy inference system with five fuzzy inputs and three outputs has been considered for the fuzzy expert system. The FL inputs include maximum voltage (Max-V), sag duration (SagDurat), swell duration (SwelDurat), transient duration (TranDurat) and minimum voltage (Min-V) which are shown in Figures 2 till 6, respectively.

The fuzzy outputs which include Output1, Output2 and Output3 are shown in Figures 7 till 9, respectively. Output1 classifies voltage sag into three categories such as instantaneous sag, non sag and momentary sag.

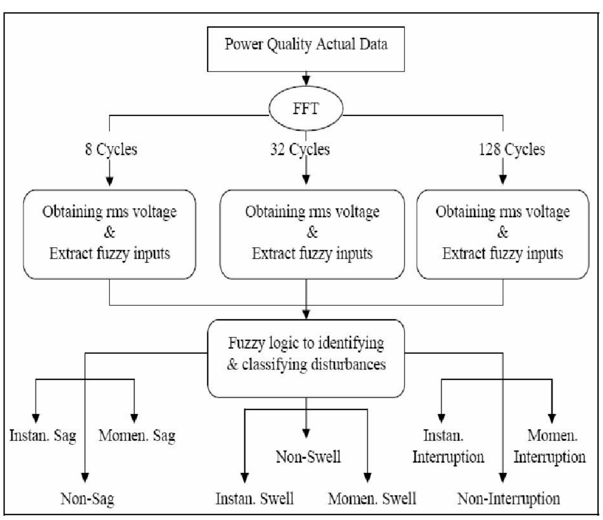

Fig. 1: Flowchart of the Fuzzy Expert System

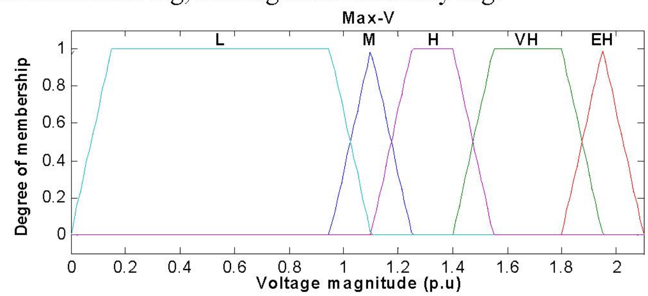

Fig. 2: Max-V Input Membership Functions

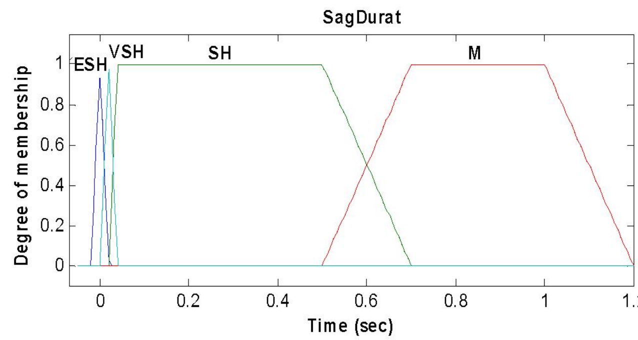

Fig. 3: SagDurat Input Membership Functions

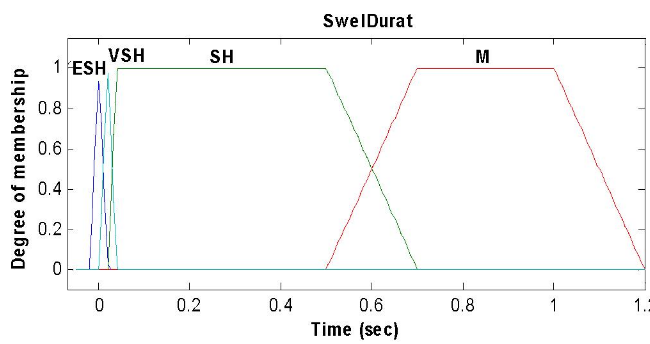

Fig. 4: SwelDurat Input Membership Functions

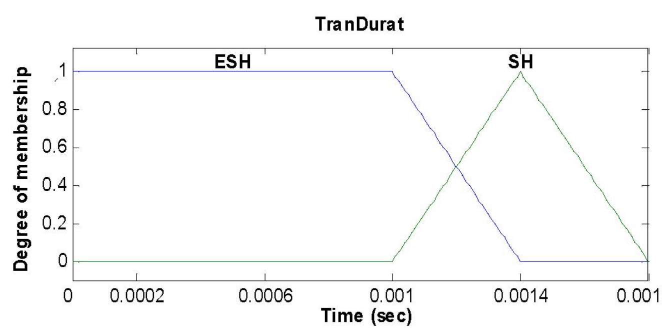

Fig. 5: TranDurat Input Membership Functions

Output2 classifies a voltage swell into three categories, namely, instantaneous swell, non swell and momentary swell and finally, Output3 classifies an interruption into instantaneous interruption, non interruption and momentary interruption. Table 1 shows the linguistic variables of membership functions used in the FL inputs and outputs.

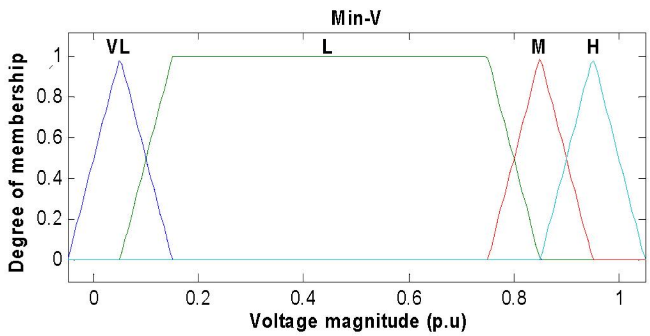

Fig. 6: Min-V Input Membership Functions

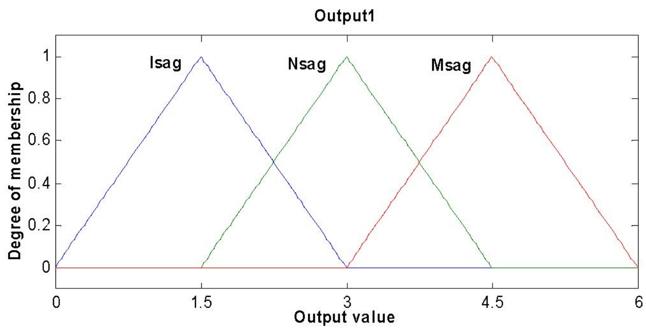

Fig. 7: Output1 Membership Functions

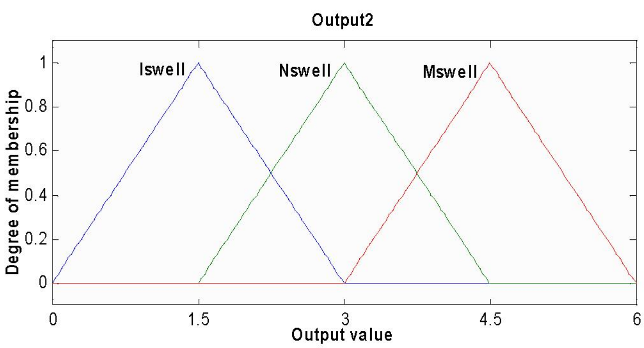

Fig. 8: Output2 Membership Functions

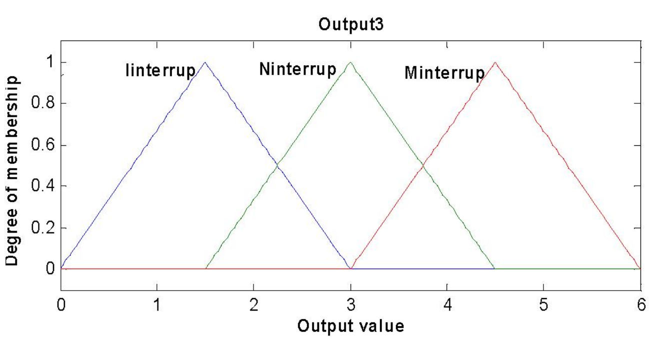

Fig. 9: Output3 Membership Functions

TABLE 1:
MEMBERSHIP FUNCTIONS AND LINGUISTIC VARIABLES OF THE FUZZY LOGIC INPUTS AND OUTPUTS

Fuzzy inputs and outputs		Membership functions and linguistic variables				
Fuzzy inputs	Max-V	Low (L)	Medium (M)	High (H)	Very high (VH)	Exactly high (EH)
	SagDurat	Exactly short (ESH)	Very short (VSH)	Short (SH)	Medium (M)	
	SwelDurat	Exactly short (ESH)	Very short (VSH)	Short (SH)	Medium (M)	
	TranDurat	Exactly short (ESH)	Short (SH)			
	Min-V	Very low (VL)	Low (L)	Medium (M)	High (H)	

Fuzzy outputs	Output1	Instantaneous sag (Isag)	Non-sag (Nsag)	Momentary sag (Msag)
	Output2	Instantaneous swell (Iswell)	Non-swell (Nswell)	Momentary swell (Mswell)
	Output3	Instantaneous interruption (Iinterrup)	Non-interruption (Ninterrup)	Momentary interruption (Minterrup)

From the fuzzy inputs, outputs and their membership functions, 139 fuzzy If-Then rules are generated for identifying and classifying sag, swell and interruption disturbances by using the Matlab fuzzy logic toolbox. The fuzzy operators and defuzzification method considered for the FL are shown in Table 2. Examples of the generated rules for the fuzzy expert system are shown as follows:

i) 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).
ii) If (Max-V is L) and (SagDurat is M) and (SwelDurat is ESH) and (TranDurat is ESH) and (Min-V is L) then (Output1 is Msag)(Output2 is Nswell)(Output3 is Ninterrup).
iii) 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).
iv) 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 OPERATORS AND DEFUZZIFICATION METHOD.

AND	Min
OR	Max
Implication	Min
Aggregation	Max
Defuzzification	Mom

III. RESULTS

The proposed fuzzy expert system has been tested with 1015 different voltage disturbance waveforms consisting of sags (544), swells (88), interruptions (2), transients (183), voltage notching (177), multiple disturbance waveforms (16) and pure sinusoidal waveform or non-disturbances (5). Table 3 shows the results of only 14 cases of PQ disturbances tested with the fuzzy expert system in which column one shows the 14 cases, columns two till six show the FL inputs, columns seven till nine represent the FL outputs, column ten represents the FL output translated in terms of the type of disturbance identified and the last column shows the actual type of disturbance.

Based on the results of testing the fuzzy expert system, the capabilities of the system has been noted as follows:

i) It can correctly identify single and multiple sag, swell or interruption disturbances.
ii) It is able to classify sag, swell and interruption disturbances into instantaneous or momentary categories such as that shown in test cases 1, 4, 5, 8 and 9 of Table 3.
iii) It can classify correctly multiple sags, swells or interruptions to instantaneous category correctly, if the total duration of disturbances is less than 0.6 seconds. This duration is the boundary used to categories between instantaneous and momentary disturbances. Fig. 10 shows an example of this kind disturbance.
iv) It can correctly classify multiple sags, swells or interruptions to momentary category correctly, if each disturbance has a duration longer than 0.6 seconds. Fig. 11 shows an example of this kind disturbance.
v) It is able to correctly identify and classify multiple disturbances which are combinations of momentary sag and swell or instantaneous sag and swell as in test cases 10 and 14 of Table 3.
vi) It identifies disturbances as non-sag, non-swell and non-interruption for disturbances other than short duration voltage variations such as that shown for test cases 2, 3, 6, 11 and 12 of Table 3.

The results have proved that the developed fuzzy expert system has accurately identified and classified 98.42% of the tested voltage disturbances. However, there are some cases in which the system is not able to identify or classify them correctly, such as cases 7 and 13 in Table 3 respectively.

In general, based on the testing results, the fuzzy system is considered accurate in identifying and classifying short duration voltage variations. An appropriate graphic user interface program has also been developed to allow users to easily use the FL system for classifying sag, swell, and interruption disturbances.

TABLE 3
TEST RESULTS OF THE FUZZY EXPERT SYSTEM.

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	Actual 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	Repetitive 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	1.0689	0	0	0	0.954	3	3	3	Non sag, non swell & non interruption	Non-disturbance
13	1.0165	0.63	0	0	0.7877	4.5	3	3	Momentary sag	Multi instantaneous sag
14	1.2757	0.26	0.0938	0.0244	0.8826	1.5	1.5	3	Instantaneous sag & Swell	Instantaneous sag & Swell

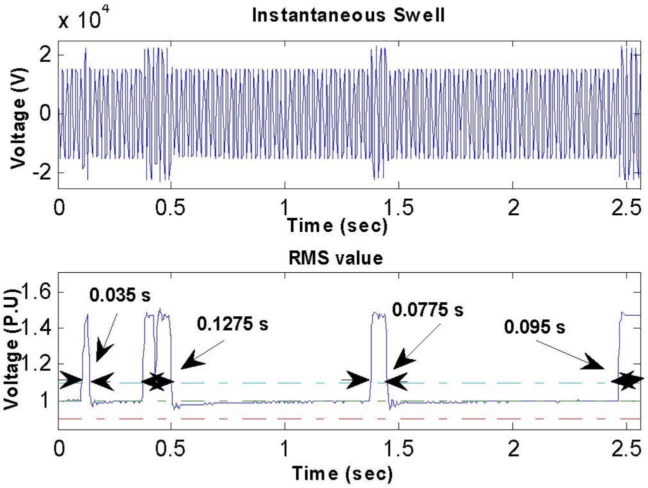

Fig. 10: Classification of Multiple Instantaneous Swells With a Total Duration of Less than 0.6 Seconds

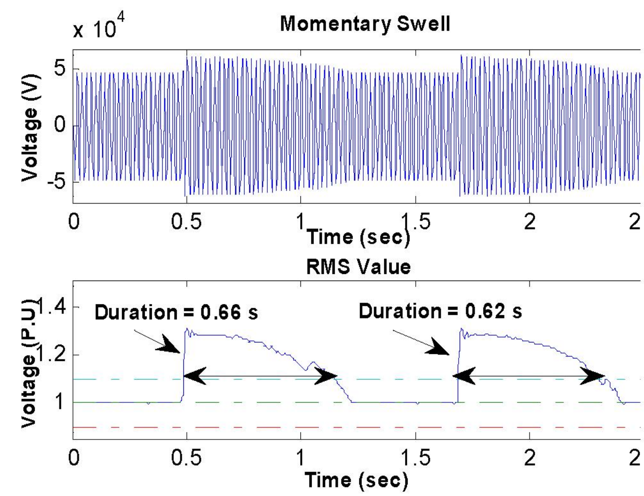

Fig. 11: Classification of Multi Momentary Swells With a Duration Greater than 0.6 Seconds

IV. 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.

V. REFERENCES

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