FPGA BASED RECOGNITION AND CATEGORIZATION OF POWER QUALITY DISTURBANCES WITH FUZZY CLASSIFIER

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Abstract: **Analysis of power system disturbances in non-stationary nature can be done using Discrete Wavelet Transform (DWT) which gives both time and frequency information. The detection and classification of power quality (PQ) events requires a suitable tool for implementing DWT algorithm with reconfigurable and shorter design cycle for hardware realization. In this paper, the primary work focus on the desired features of distorted power signal generated in MATLAB environment are extracted by evaluating DWT coefficients. These coefficients can be obtained by implementing the DWT algorithm on reconfigurable FPGA Spartan 3E kit experimentally. In the next stage, Fuzzy logic technique is used for classification of Power Quality (PQ) events that occur in system disturbances by framing rule base table. From the results the approach of using FPGA based hardware realization of wavelet transform is tested in classification of three types of PQ events.**

Key words **- Discrete Wavelet Transforms, Field Programmable Gate Array, Fuzzy logic system, multiresolution analysis, Power Quality**

I. INTRODUCTION

The operation of nonlinear loads in industry which makes use of power electronic elements causes dynamic voltage distortions and pollutes the electric power. Poor quality of electric power normally causes several power-line disturbances such as voltage sag, swell, momentary interruptions, harmonic distortion and flicker, resulting in failure of end-user equipment [1]. The quality of electric power can be improved by knowing the sources and causes of such disturbances prior to mitigate them. A possible approach to achieve this is to incorporate detection capabilities into monitoring equipment so that events of interest will be recognized, captured and classified automatically. The fundamental block diagram of automatic power quality classifier [2], [3] is as shown in Fig. 1.

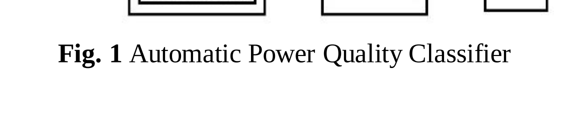

Fig. 1 Automatic Power Quality Classifier

It mainly consists of three blocks viz., pre-processing, processing and post-processing blocks. The distorted waveform is given as input to pre-processing block. This block contains segmentation and feature extraction. Segmentation means data is separated in to more number of transition segments which corresponds to sudden change in signal and event segments. The segments which appeared between transition segments are termed as events. Extraction of suitable information from raw signal is known as feature extraction [4]. The choice of appropriate features plays vital role for classification of PQ problems. The proper selection of features decreases the burden on the classifiers [5]. In this paper, the features are extracted by using signal processing techniques and it is given as input to the PQ classification system.

Various DSP techniques are used to extract desired features from the signals. Among them, primarily Fast Fourier Transform (FFT) is used for extracting the frequency component but it fails to provide the appearance time of the particular frequency component. Secondly, Short Time Fourier Transform (STFT) [6] slightly relieve from this problem but it is not the sufficient tool for the analysis of non-stationary signals due to the drawback of fixed window length. In other words, one should compromise between the time resolution and frequency resolution before perceiving a particular feature of a signal. The fixed resolution problem of STFT can be resolved by using Wavelet transform approach [7]. This approach develops a window which can adjust its length to provide both time and frequency resolutions. In this approach, good time resolution is provided for high frequency components of a signal and good frequency resolution is provided for high frequency components. The Fig. 2 compares STFT and Wavelet. In this figure, Wavelet contains so many windows with variable widths and heights, each window represents a portion of time – frequency plane with different proportions of time and frequency. As the frequency increases, the window becomes narrow and the window becomes wider when the frequency decreases. So, Narrow window is used for good time resolution and poor frequency resolution; in similar way, Wide window is used for good frequency resolution and poor time resolution. Hence the features obtained from the wavelet transforms are well suited for power Quality analysis.

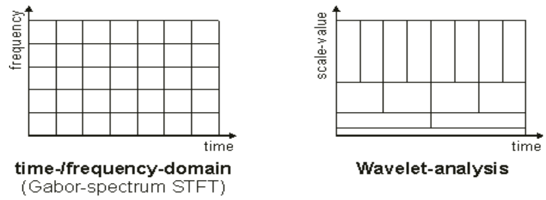

Fig. 2 Comparison between STFT and Wavelet Transforms

II. METHODOLOGY

A. Feature extraction using Wavelet Transform

The signals encountered in the power system for power quality studies are of time-varying in nature. In other words, the signals have a relatively low frequency component throughout the entire signal and relatively high frequency component for a short duration where the fault occurs. In order to analyse those signals, Multi Resolution Analysis (MRA) is needed [8]. It analyses the signal at different frequencies with different resolutions. The resolution of the signal, which is a measure of the amount of detail information in the signal. MRA is designed to give good time resolution and poor frequency resolution at high frequencies and good frequency resolution and poor time resolution at low frequencies. This approach finds application when the signal has high frequency components for short durations and low frequency components for long durations. The wavelet transform has MRA property, so this makes the reason for selecting it to extract the desired information from the distorted signal.

The wavelet coefficients can be obtained in three different ways.

- Wavelet Series (WS) which maps a function of continuous variable into a sequence of coefficients.
- Continuous Wavelet Transform (CWT) maps a function of a continuous variable into a function of two continuous variables (scaling and translation factors).
- Discrete Wavelet Transform (DWT), which is used to decompose a discretised signal into different resolution levels. It maps a sequence of numbers into a different sequence of numbers.

Continuous Wavelet Transform (CWT) is defined as follows

$$CWT(\tau,s)=\Psi(\tau,s)=\frac{1}{\sqrt{|s|}}\int x(t)\psi^*\left(\frac{t-\tau}{s}\right)dt \qquad (I)$$

From the above equation, the transformed signal is a function of two variables i.e., translation parameter (τ) and scale parameter (s). The translation parameter indicates the window location. The scale parameter refers to the reciprocal of frequency. Here high scale corresponds to low frequency which gives global information and low scale corresponds to high frequency components which gives the detailed information of hidden part in the signal. The high frequency component exists only for short interval of time.

The wavelet series is a sampled version of CWT, it provides highly redundant information. This redundancy requires a significant amount of computation time and resources. On the other hand, Discrete Wavelet Transform (DWT) provides sufficient information both for analysis and synthesis.

CWT can be calculated by multiplying the signal with the change in window scale and shift in window time, and integrate over all times. In DWT, filters of different cut-off frequencies are used to analyze the signal at different scales. The signal is passed through a series of high pass filters to obtain high frequency component and a series of low pass filters to obtain low frequency component.

The resolution of the signal is changed by the filtering operations, and the scale is changed by subsampling (upsampling or downsampling) operations. DWT services scaling functions and wavelet functions which are related with low pass and high pass filters respectively. The time domain signal is decomposed into various frequency bands by passing through successive high pass and low pass filters. When the original signal x(n) is passed through a half band high pass filter g(n) and a low pass filter h(n) then the signal can be subsampled by 2. Thus the first level of decomposition can be completed and it is expressed mathematically as follows:

$$y_{high}(k)=\sum_n x(n)*g(2k-n) \qquad (II)$$

$$y_{low}(k)=\sum_n x(n)*h(2k-n) \qquad (III)$$

where $y_{high}(k)$ and $y_{low}(k)$ are the outputs of the high pass and low pass filters, respectively, after subsampling by 2. Thus the first level decomposition reduces time resolution by half and doubles the frequency resolution, since the frequency band of the signal now spans only half the previous frequency band, effectively reducing the uncertainty in the frequency by half. This phenomenon is known as subband coding [9], [10]. The same phenomenon can be repeated for further decomposition. The following Fig. 3 clearly demonstrates this phenomenon.

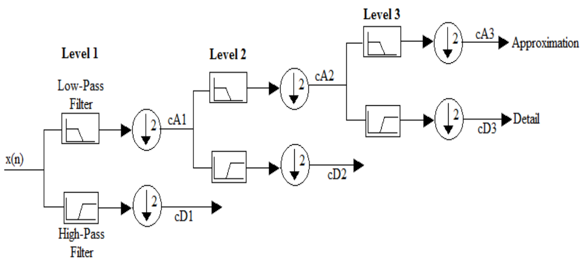

Fig. 3 subband coding in DWT

B. Field Programmable Gate Array

With the advent of VLSI technology, the design procedure of a prototype can be significantly reduced with the Application Specific Integrated Circuit (ASIC). It consists of interconnection of complex analog and digital circuits by make use of basic cells library. Among various ASICs, the field-programmable gate array (FPGA) is sufficient tool to increase the hardware realization [11]. FPGA originates with the assets of lower cost, higher density, and shorter design cycle, keeping in view of these advantages in computer-aided design, unlike the conventional PAL and PLA, FPGA consists of more number of building blocks, comprises of programmable look-up table and registers. The interconnections between the blocks can be programmed through any hardware descriptive language such as Verilog or VHDL.

FPGA consists of several logic elements which can be connected in any desired structure to implement an algorithm for a given specified application. The model can thus be created, tested and changed as necessary within a short time. FPGAs are estimated program driven devices based on the programming techniques, they can be classified into two types: antifuse based devices and static memory based devices. In antifuse based devices, FPGA can be programmed for only once. In static memory based devices, FPGA can be programmed and reprogrammed in any time [12]. In this paper, FPGA can be programmed in Verilog using Xilinx software.

Generally FPGA consists of three elements: Configurable Logic Blocks (CLB), input/output blocks (IOB), and programmable interconnects. It is illustrated in the shown Fig. 4.

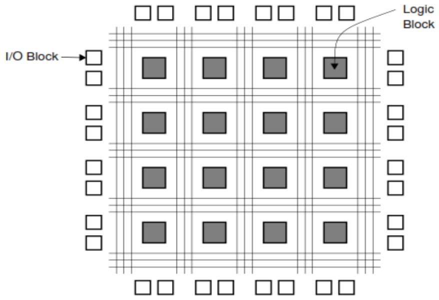

Fig. 4 Block diagram of FPGA

Each CLB contains the programmable combinational logic and sequential logic for the design requirements. The CLB can be used to implement both logic functions and latching data for the desired application. IOB offers to interface the external package pins with the internal logic and the programmable interconnects provide the routing paths for connecting the CLB and IOB into networks.

C. Fuzzy classification of Power Quality Events

Fuzzy logic system is a dominant classification tool for PQ events. This system has robust inference capabilities which makes computationally simple and fairly. The rules of this technique are framed on basis of human experience and expertise. The general block diagram of fuzzy logic system is shown in Fig. 5.

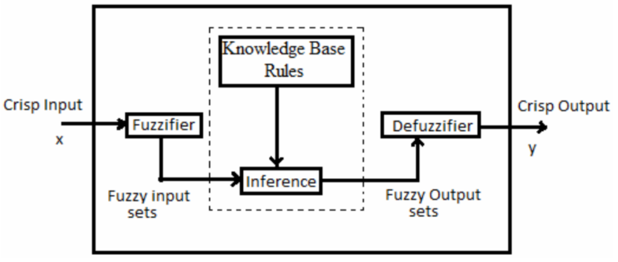

Fig. 5 Block diagram of Fuzzy logic system

The fuzzifier maps crisp values into fuzzy values and activate rules in terms of linguistic variables having fuzzy sets associated with them. Knowledge base consists a set of fuzzy rules with several if-then statements created by the experts. Based on the degree of input variable matches with fuzzy rules, the membership function of output variable is assigned. Finally, the defuzzifier maps fuzzy values into crisp values.

In the proposed method, fuzzy expert system [13], [14] is used for categorizing 6 types of power quality events. The captured distorted waveform has been passed through a DWT block to extract frequency and time information of waveform. The extracted features in discrete wavelet transform are used to frame the linguistic rules. The efficiency and accuracy of the system must be dependent on knowledge base rules framed by the human experts. If the system does not work properly, then the rules are changed so as to achieve desired results.

III. SYSTEM DEVELOPMENT AND IMPLEMENTATION

The power system models and algorithms for wavelet to detect power quality problem can be designed using high level languages like MATLAB/Simulink. With some limitations, those algorithms cannot be directly implemented on real hardware circuit. In this work, only the PQ events are generated in MATLAB/ Simulink event and the desired features of distorted voltage signal are extracted by evaluating approximation and detailed coefficients of DWT on hardware circuit. DWT algorithm is implemented on hardware circuit by developing Verilog code in Xilinx software. The Verilog code brings model based design approach into the domain of Field Programmable Grid Array (FPGA). The methodology is summarized in step-by-step procedure as follows:

Step 1: The simulation circuits and distorted voltage waveforms for creation of PQ events in MATLAB/Simulink environment are given in Fig. 6. The details of type, causes and duration of PQ event are tabulated in Table 1. The distorted voltage waveform is treated as the non-stationary signal and it is given as input to the Spartan 3E kit.

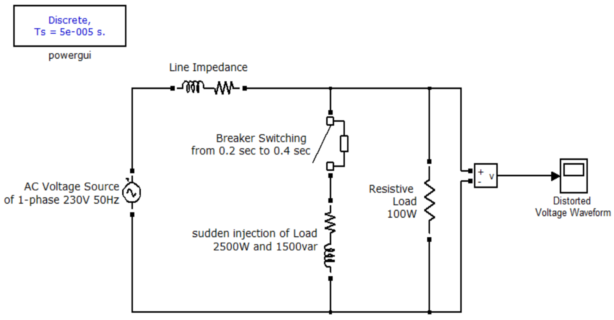

Fig. 6a Simulation circuit for generating PQ event type1

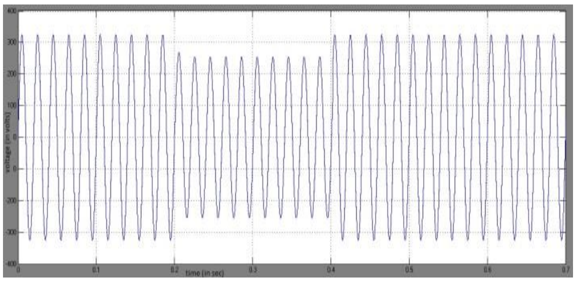

Fig. 6b distorted voltage waveform due to PQ event type1

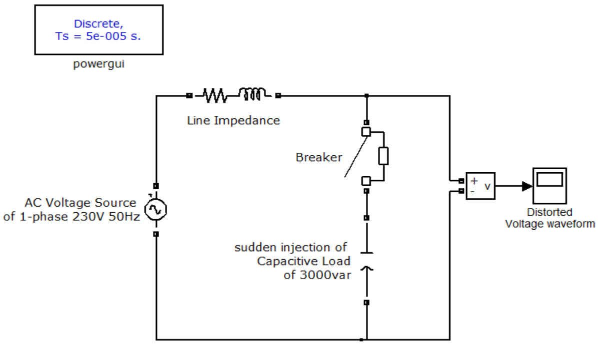

Fig. 6c Simulation circuit for generating PQ event type2

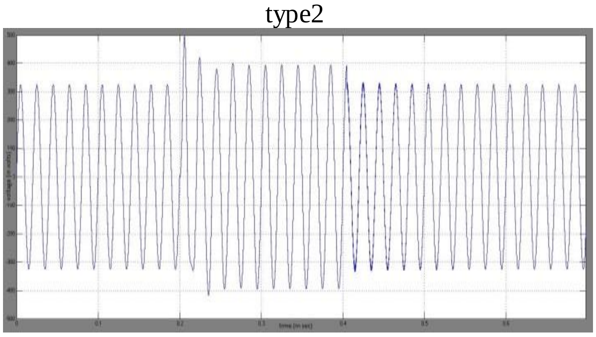

Fig. 6d distorted voltage waveform due to PQ event type2

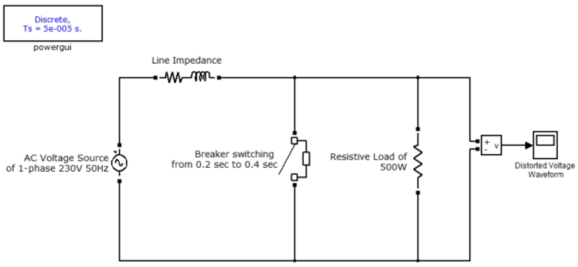

Fig. 6e Simulation circuit for generating PQ event type3

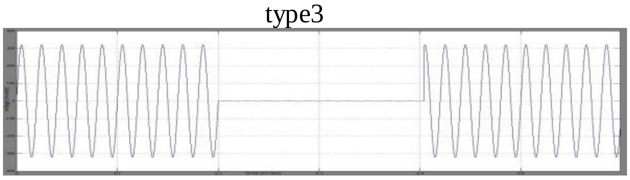

Fig. 6f distorted voltage waveform due to PQ event type3

Step 2: The pins on FPGA board which is used for this work is assigned by user constrained file. Synthesize the entire system using .v file and user constrained file, the bit file is developed which is to be implement on FPGA board.

Table 1: Typical parameters of the simulation

Type of event	Disturbance Caused due to	Voltage magnitude (in rms)
PQ event type1	Switching of inductive load in 0.2 sec duration	190 volts
PQ event type2	Switching of Capacitive Load in 0.2 sec duration	283 volts
PQ event type3	Short circuit in 0.2 sec duration	0 volts

Step 3: Verilog code developed in Xilinx environment as .v file to build the DWT module are illustrated in Annexure and the schematic view of the modules are shown in Fig. 7.

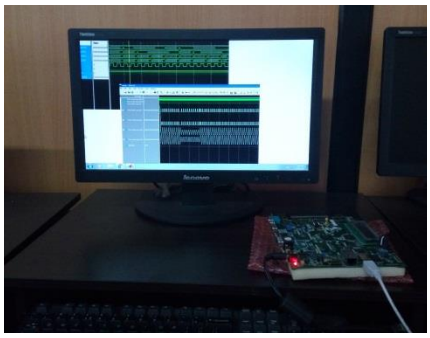

Fig. 7a FPGA kit connected to PC with MATLAB

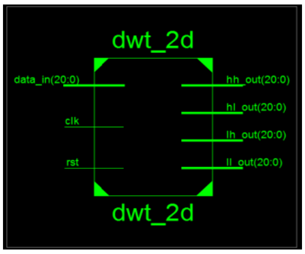

Fig. 7b DWT module view

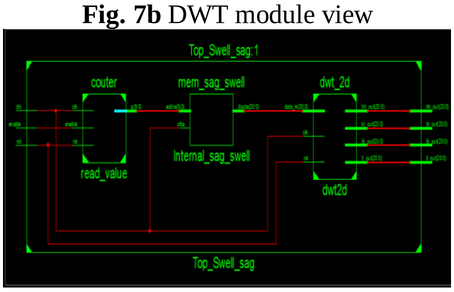

Fig. 7c Total module view

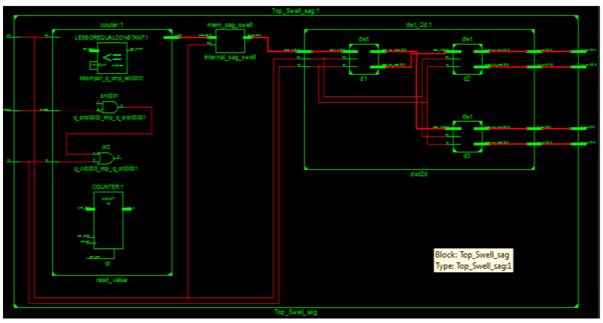

Fig. 7d Technology schematic view of total module

Step 4: In this stage, the DWT coefficients are calculated for the distorted voltage waveform created in step 1.

The approximation and detailed coefficients are used to analyse PQ event. The DWT module outputs LL and HL are approximation coefficients and the outputs LH and HH are detailed coefficients. The coefficients for three different PQ event types obtained on FPGA kit are shown in Fig. 8.

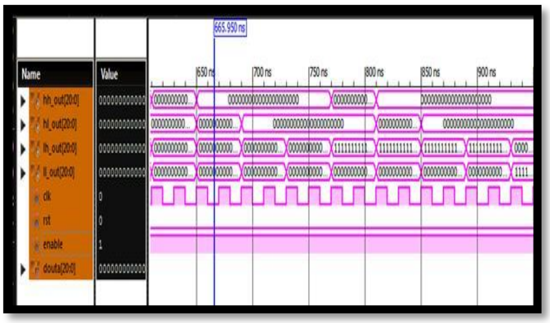

Fig. 8a timing chart of DWT module for PQ event type1

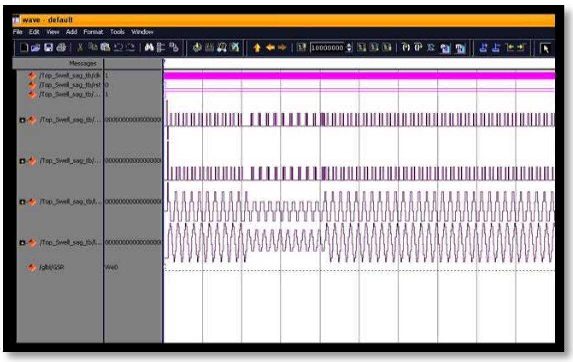

Fig. 8b timing chart of PQ event type1 using ModelSim software

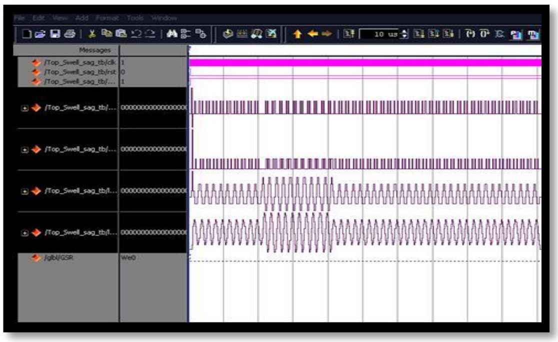

Fig. 8c PQ event type2 using ModelSim software

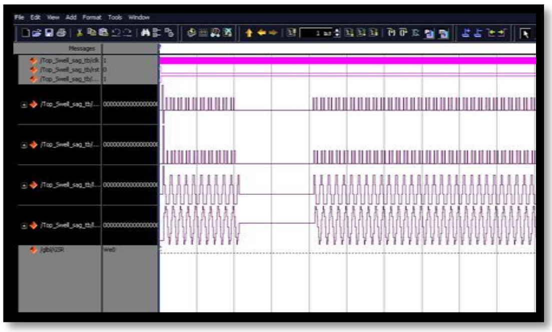

Fig. 8d PQ event type3 using ModelSim software

Step 5: The detailed coefficients calculated in step 4 and time duration of the particular event are given as inputs to the fuzzy classifier system for the classification of power quality events. Based on the magnitude of detailed coefficient and time duration, the fuzzy classifier system is developed and it is shown in Fig. 9.

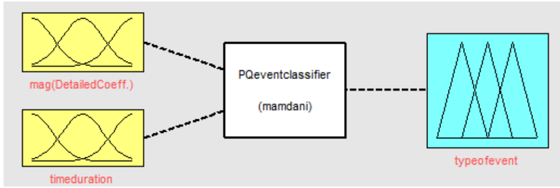

Fig. 9 Fuzzy system for PQ event classifier system

Step 6: The linguistic variables for

- magnitude of detailed coefficients are VERY LOW, LOW and HIGH.
- Time duration is SHORT and LONG.
- PQ event type is SAG, SWELL, MOMENTARY INTERRUPTIONS, UNDERVOLTAGE, OVERVOLTAGE and SUSTAINED INTERRUPTIONS.

All these linguistic variables are designed from IEEE standards [15]. The membership functions for voltage magnitude, time duration and PQ event type is shown in Fig. 10a, b & c respectively.

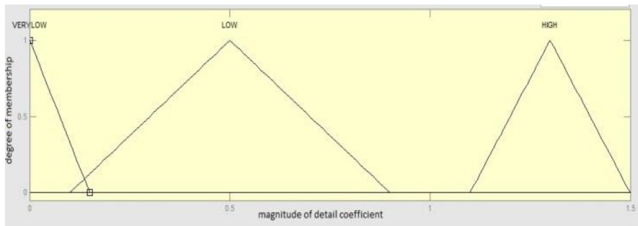

Fig. 10a Membership function for detailed coefficient magnitude

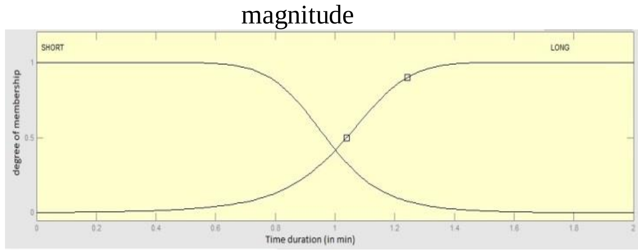

Fig. 10b Membership function for Time duration

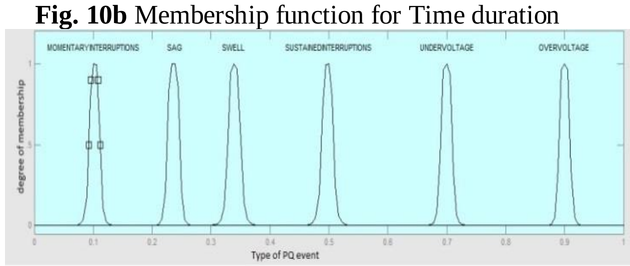

Fig. 10c Membership function for PQ event type

Step 7: Based on the voltage magnitude and time duration, the fuzzy classifier system is worked as per the rule base table mentioned in Table 2.

Table 2. Rule base table for fuzzy classifier system

		Time duration	
		SHORT	LONG
Magnitude of Detailed coefficients	LOW	Sag	Under voltage
	HIGH	Swell	Over voltage
	VERY LOW	Interruptions	Sustained interruptions

IV. CONCLUSION

Power quality events identification using DWT technique on FPGA kit and classification by using fuzzy classifier was successfully carried out in this paper. The simulation results show the proposed method is simple, flexible and accurate. Short duration faults were only studied. Long duration faults and verifying the results of the proposed method with the existing power quality analysing instruments will be reported in the near future.

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