POWER QUALITY ANALYSIS USING FUZZY LOGIC

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ABSTRACT

Over the last decade, power quality has become an imminent issue. Power quality is one of the major and significant factor to be considered by power system utilities while satisfying the needs of power distributor and customers. Therefore, it becomes extremely essential to analyze the influence quality system to discern the disturbances in power quality. A number of exploration studies regarding the power quality have been done earlier targeting the collection of information for an additional analysis. As a result, the repercussions of the varied disturbances in power systems may be investigated and analyzed. In our proposed work, we have developed a technique that inherently deals with the implementation of a hardware model of small demo transmission line. The range of transmitting voltage is between that of 25 to 50 V AC. The transmission line parameters are then measured using current transformers (CT) and potential transformers (PT) sensors. That values measured from CT and PT sensors are then transferred to the MATLAB simulink fuzzy logic controller where the power quality is further detected and analyzed.

After the detection and analysis, then all these types of power quality disturbance signals are further classified using Fuzzy Logic based Controller (FLC). The complete system is designed in MATLAB 2015R software atmosphere or using hardware model implementation whose analysis done in MATLAB 2015R software. In the end, we have compared the Fuzzy Logic based Controller (FLC) system with Artificial Neural Network (ANN) system for power quality analysis.

Keyword: - *ANN, Fuzzy logic, Power quality*

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1. INTRODUCTION

Power system is a complex interconnected network. It consists of three major categories namely generation, transmission and distribution. It is for a fact that in order to transfer the electricity produced by the generating units, an inter-connected complex transmission system is necessary.

Transmission lines are used to interconnect neighboring utilities. This is done by transferring power within the regions during normal conditions. Or in case of emergencies, the transmission lines can be used to transfer power between regions. Next is the distribution system where the substations feed the power to the consumer end through overhead or underground cables. The power system load can be categorized as industrial, commercial and residential depending upon the equipment used that may consist of a large number of lighting, heating and cooling equipments.

As a result, power quality becomes an important parameter for anyone who depends on power equipment and power systems. Hence, it won't be totally unwise to say that the perception of power quality characterization is entirely different for utilities, equipments manufacturers and customers. The power quality is treated on the basis of the system reliability in case of utilities. The proper working of equipment is the prime view of equipment manufacturers. For them, the power quality is considered as those characteristics of the power supply system that allows the inherently rely on the working the electrical equipment under normal conditions as well as abnormal conditions. In case of customers, they consider the quality of power which as a measure that ensures the continuous running of electricity.

As per the national standards, the electrical power provider should supply a pure sine wave that is coherent with the system specifications along with zero ohm impedance at all frequencies. All the electric power provider in India are supposed to provide a sine wave with 50Hz frequency at a designated voltage of 230V for residential customers or 440V three phase for many commercial or industrial customers. It is, therefore, very essential to provide a clean sinusoidal waveform to the customers. But the problem is that the one cannot easily quantify the power quality. One most widely used technique that measure power quality is by the ability to maintain the power at constant amplitude, in a smooth sinusoidal wave, and at a constant frequency at all times.

There are various kinds of power quality events that exist in distribution systems. A considerable research is done on power quality events and handling of power quality issues and a lot of research work has been done on this topic. The power quality events can occur at the supply network, or by the load itself. It is observed that the power quality events mostly depend on the voltage magnitude deviations in the form of voltage fluctuations. Voltage sags, flickers, interruptions and transient over voltage are some of the other voltage supply problems. As the users may face various different types of power quality events, it becomes necessary to analyze and investigate the types of power quality events. The effect of power quality events becomes also very crucial to understand.

In the recent electrical energy systems, it is observed that the supply has become more unstable with lesser sinusoidal and periodical waveforms. The large numbers of non-linear loads and generators have caused to alter the steady state behavior. All the processes and equipment are being affected. Some systems have worsen the waveform shape of the power system. These systems include inverters, power supplies for IT equipment, power electronic based systems, high efficiency lighting, drives, and adjustable speed drives.

Hence, for the characterization of the disturbances on common indices like voltage disturbances, wave form distortions, voltage unbalance and voltage fluctuation and flicker, the power quality analysis becomes necessary. These common indices are defined as mentioned below.

2. LITERATURE SURVEY

2.1 Power Quality Studies

Monitoring power quality disturbances is the preliminary step [1] – [4]. A compilation of the various power quality disturbances possible in power distribution scenario is provide in [3]. A survey of a number of distribution sites is done in [1]. It was concluded that the majority of the voltage sags have a magnitude of around 80%. Thetotal harmonic distortion is around 1.5 times the normal value. The voltage sags had a duration of around 4 to 10 cycles [1].

2.2 Detection Method

Wavelet transform is a powerful processing tool which can be used in a wide range of detection and analysis techniques including disturbance detection in PQ. Wavelets provides accurate frequency resolution and poor time localization at low frequencies. Whereas they provide frequency resolution and excellent time localization at high frequencies. Wavelets integrate to zero and this property illustrates the ability of the standard deviation of different resolution levels which can be used to represent the distribution of the distorted signals. The short duration variations within the power signals can be classified and quantified using this property. A number of researcher have explored this property of wavelets [5] – [9] to classify power quality disturbance.

The possibility of using CWT, Multi-resolution analysis and QT for the detection of the disturbances is explored where the analysis shows that the power transients in the signals and frequency transients can be detected [9]. The CWT and QT can compute the value of the signal. However, it can be observed that none of these methods can be individually or combined applied to detect all the kinds of disturbances.

A method of using CWT to detect and analyze voltage sags and transients was proposed wherein the parameters of the signals were measured and compared with the standard benchmark values [10]. The disturbances were described by the occurring inconsistencies. It was claimed that the algorithm enabled accurate measurement of voltage sags, the time localizations, and identification of transients. A number of AI based automated detection techniques followed this research.

S-transform, which is an extension of WT was proposed wherein it had many imposing time-frequency resolution characteristics [11]. CWT when multiplied by phase factor gives the S-transform as

$$s(\tau,\alpha) = e^{i2\Pi\tau\rho} * F(\tau,\alpha)$$

$$F(\tau,\alpha)=\int_{-\infty}^{+\infty}h(t)\,f(t-\tau,\alpha)dt$$

Where, F (Ʈ, α) is the mother wavelet.
The fixed modulating sinusoids with respect to the time axis defines the properties of the S-transform. However, the localizing scalable Gaussian window dilates and translates in S-Transform. A considerable research [12-16] is done on this method applying WT for power quality analysis.
A scope of research lies in this area wherein a better feature extraction tool can be searched. Many approaches combined FT with various WT functions [17].

2.3 Classification Method

Pattern recognition techniques (PRT) are used to classify of power disturbance signals. It is a process of recognizing a pattern of a given object based on the knowledge already possessed [18]. So automated PRT uses various AI techniques like FL, ANN and AFL for the classification of disturbance signals.
Recently techniques based on probabilistic models are also proposed. A brief survey of all such techniques is given in [19] pertinent to power quality research.
ANN [20] and FL [21] is the next approach in pattern recognition techniques. These intelligent systems are developed from the fact that human brain trains itself from past experiences and that the brain doesn't make decisions based on sharp decision boundaries. A number of approaches which combine both ANN and FL are proposed [22-26].
An approach of using a fuzzy system for the recognition and classification of PQ disturbances was proposed [27-28]. FL is used for the sorting the disturbance signals into different categories. In this method, a combination of FT and WT is used for the detection of signals. The classification results were then compared with the results obtained using ANN. It was found that the proposed method proves computationally efficient and accurate while PQ classification.
A method [29] used the combination of Fourier Linear Combiner (FLC) and a fuzzy system for the categorization of signals. The FLC computes the peak amplitude of the voltage signal and also computes the rate of change. The input to the fuzzy system are the values provided by FLC where then further classification the PQ disturbances takes place. However, the computational error efficiency is not provided in this paper to prove its merits over the existing methods.
The use of computationally simple PRT is proposed in [15] wherein the wavelet multi-resolution transform method is used for the feature extraction. For pattern recognition of signals, classifiers are used. Dynamic Time Wrapping (DTW)is another method derived from dynamic programming demonstrated in [30] wherein the test signal is compared with the stored templates. In this techniques, a measure of similarity is calculated depending on which a decision can be reached. However, DTW is computationally inefficient as it requires huge computational time.
HMM comprises of a fundamental double stochastic process that produces a sequence of observations [31]. Dempster-Shafer takes into consideration several pieces of evidences posturing on a hypothesis to evaluate the certainty of the proposed hypothesis. The research on this Dempster-Shafer theory is utilized in the methods found in [32], [33].

3. SIMULATION MODEL AND RESULTS

3.1 Fuzzy Logic Approach

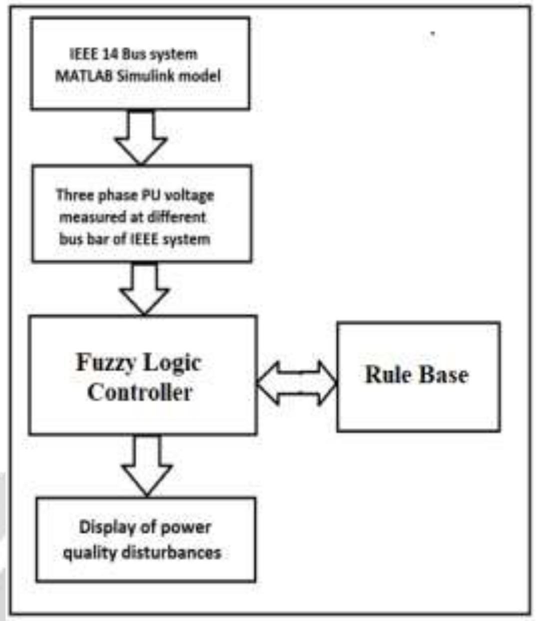


Fig-1: Flow block diagram of fuzzy logic controller (FLC) based power quality disturbance classification approach

Figure 1 flow shows the block diagram of proposed fuzzy logic (FLC) controller based power quality disturbance classification in which IEEE 14 bus power system design in matlab simulink using IEEE 14 bus power system data The three phase voltage measured at IEEE 14 bus power system on common bus bar 7 and sends that voltage to calibration of root mean square (RMS) measurement of voltage. That measured voltage is then sending to fuzzy logic controller for classification of power quality disturbances.
Figure 2 represents the fuzzy logic controller (FLC) design in matlab 2015R software using fuzzy toolbox in which there are three input voltages as input of controller and one output which shows the status of different power quality disturbances classes.

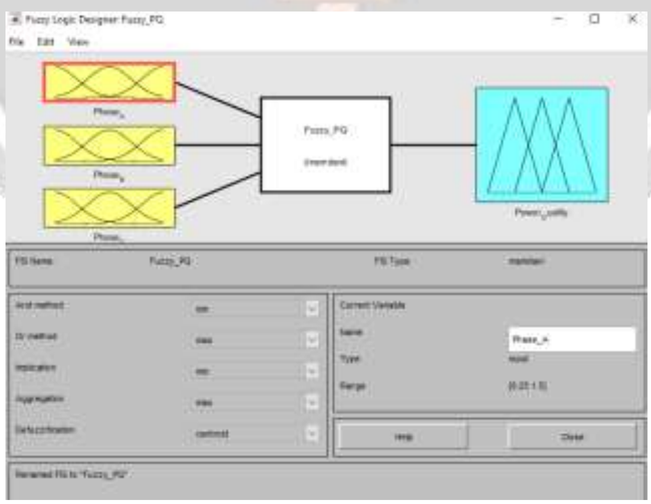


Fig-2: Fuzzy logic controller designer in MATLAB simulink

Figure 3 depicted the fuzzy logic controller inputs voltages membership functions for inputs voltages Va, Vb and Vc in per unit. For all three voltages, triangular membership function is design and details of membership functions shown in table 1

Table-1: Three phase voltage Va, Vb and Vc inputs membership functions details

Name of variable	Type of Membership Function	Range of membership function in Per Unit
Very Low (VL)	Triangular	0.25 to 0.3 to 0.33
Low (L)	Triangular	0.36 to 0.38 to 0.4
Medium (M)	Triangular	0.5 to 0.51 to 0.52
High (H)	Triangular	0.83 to 0.85 to 0.92
Very High (VH)	Triangular	1.2 to 1.4 to 1.5

Fig-3: Fuzzy membership function for input voltages Va, Vb and Vc RMS values

Table-2: Power quality classification output membership functions details

Name of variable	Type of Membership Function	Range of membership function
Sag	Triangular	0 to 0.5 to 1
Momentary Interruption	Triangular	1.1 to 1.5 to 2
Harmonics	Triangular	2.1 to 2.5 to 3
Normal	Triangular	3.1 to 3.5 to 4
Swell	Triangular	to 4.5 to 5

Table 3 represents the all fuzzy based rule base for fuzzy logic controller (FLC) which classify the all five types of power quality conditions. There are total 5 rule base which If then and based rule. Also for de-fuzzification process, the centroid de-fuzzification method is used.

Table-3: Fuzzy Rule base for power quality classification

Rules	Inputs			Output
	Va	***Vb***	***Vc***	
Rule-1	VL	VL	VL	Sag
Rule-2	L	L	L	Momentary Interruption
Rule-3	M	M	M	Harmonics
Rule-4	H	H	H	Normal
Rule-5	VH	VH	VH	Swell

Where, here full form are like VH= Very High, VL=Very Low, M= Medium, L= Low, H = High

Figure 4 depicted the fuzzy logic controller rule base editor designer in MATLAB software. In this there are total 5 rule base design which are "IF THEN AND" rule bases. Also figure 5 shows the same fuzzy rule bases with membership functions representation. Also in figure 5, there are feature of entering the fuzzy logic controller inputs and then getting corresponding fuzzy output decision.

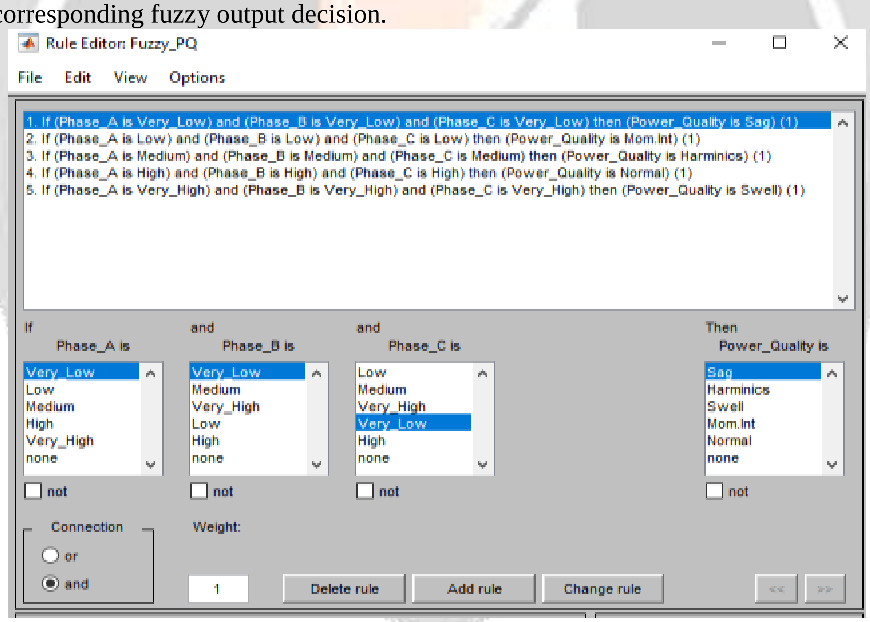


Fig-4: Fuzzy rule base editor for designing rule base in matlab simulink

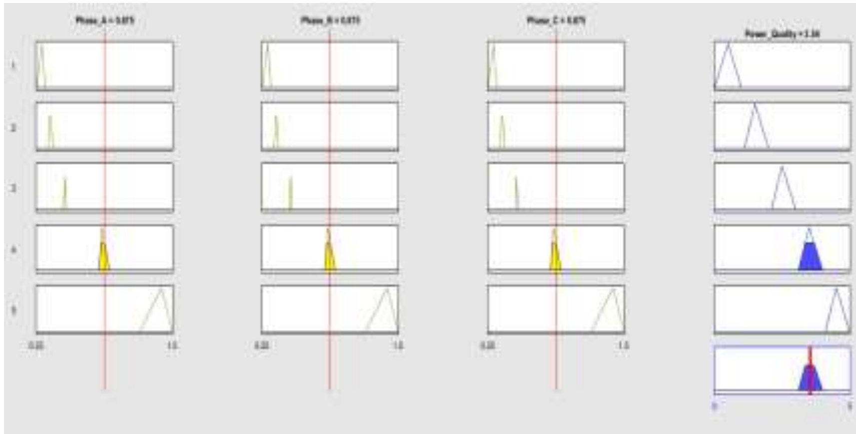


Fig-5: Membership functions for all rule base

Table-4: Result of fuzzy logic controller for power quality classification

Power quality condition	Bus number	Fuzzy output range	Actual Output
Normal	6	3.1 to 3.5 to 4	3.55
Normal	13	3.1 to 3.5 to 4	3.55
Sag	6	0 to 0.5 to 1	0.5
Sag	13	0 to 0.5 to 1	0.5
Swell	6	4.1 to 4.5 to 5	2.5
Swell	13	4.1 to 4.5 to 5	4.451
Harmonics	6	2.1 to 2.5 to 3	2.553
Harmonics	13	2.1 to 2.5 to 3	2.533
Mont. Intr	6	1.1 to 1.5 to 2	1.546
Mont. Intr	13	1.1 to 1.5 to 2	1.547

Table 4 depicted the all cases results of fuzzy logic controller (FLC) for power quality disturbance classification in which it is observed that, only one condition of power quality disturbance detection are fails o classify. During voltage swell condition measured at bus bar 6 is fails to classify by the fuzzy logic controller. Hence out of 10 condition 9 condition are classify by fuzzy controller while one condition of swell at bus 6 not classify. Hence, overall efficiency of fuzzy logic controller is 90% when RMS voltage measurement based fuzzy controller designed.

3.2 Artificial Neural Network Approach

Figure 6 debited the block diagram of proposed ANN approach in which IEEE 14 bus power system simulink model was design in MATLAB 2015R software environment using Sim Power system and ANN toolbox. Then after different power quality disturbances was simulated using circuit breaker, variable loads, harmonics generators etc. The per unit voltages was measured at different bus of IEEE 14 bus system and that measures per unit voltages is note down to excel sheet for generation of training data set for ANN training. That training data sets are utilized for training of back propagation based ANN (BP-ANN) for classification of different power quality disturbances events.

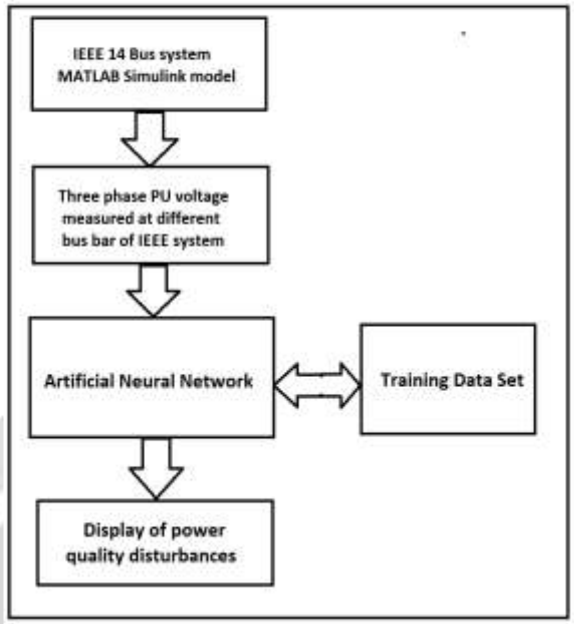


Fig-6: Block diagram of proposed methodology

Figure 6 depicted the complete MATLAB simulation model for power quality disturbance classification using RMS voltage measurement and artificial neural network approach. In this approach, the different voltage measured using RMS measurement subsystem and that measured voltage data are used for training data set generation. The rms voltages are measured for different power quality disturbance voltages are measured and send to the Back propagation training algorithm based Artificial Neural Network (BP-ANN). After successful training that ANN model will be connect after RMS voltage measurement subsystem.

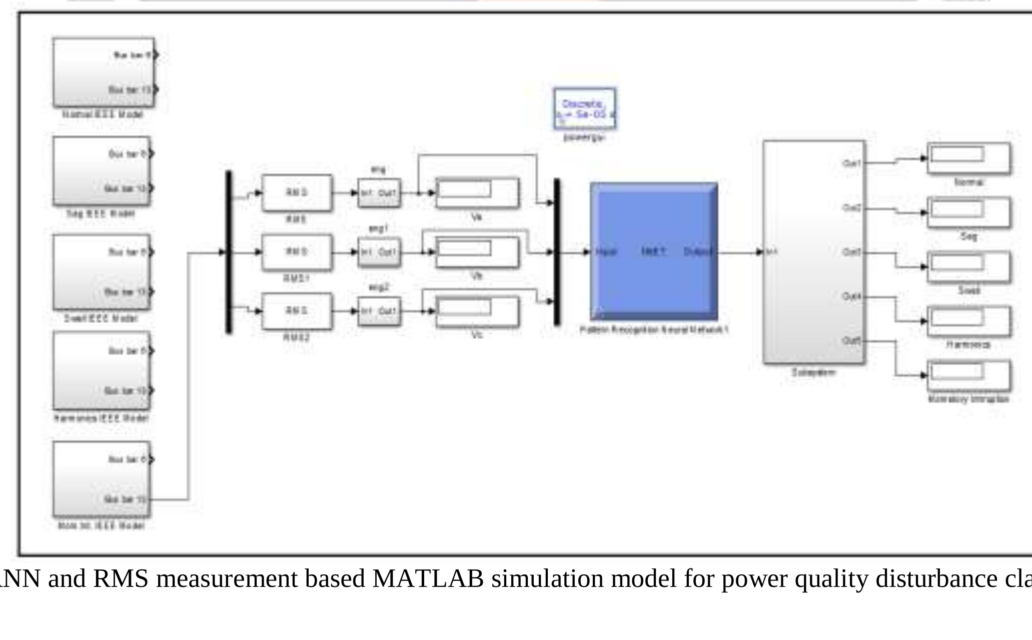


Fig-7: ANN and RMS measurement based MATLAB simulation model for power quality disturbance classification

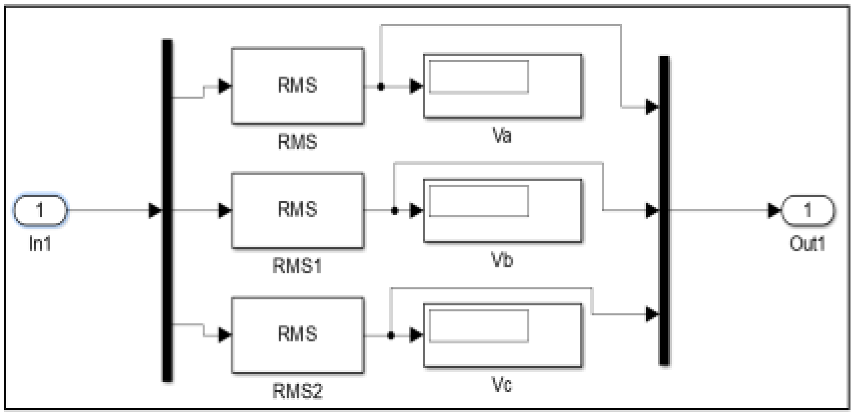


Fig-8: RMS Voltage measurement subsystem model

Figure 8 shows the RMS voltage measurement subsystem which measures the Root mean Square value of each three phase voltages that is Va, Vb and Vc. And that data are constant magnitude data that useful for ANN training. RMS calibration system can measured the average value from sinusoidal three phase voltages.

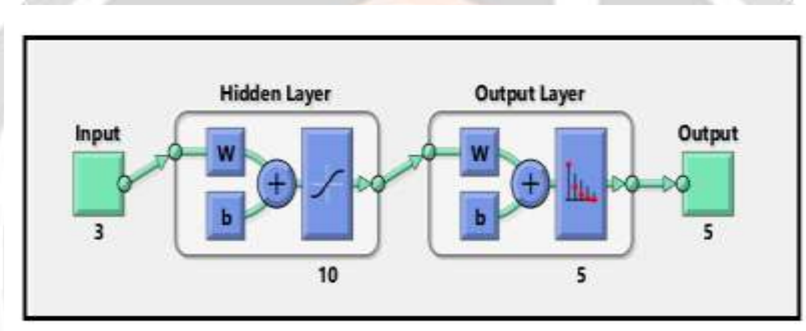


Fig-9: Generalized structure of neural network in MATLAB Simulink model

Figure 9 represents the each block of artificial neural network in matlab simulation in which there are 10 numbers of hidden neurons and three numbers of output neurons are selected for training. There are total three inputs contains three phase RMS voltages and output of ANN are five includes five types of power quality disturbance events classes like Normal voltage condition, voltage Sag condition, Voltage Swell condition, Voltage Harmonics condition and three phase voltage momentary Interruption condition.

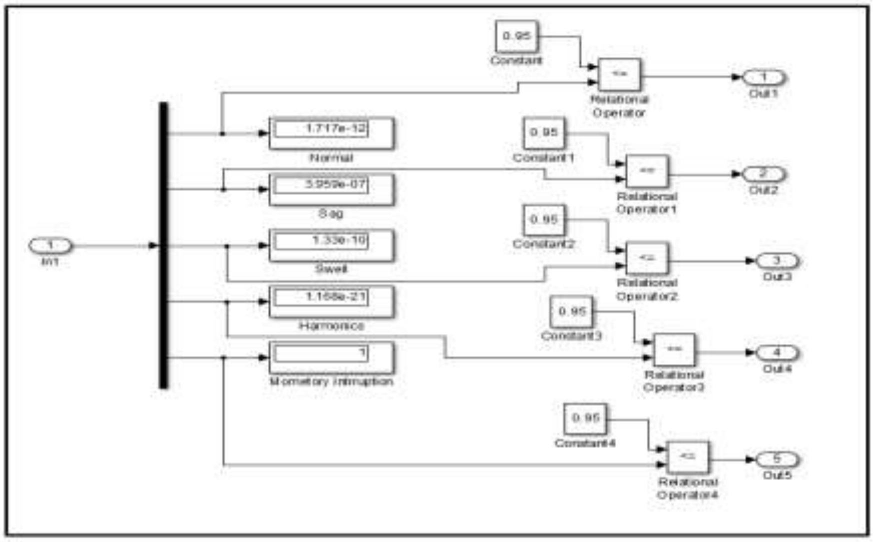


Fig-10: Output correction subsystem matlab simulink model

Figure 10 shows the ANN actual output correction subsystem matlab simulink model in which the actual output of ANN decided by user is generated. But in practical conditions in some cases of power quality disturbances that time ANN not generate the output same as decided target output. And hence we need make that output same as target output using ANN correction subsystem model. In this case if answer of neural network becomes more than 0.95 then consider as one otherwise answer becomes zero generated by correction subsystem model.

Back propagation training algorithm based Neural network training for power quality disturbance classification is presented. For achieving, the separate (BP-ANN) neural network structure are utilized and input for Neural network is taken from IEEE 14 bus system three phase per unit voltage which measured at different bus bar location like bus bar 2, bus bar 6 and bus bar 13. Similarly, three phases per unit voltage will be measured at different bus bar locations. Neural network train for 15 power quality disturbance cases at different bus bar location i.e. bus bar 2, 6 and 13. These Power quality disturbance cases simulate in IEEE 14 bus subsystem models by taking different loading conditions and by taking harmonics effect on IEEE 14 bus based power system model.

Table-5: Training input data set for Artificial Neural Network

Sr No	Condition	Bus Bar No.	Va (PU)	Vb (PU)	Vc (PU)
1	Normal	6	0.9171	0.9171	0.9171
2	Sag	6	0.3247	0.3254	0.3255
3	swell	6	1.539	1.561	1.5
4	Harmonics	6	0.51	0.5098	0.5099
5	Mom. Intrp.	6	0.1297	0.1462	0.1339
6	Sag	13	0.318	0.3187	0.3189
7	Normal	13	0.8319	0.8319	0.8319
8	swell	13	1.321	1.337	1.285

9	Harmonics	13	0.4872	0.487	0.487
10	Mom. Intrp.	13	0.1238	0.1397	0.1282

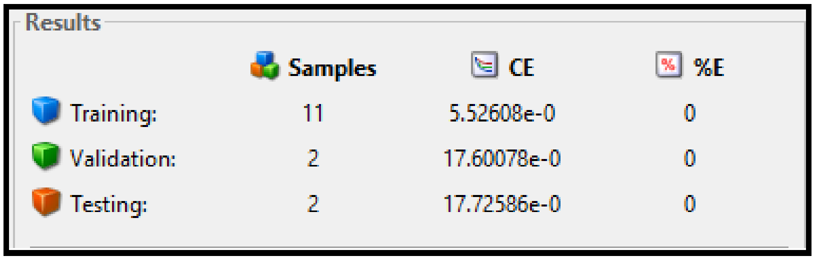
The three phases per unit voltage was measured during power quality disturbance like Normal voltage condition, voltage Sag condition, Voltage Swell condition, Voltage Harmonics condition and three phase voltage momentary Interruption condition. for simulation time of 2.5 seconds. Because all types of power quality disturbances was simulated in between 1.5 sec to 3 sec time duration so that 2.5 sec was best time for measurement of power quality disturbances voltages.

Table 5 represents the input training data set for back propagation ANN model in matlab simulink which measured at different bus bars like bus bar 2, 6 and 13. Similarly table 6 shows the required target output for corresponding serial number power quality disturbance for corresponding three phases input per unit voltages.

Table-6: Training target data set of Artificial Neural Network

Sr No	**Condition**	**Bus Bar No.**	**Normal**	**Sag**	**Swell**	**Harmonics**	**Momentary Interruption**
1	Sag	2	0	1	0	0	0
2	swell	2	0	0	1	0	0
3	Harmonics	2	0	0	0	1	0
4	Mom. Intrp.	2	0	0	0	0	1
5	Normal	2	1	0	0	0	0
6	Sag	6	0	1	0	0	0
7	swell	6	0	0	1	0	0
8	Harmonics	6	0	0	0	1	0
9	Mom. Intrp.	6	0	0	0	0	1
10	Normal	6	1	0	0	0	0
11	Sag	13	0	1	0	0	0
12	swell	13	0	0	1	0	0
13	Harmonics	13	0	0	0	1	0
14	Mom. Intrp.	13	0	0	0	0	1

15	Normal	13	1	0	0	0	0



Results

	Samples	CE	%E
Training:	11	5.52608e-0	0
Validation:	2	17.60078e-0	0
Testing:	2	17.72586e-0	0

Fig-11: Training performance parameter for neural network for power quality disturbance classification

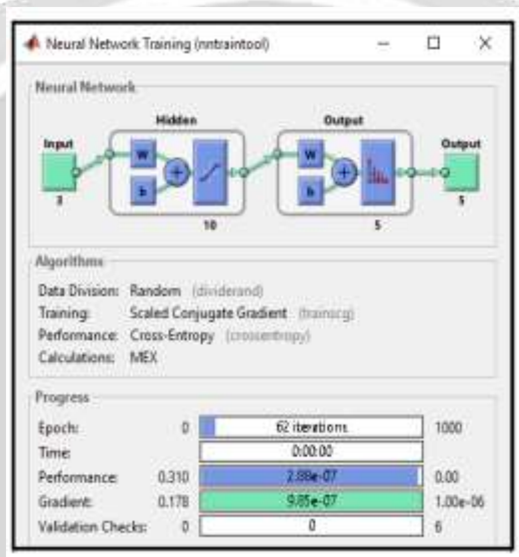


Fig-12: Training performance window for ANN

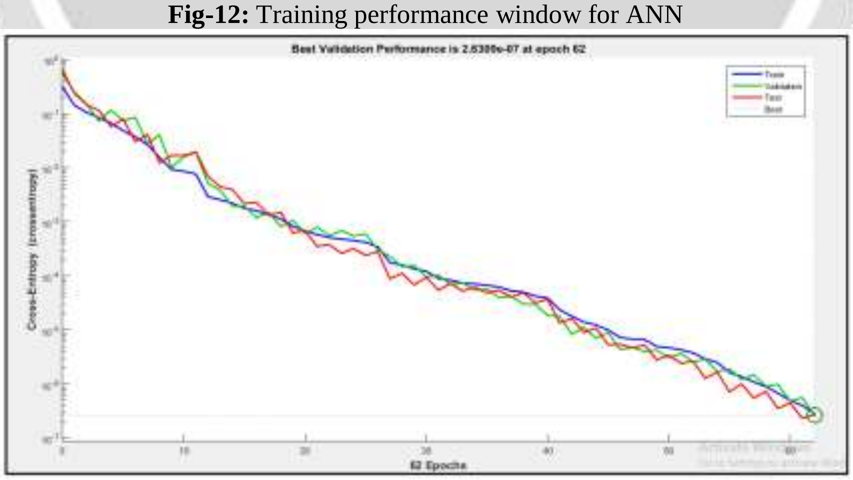


Fig-13: Training performance characteristics of ANN for power quality disturbance classification

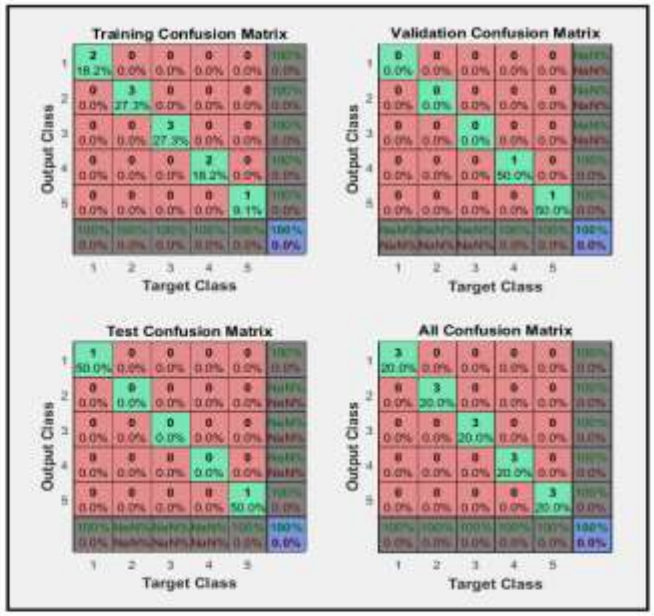


Fig.14: ANN confusion matrix after training in MATLAB simulation

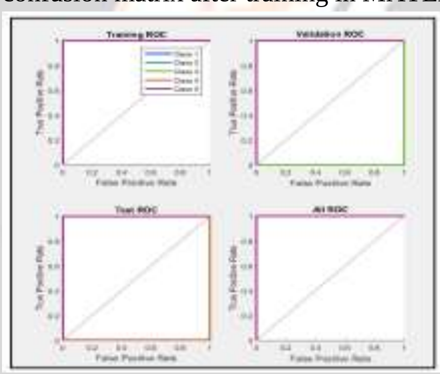


Fig-15: BP-ANN receiver operating characteristics for PQ disturbance classifications

Figure 14 represents the confusion matrix for ANN model after training in which it is observed that ANN has 100% classification efficiency for classification of power quality disturbances types. Also figure 15 represents the receiver operating characteristics in which all classes means PQ disturbances classes lines are near to the true positive rate. Hence all data are classify from ANN side after training.

5. CONCLUSION

The results show that our proposed method has the efficiency of 100 % while classifying the different power quality disturbances. We've trained an ANN for various types of voltage data for different power quality disturbance conditions. Load flow analysis and study is done on the IEEE 14 bus based power system while considering the different PQ conditions events. We've designed the entire system in MATLAB R2015. For the system analysis and designing, we've used the toolboxes of power system, neural network and load flow analysis.
From the analysis of the experimental results, it can be concluded that

- FLC classifier efficiency is 90% for PQ disturbance classification when the RMS fuzzy logic approach is used.
- Artificial neural network classifier efficiency is 100 % for PQ disturbances when the RMS ANN approach is used.

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