



“Review: Investigation & Mitigation of Power Quality Events”

Engineering

Chetan E. Morkhade

ME Student, Electrical Engg.Dept. GHRCEM, Amravati

Chetan M. Bobade Assistant Professor, Electrical Engg.Dept. GHRCEM, Amravati.

ABSTRACT

Development of electrical power supplies began more than one hundred years ago. At the beginning, there were only small DC networks within narrow local boundaries, which were able to cover the direct needs of industrial plants by means of hydro energy. With an increasing demand on energy and the construction of large generation units, typically built at remote location from the load centers, the technology changed from DC to AC. Power to be transmitted, voltage levels and transmission distances increased. Power quality (PQ) issue has attained considerable attention in the last one and half decade due to large penetration of power electronics based loads and/or microprocessor based controlled loads. On one hand these devices introduce power quality problem and on other hand these mal-operate due to the induced power quality problems. PQ disturbances/events cover a broad frequency range with significantly different magnitude variations and can be non-stationary, thus, accurate techniques are required to identify, classify and mitigate these events/disturbances. This paper presents a comprehensive overview of different techniques used for PQ event's classifications and mitigations. Various artificial intelligent techniques which are used in PQ event classification are also discussed. Major Key issues and challenges in classifying PQ events are critically examined and outlined.

KEYWORDS:

Power quality, PQ event classifiers, artificial intelligence techniques, PQ Solver, DVR, PWM, USSC, PQ key issues.

1. Introduction

An electrical power system is expected to deliver undistorted sinusoidal rated voltage and current continuously at rated frequency to the end users. However, large use of power electronics devices along with restructuring of the electric power industry and small-scale distributed generation have put more stringent demand on the quality of electric power supplied to the customers. To define power quality (PQ), the views of utilities, equipment manufacturers, and customers are completely different. Utilities treat PQ from the system reliability point of view. Equipment manufacturers, on the other hand, consider PQ as being that level of power supply allowing for proper operation of their equipment, whereas customers consider good PQ that ensures the continuous running of processes, operations, and business. A PQ problem can be defined as “any power problem manifested in voltage, current and/or frequency deviations that result in failure or mal-operation of customer's equipment”. In early days, power quality were concerned with the power system transient arising due to switching and lightning surges, induction furnace and other cyclic loads. Increased interconnection, widespread use of power electronics devices with sensitive and fast control schemes in electrical power networks have brought many technical and economic advantages, but these have also introduced new challenges for the power quality engineers.

All the possible PQ issues can be detected and classified by using standard techniques and also can be solved by utilizing following techniques. This work can be carried out by PSCAD/MATLAB software tool. The same methodology can be applied on real system.

1.1 Classification of PQ events

The power quality events/disturbances can further be classified according to the nature of the waveform distortion. The information regarding typical spectral content, duration and magnitude for each category of electromagnetic disturbances are shown in Table 1. which described further by various appropriate ton. For steady-state disturbances, the amplitude, frequency, spectrum, modulation, source impedance, notch depth and notch area attributes can be utilized. However, for non-steady state disturbances, other attributes such as rate of rise, rate of occurrence and energy potential are useful. The main reasons for the increased interest in PQ can be summarized as follows:

- Modern electric appliances are equipped with power electronics devices utilizing microprocessor/microcontroller. These appliances introduce various types of PQ problems.
- Industrial equipments such as high-efficiency, adjustable speed motor drives and shunt capacitors are now extensively used.
- The complexity of industrial processes, which results in huge economic losses if equipment fails or malfunctions.
- The complex interconnection of systems, resulting in more severe consequences if any one component fails. Moreover, various sophisticated power electronics equipments, which are very sensitive to the PQ problems, are used for improving system stability, operation and efficiency.
- There has been a significant increase in embedded generation and renewable energy sources which create new power quality problems, such as voltage variations, flicker and waveform distortions.
- Introduction of competitive electricity market gives right to the customers to demand high quality of supply.

Table 1: Classification of various power quality events

| S. No. | Categories | Duration | Voltage Magnitude | | | | |
|------------------|--------------------------|--------------|-------------------|-----------------------------|---------------|------------------|------------|
| I | Short Duration Variation | 0.5-30 cycle | 0.1-0.9 pu | | | | |
| | | | | (a) Sag | Instantaneous | 30 cycles-3 sec. | 0.1-0.9 pu |
| | | | | Momentary | 3sec-1min. | 0.1-0.9 pu | |
| | (b) Swell | 0.5-30 cycle | 30 cycles-3 sec. | 1.1-1.8 pu | | | |
| | | | | | Instantaneous | 1.1-1.4 pu | |
| | | | | | Momentary | 1.1-1.2 pu | |
| (c) Interruption | 0.5cycles-3sec. | 3sec-1min. | <0.1 pu | | | | |
| | | | | Momentary | <0.1 pu | | |
| | | | | Temporary | <0.1 pu | | |
| II | Long Duration Variation | >1min | 0.0 pu | | | | |
| | | | | (a) Interruption, Sustained | >1min | 0.8-0.9 pu | |
| | | | | (b) Undervoltage | >1min | 1.1-1.2 pu | |
| (c) Overvoltage | >1min | 1.1-1.2 pu | | | | | |
| III | Transients | <50msec | 0.4 pu | | | | |
| | | | | (a) Impulsive | Nanosecond | 50-1msec. | 0.8 pu |
| | | | | | Microsecond | >1msec. | 0.4 pu |
| | Millisecond | | | | | | |
| | (b) Oscillatory | 0.3-50msec. | 20msec. | 0.4 pu | | | |
| | | | | | Low frequency | | |
| Medium freq. | | | | | | | |
| | High freq. | | | | | | |
| IV | Voltage Imbalance | Steady state | 0.5-2% | | | | |
| V | Waveform Distortion | Steady state | Steady state | | | | |
| | | | | (a) Harmonics | Steady state | | |
| | | | | (b) Notching | Steady state | | |
| | | | | (c) Noise | Steady state | | |

2. Literature review

2.1 Classification techniques

1) "Detection and Classification of Multiple Power-Quality Disturbances with Wavelet Multiclass SVM" This paper presents an integrated model for recognizing power-quality disturbances (PQD) using a novel wavelet multiclass support vector machine (WMSVM). The so-called support vector machine (SVM) is an effective classification tool. It is deemed to process binary classification problems. This paper combined linear SVM and the disturbances-versus-normal approach to form the multiclass SVM which is capable of processing multiple classification problems. Various disturbance events were tested for WMSVM and the wavelet-based multilayer-perception neural network was used for comparison. A simplified network architecture and shortened processing time can be seen for WMSVM.

WMSVMs were designed with a simple network architecture to shorten the processing time. The proposed architecture could effectively detect information from distorted waves using WT and MSVM techniques. In a real power system, where DA is not available, training data could be periodically collected by portable recording instruments placed at measurement points. The special patterns could also be extracted from real-world monitors at measurement points including oscillatory transients, sag rung between 0.1 and 0.7 p.u., and voltage flicker. Some advantages of the WMSVM-based DEDS are that: WMSVM has a fast processing procedure; WMSVM has a strong classification capability with less sampling rates; WMSVM uses the simple QP technique to produce a unique optimal solution; a minimum-sized network can be built using simple learning algorithms with minimal training data; the DVN approach and linear SVM are used to solve the nonlinearly separable problems, such as PQD; WMSVM can work either with existing DA interface or portable recorders; WMSVM could detect multiple harmonics and voltage disturbances simultaneously at each observation location; WMSVM has good classification performance, detection accuracy, and robustness. Computer simulation shows that WMSVM-based DEDS are precise, easy to work with, and are very effective and robust.

2) "Power Quality Problem Classification Based on Wavelet Transform and a Rule-Based method" This paper describes a Wavelet Transform and Rule-Based method for detection and classification of various events of power quality disturbances. In this model, wavelet Multi-Resolution Analysis (MRA) technique was used to decompose the signal into its various details and approximation signals, and unique features from the 1st, 4th, 7th and 8th level detail are obtained as criteria for classifying the type of disturbance occurred. These features and together with the duration of disturbance of occurrence obtained from 1st level of detail, they form the criteria for a Rule-Based software algorithm for detecting different kinds of power quality disturbances effectively. From the results of the simulation say that it is feasible to classify the type of power quality disturbance using MRA technique together with Rule Based Algorithm even though there is some difficulty in detecting the sag with a shallow dip. The program is fast because it is not computational intensive.

3) "Power quality event classification: an overview and key issues" This paper presents novel power quality disturbance detection and classification method of distribution power system based on complex wavelet transform (WT) and radial basis function (RBF) neural network. The complex supported orthogonal wavelets is employed to extract the feature information of disturbance signal, and finally proposed to explore several novel wavelet combined information (CI) to analyze the disturbance, superior to real wavelet analysis result. The feature obtained from WT coefficients are inputted into RBF network for power quality disturbance pattern classification. The power quality disturbance classification model is established and the synthesized method of recursive orthogonal least squares algorithm (ROLSA) with improved givens transform is used to fulfill the network structure parameters. By means of choosing enough samples to train the recognition model, the type of

disturbance can be obtained when signal representing fault is inputted to the trained network. The simulation results demonstrate that the complex WT combined with RBF network are more sensitive to signal singularity, and found to be significant improvement for acquiring signal feature information. This paper has presented a new technique which possesses the advantages of complex wavelet transform to extract the power quality disturbance signals superimposing on the stationary power frequency components in distribution power system, and after the recursive orthogonal least squares algorithm (ROLSA) training phases the radial basis function (RBF) network is developed to effectively recognize power quality disturbances pattern. A method using the combined information (CI) with modulus maxima and polarities of complex wavelet coefficients has been developed to improve the flexibility and discriminability of voltage disturbance signals. The properties of both time and frequency domain localizations demonstrate that the complex wavelet transform is an excellent tool for processing the transient signal of power system faults. Taking advantage of complex wavelet transform, combined information can be obtained from both the magnitudes and arguments of complex wavelet transform coefficients to extract the desired band of the transient signal and detect the fault position for relay operation. The simulation results have shown that the satisfactory performance has been achieved under different disturbances conditions and system configurations.

4) "Power Quality Disturbances Detection and Classification Using Complex Wavelet Transformation and Artificial Neural Network" Adaptive neuro-fuzzy system (ANFS) is a hybrid system incorporating the learning abilities of ANN and excellent knowledge representation and inference capabilities of fuzzy logic (Jang, 1993; Jang et al, 1995; Lin et al, 1991) that have the ability to self modify their membership function to achieve a desired performance. An adaptive network, which subsumes almost all kinds of neural network paradigms, can be adopted to interpret the fuzzy inference system. ANFS utilizes the hybrid-learning rule and manage complex decision-making or diagnosis systems. ANFS has proven to be an effective tool for tuning the membership functions of fuzzy inference systems. It is showed that adaptive fuzzy systems are very successful in learning power quality waveform. The new adaptive neuro-fuzzy tool will enhance the performance of the existing power quality service in several ways:

- Maximizing the knowledge gain from the huge amount of power quality data available.
- By setting the proper boundaries of abnormal behavior, unnecessary invocation of more complex PQ analysis software will be prevented, hence the efficiency (including cost effectiveness) of the service currently offered will be increased drastically.
- The adaptive technique used eliminates the need for any prior PQ knowledge on behalf of the customer or system engineers.

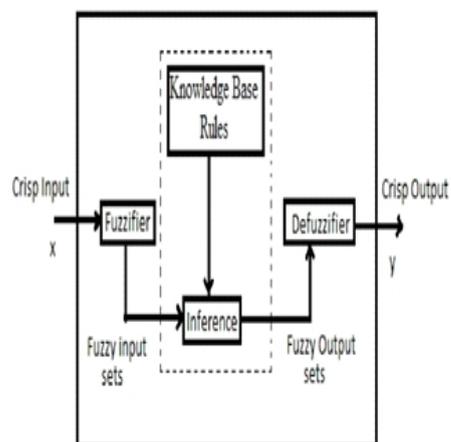


Figure- 1. Fuzzy logic system

Table-2 shows different classification approaches

| Classification Approaches | Ratings |
|---|-----------|
| Artificial Neural Network Based Classifiers | Good |
| Expert System Based Classifier | Bad |
| Fuzzy Expert System Based Classifiers | Bad |
| Adaptive Neuro-Fuzzy System Based Classifier | bad |
| Support Vector Machines | Excellent |
| Artificial Neural Network & Support Vector Machines | Very good |

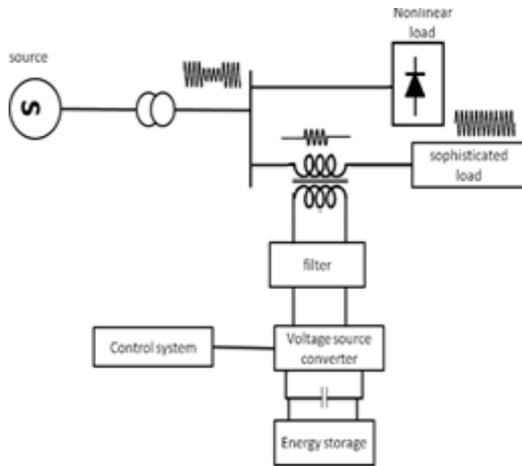


Figure-2. Schematic Diagram of DVR Configuration

2.2 Mitigation Techniques

1) "A PSCAD/EMTDC Model for H-Bridge Converter Based DVR for Mitigation of All Symmetrical & Asymmetrical Faults This paper presents the analysis & design of three phase H-bridge converter based DVR for protect sensitive load from polluted distributed network. The main objective of this paper is to save sensitive load from non linear voltages, currents and avoid PQ problem like voltage sag, swell conditions, in addition to the phase angle jump. Modeling & simulation of proposed DVR are implemented in PSCAD/EMTDC platform.

Dynamic Voltage Restorer is a series connected device designed to maintain a constant voltage value across a sensitive load. The DVR considered consists of:

- a) an injection / series transformer,
- b) a harmonic filter,
- c) a Voltage Source Converter (VSC),
- d) an energy storage and
- e) a control system

The main function of a DVR is the protection of sensitive loads from voltage sags/swells coming from the network. Therefore as shown in Figure 1, the DVR is located on approach of sensitive loads. If a fault occurs or any nonlinear load connected with other lines, DVR inserts series voltage VDVR and compensates load voltage to a pre-fault value. The amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage VL. This means that any differential voltages caused by transient disturbances in the AC feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer. The DVR works independently of the type of fault or any

event that happens in the source side, provided that the whole system remains connected to the supply grid, i.e. the line breaker doesn't trip. For most practical cases, a more economical design can be achieved by only compensating the positive and negative sequence components of the voltage disturbance seen at the input of the DVR. This option is Reasonable because for a typical distribution bus configuration, the zero sequence part of a disturbance will not pass through the step down transformer because of infinite impedance for this component.

The DVR has two modes of operation which are: standby mode and boost mode. In standby mode (VDVR=0), the booster transformer's low voltage winding is shorted through the converter. No switching of semiconductors occurs in this mode of operation, because the individual converter legs are triggered such as to establish a short-circuit path for the transformer connection. Therefore, only the comparatively low conduction losses of the semiconductors in this current loop contribute to the losses. The DVR will be most of the time in this mode. In boost mode (VDVR>0), the DVR is injecting a compensation voltage through the booster transformer due to a detection of a supply voltage disturbance. The main advantages of the proposed DVR are simple and efficient adaptive control and fast response.

2) "Mitigation of Various Power Quality Problems Using Unified Series Shunt Compensator in PSCAD/EMTDC This paper deals with the simulation of a Unified Series Shunt Compensator (USSC), which is aimed at mitigating most of the Power Quality problems such as, Voltage Sag compensation, Voltage Swell compensation, Voltage Flicker reduction, Voltage Unbalance mitigation, UPS mode of operation and Harmonics elimination. The modeling and simulation of the USSC has been carried out by using Power Systems Computer Aided Design (PSCAD) software. The USSC simulation model comprises of two 12-pulse inverters which are connected in series and in shunt to the system. A generalized sinusoidal pulse width modulation switching technique has been developed in the proposed controller design for fast control action of the USSC. The USSC has mitigated several Power Quality problems giving better performance.

The USSC has effectively compensated the voltage sag of 0.5 p.u. for duration of 0.75 s by maintaining the load voltage at 1p.u. throughout the duration with maximum and minimum voltages of 1.1 p.u. and 0.91 p.u. at starting and ending of the sag respectively. The voltage swell of 1.3 p.u. for duration of 0.75 s has been reduced to the rated voltage 1 p.u. by using USSC in the system with maximum and minimum voltages of 1.07 and 0.94 respectively during starting and ending of the voltage swell. The unbalance in the three phase voltages has been reduced to below the voltage unbalance limit of 2%. The voltage flicker generated by the variable electric load has been reduced from 0.321 to 0.013 which is below the voltage flicker index limit of 0.07 by connecting the USSC to the system. The USSC has operated in UPS mode during an outage for a period of 0.75 s, supplying power to the load and retaining the rated voltage. It was also observed that the harmonics generated by the USSC has been significantly reduced to below 5% from about 60% by inserting a passive LC filter into the system.

Thus, it is observed that the USSC has responded well in mitigating voltage sag, voltage swell, voltage unbalance, voltage flicker, UPS mode of operation for improvement of power quality in distribution system.

3) "New Control Technique Applied in Dynamic Voltage Restorer for Voltage Sag Mitigation" Simulation and experimental investigation toward new algorithms development based on SVPWM. Understanding the nature of DVR and performance comparisons between the various controller technologies available. The proposed controller using space vector modulation techniques obtain higher amplitude modulation indexes if compared with conventional SPWM techniques. Moreover, space vector modulation techniques

can be easily implemented using digital processors. Space vector PWM can produce about 15% higher output voltage than standard Sinusoidal PWM. The purpose of this research was to study the implementation of SVPWM in DVR. The proposed control algorithm was investigated through computer simulation by using PSCAD/EMTDC software. The simulation and experimental results of a DVR using PSCAD/EMTDC software based on SVPWM technique showed clearly the performance of the DVR in mitigating voltage sags. The DVR operates without any difficulties to inject the appropriate voltage component to correct rapidly any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value.

The efficiency and the effectiveness in voltage sags compensation showed by the DVR makes it an interesting power quality device compared to other custom power devices. The results of the PSCAD/EMTDC simulation and experimental also verify the proposed control algorithm based on Space Vector Pulse Width Modulation (SVPWM) technique to generate the pulses for mitigating voltage sags.

4) "Mitigation of Voltage Sags/Swells using PWM Switched Autotransformer"

This paper presents modeling and analysis of PWM switched autotransformer as a mitigating device for voltage sag and swells disturbances. The proposed system has less number of switching devices and has good compensating capability in comparison to commonly used compensators. Simulation analysis of three-phase compensator is performed in PSCAD/EMTDC and performance analysis of the system is presented for various levels of sag and swell. The THD of the load voltage when the compensator is functioning during disturbance condition are within the limits. Also the compensator can maintain the load real and reactive powers constant.

The proposed technique is simple and only one IGBT switch per phase is required. Hence the system is more simple and economical compared to commonly used DVR or STATCOM. Simulation analysis is performed for three phase system and simulation results verify that the proposed device is effective in compensating the voltage sag and swell disturbances.

5) "Mitigation of Back-to-Back Capacitor Switching Transients on Distribution Circuits" In this paper we evaluate three technologies used to mitigate transients caused by capacitor switching in distribution feeders. The basic theory concerning capacitor bank switching transients, along with each mitigating technology, is presented. They used the software package ATP to simulate the energization of a controlled capacitor bank in a specific substation feeder, with and without employing mitigation devices. Mathematical computations of quantities such as peak transient voltages, currents, and frequencies are provided for each case. The synchronous circuit breaker was the ideal component to mitigate the effects of the back-to-back capacitor switching. This equipment had the advantage of closing each pole independently near the zero-crossing of the voltage waveform. This operation reduced the transients to levels that would not severely affect most sensitive equipment.

The other two technologies considered, pre-insertion resistors and current-limiting reactors were able to reduce the magnitudes of the transients in the voltage and current waveforms, but to a lesser degree. Still, its effects were still noticeable and lasted for a few milliseconds.

3. Conclusion

Electric power quality, which is a important concern to several power utilities all over the world, is often severely affected by PQ problems. Due to increased use of various power electronic devices in modern power systems, power quality is becoming an important and

challenging issue for the power engineers. There is no unique model which can assess the power quality problem and to identify and classify them properly. Existing automatic recognition methods need improvement in terms of their versatility, reliability, and accuracy.

This paper addresses different PQ classification approaches in general and AI tools are reviewed in particular. Major key issues and challenges related to these advanced techniques in automatic classification of PQ problems are highlighted. New intelligent system technologies using DSP, expert systems, AI and machine learning provide some unique advantages in intelligent classification of PQ distortions.

From the above discussion we can conclude that new AI systems and modified DVR system can be suitable for classification and mitigation of PQ events respectively.

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