Power Quality Disturbance Classification Using Frequency Domain Features

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By

Md. Adib Ibne Yousuf – 201016034

S.M. Shamim - 201016036

Md. Touhidur Rahman Akanda – 201016050

DEPARTMENT OF ELECTRICAL, ELECTRONIC AND COMMUNICATION ENGINEERING (EECE)

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APPROVAL

The thesis titled **"Power Quality Disturbance Classification Using Frequency Domain Features"** submitted by Md. Adib Ibne Yousuf (201016034), S.M. Shamim (201016036) and Md. Touhidur Rahman Akanda (201016050), Session: 2009-10 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of **BACHELOR OF SCIENCE IN ELECTRICAL, ELECTRONIC AND COMMUNICATION ENGINEERING** on December, 2013.

APPROVAL OF THE SUPERVISOR

Hafiz Imtiaz
Assistant Professor
Department of Electrical and Electronic Engineering
BUET, Dhaka-1000, Bangladesh.

DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

SUBMITTED BY

Md. Adib Ibne Yousuf

S.M. Shamim

Md. Touhidur Rahman Akanda

DEDICATION

To Our Beloved Parents

ABSTRACT

Discrete Cosine Transform feature has become an effective feature extraction method in modern power system. In this paper, we used algorithm of a unique feature for power quality (PQ) disturbance signal classification. Here, we proposed the extraction of spectral features from Discrete Cosine Transform (DCT) domain. This feature extraction offers the ability to detect and localize harmonic events and it also classifies different power quality disturbance signals. A useful technique of selecting significant DCT coefficients is proposed for optimal feature selection. This process offers dimensional feature reduction. In this paper we consider seven types of power quality disturbance signals and simulate for each of the given categories. Using this extracted feature we can get not only very high classification accuracy but also a low computational burden. This feature extraction using Discrete Cosine Transform is one of the best feature extraction formula, we have ever seen.

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ABBREVIATION

PQ= Power Quality.

DCT= Discrete Cosine Transform.

FkNN= Fuzzy k-nearest Neighbour.

GA= Genetic Algorithm.

DFT= Discrete Fourier Transform.

SVM= Support Vector Machine .

Chapter 1

Introduction

1.1 Power Quality

Power quality is an emerging area of research in the field of electric power distribution system. It has acquired a lot of importance since the advancement & modernization of highly Sensitive electrical and electronic equipment. Power quality issues and the resulting problems are the consequences of the increasing use of solid state switching devices, non-linear and power electronically switched loads.

The term "Power Quality" simply focuses on the measurable features of the power, which is supplied in a power system. Power Quality is one of the hot topics in energy industry. Supplied power for some load is basically said to have quality (actually this is an hypothetical term), if the supplied voltage magnitude is at rated value and the frequency of it is constant at system synchronous frequency with no other frequency components. In addition to this simple definition, the term power quality can be enlarged to general term to represent a power system that does not contain any unintended, harmful components of voltage, current or power and any unintended phenomena at supplied voltage.

The design specifications which are determined considering the rated values of an ideal mains supply ,all loads in a power system are designed to operate according to it. Thus, any unintended failures, voltage phenomena or harmful current components nearby are harms most of the loads. Actually, some of them are very vulnerable to unintended behaviours of mains. A supply with less quality causes trouble to industrial loads and consequently this means the loss of labor, time and money for industrial plants. The power quality problems may be seen in supply voltage, frequency or nearby currents.

Power quality shows the fitness of electrical power to consumer devices. Synchronization of the voltage frequency and phase allows electrical systems to function in their intended manner without significant loss of performance or life. The term ‘power quality’ is used to describe electric power that drives an electrical load and the load's ability to function properly. Without the proper power, an electrical device or load may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power. The electrical power industry comprises electricity generation(AC power), electric power transmission and ultimately electricity distribution to an electricity meter located at the premises of the end user of the electric power. The electricity then moves through the wiring system of the end user until it reaches the load. The complexity of the system to move electric energy from the point of production to the point of consumption combined with variations in weather, generation, demand and other factors provide many opportunities for the quality of supply to be compromised. While "power quality" is a convenient term for many, it is the quality of the voltage—rather than power or electric current —that is actually described by the term. Power is simply the flow of energy and the current demanded by a load is largely uncontrollable.

We can think of power quality as a compatibility problem. Compatibility problems always have at least two solutions: in this case, either clean up the power, or make the equipment together. Ideally, AC voltage is supplied by a utility as sinusoidal having an amplitude and frequency given by national standards (in the case of mains) or system specifications (in the case of a power feed not directly attached to the mains) with an impedance of zero ohms at all frequencies.

1.2 Objectives of Power Quality

Now a days, the power quality objectives have become more and more explicit either in the form of agreements negotiated with customers, or in the form of definite goals agreed with the regulators. Moreover, a number of regulators already has planned to establish the power quality objectives to be met by the electricity supply systems. In some countries, regulators may even impose penalties in case of non-observance of power quality objectives.

It is the key feature of meeting power quality targets that the interested parties agree on the methods of gathering and presenting the power quality data. All the relevant power quality indices are prerequisites for assessing site and system performance with respect to power quality. These indices eventually facilitate the task of system operators with their obligation to report the power quality performance. As the system operators are at the risk of being exposed to the penalty payment for excursions in quality beyond the objective values, it is essential that the objectives are seen not only as achievable but also as being cost effective for all customers. Optimizing the power quality performance of electrical system is one of the objectives of system operator. The role of regulator is to ensure that this objective is carried out in a cost effective manner. If customers expect power quality to be an intrinsic characteristic of the product simultaneously, they also want it at the lowest price.

1.3 Power Quality Disturbance:

A power quality (PQ) problem mainly includes a variation in the voltage or current, such as **voltage sag, voltage swell, harmonics, flicker, oscillatory transient, sag with harmonics, swell with harmonics, interruptions.**Proper grounding of equipment is essential for safe and proper operation of sensitive electronic equipment. In times past, it was thought that equipment grounding as specified in the U.S. by the National Electric Code was in contrast with methods needed to insure power quality. Since those early times, significant evidence has emerged to support the position that, in the vast majority of instances, grounding according to the National Electric Code is essential to ensure proper and trouble-free equipment operation, and also to ensure the safety of associated personnel.

Voltage sags due primarily to system faults are probably the most significant of all power quality problems other than poor grounding practices. Voltage sags due to short circuits are often seen at distances very remote from the fault point, thereby affecting a potentially large number of utility customers. Coupled with the wide-area impact of a fault event is the fact that there is no effective preventive for all power system faults. End-use equipment will, therefore, be exposed to short periods of reduced voltage which may or may not lead to malfunctions.

As like as voltage sags, the concerns associated with flicker are also related to voltage variations. Voltage flicker, however, is tied to the likelihood of a human observer to become annoyed by the variations in the output of a lamp when the supply voltage amplitude is varying. In most cases, voltage flicker considers (at least approximately) periodic voltage fluctuations with frequencies less than about 30–35 Hz that are small in size. Human perception, rather than equipment malfunction, is the relevant factor when considering voltage flicker.

The power of classical Fourier series theory can be applied, for many periodic waveform either voltage or current variations. This term in the Fourier series is called harmonics. Relevant harmonic terms may have frequencies above or below the fundamental power system frequency. In most cases, non-fundamental frequency equipment currents produce voltages in the power delivery system at those same frequencies. This voltage distortion is present in the supply to other end-use equipment and can lead to improper operation of the equipment.

The power quality disturbance that occurs due to grounding, voltage sags, harmonics, and voltage flicker are those, which are most often encountered in practice. It should be recognized that the voltage and current transients associated with common events like lightning strokes and capacitor switching can also negatively impact end-use equipment.

No real-life power source is ideal and generally can deviate in at least the following ways:

Variations in the peak or RMS voltage are both important to different types of equipment.

When the RMS voltage exceeds the nominal voltage by 10 to 80% for 0.5 cycle to 1 minute, the event is called a "swell".

"sag" is the opposite situation: the RMS voltage is below the nominal voltage by 10 to 90% for 0.5 cycle to 1 minute.

Random or repetitive variations in the RMS voltage between 90 and 110% of nominal can produce a phenomenon known as "flicker" in lighting equipment. Flicker is rapid visible changes of light level. Definition of the characteristics of voltage fluctuations that produce objectionable light flicker has been the subject of ongoing research.

Abrupt, very brief increases in voltage, called "spikes", "impulses", or "surges", generally caused by large inductive loads being turned off, or more severely by lightning.

"Under-voltage" occurs when the nominal voltage drops below 90% for more than1 minute.

The term "brownout" is an apt description for voltage drops somewhere between full power (bright lights) and a blackout (no power – no light). It comes from the noticeable to significant dimming of regular incandescent lights, during system faults or over-loading etc., when insufficient power is available to achieve full brightness in domestic lighting. This term is in common usage has no formal definition but is commonly used to describe a reduction in system voltage by the utility or system operator to decrease demand or to increase system operating margins.

"Overvoltage" occurs when the nominal voltage rises above 110% for more than 1 minute.

Variations in the frequency.

Variations in the wave shape – usually described as harmonics.

Non-zero low-frequency impedance (when a load draws more power, the voltage drops).

Non-zero high-frequency impedance (when a load demands a large amount of current, the stops demanding it suddenly, there will be a sag or spike in the voltage due to the inductances in the power supply line).

Every power quality problems has a different cause. Some problems are a result of the shared infrastructure. For example, a fault on the network may cause a dip that will affect some customers; the higher the level of the fault, the greater the number affected. A problem on one customer's site may cause a transient that affects all other customers on the same subsystem. Problems, such as harmonics, arise within the customer's own installation and may propagate onto the network and affect other customers. Harmonic problems can be dealt with by a combination of good design practice and well proven reduction equipment.[1]

To avoid these disturbance signals we have proposed the DCT domain feature extraction process. Using this feature extraction, we can ensure the highest accuracy of disturbance signal extraction.

Chapter 2

Discussion on Power Quality Disturbances

There are many types of disturbances. They are responsible for power loss. Disturbance signals have bad effects on equipment .Disturbance signals are:-

1. Voltage Sag.
2. Voltage Swell.
3. Harmonics.
4. Flicker.
5. Transient.
6. Interruption.
7. Notching.

2.1 Voltage Sag

Voltage sags means the reductions in rms. voltage, for short duration. Voltage sag is mainly caused by short circuits and starting of large motors. Voltage sags create a lot of problems on several types of equipment. Adjustable-speed drives, process-control equipment, and computers are especially notorious for their sensitivity .Some pieces of equipment trip when the rms. voltage drops below 90% for longer than one or two cycles. Such a piece of equipment will trip tens of times a year. If this is the process-control equipment of a paper mill, one can imagine that the costs due to voltage sags can be enormous. A voltage sag is not as damaging to industry as a interruption, but as there are far more voltage sags than interruptions, the total damage due to sags is still larger. Another important aspect of voltage sags is that they are hard to mitigate. Short interruptions and many long interruptions can be prevented via simple, although expensive measures in the local distribution network. Voltage sags at equipment terminals can be due to short-circuit faults hundreds of kilometers away in the transmission system. It will be clear that there is no simple method to prevent them.

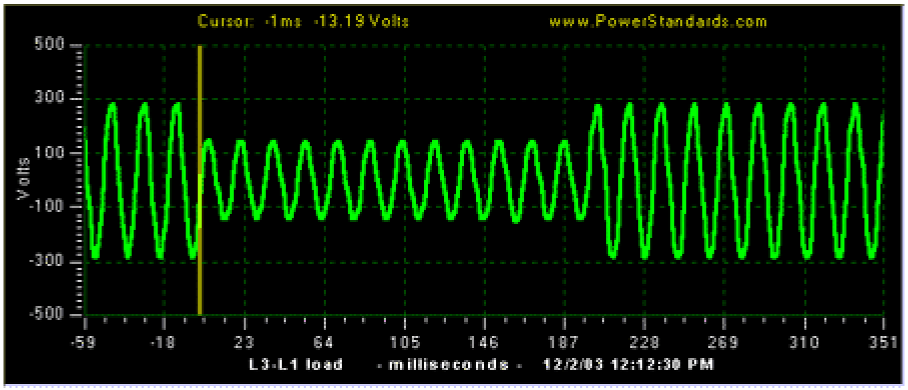

Figure-2.1.1 : voltage sag [2]

2.1.1 Voltage Sag Characteristics

The magnitude of voltage drops to a value of about 20% of its pre-event value for about two and a half cycles. After this, the voltage recovers again. The event shown in Figure can be characterized as a voltage sag down to 20% of the pre-event voltage for 2.5 cycles. This event can be characterized as a voltage sag with a magnitude of 20% and a duration of 2.5 cycles.

2.1.2 Voltage Sag Magnitude—Monitoring

The rms. voltage for the sag is shown in previous figure. The magnitude of a voltage sag is determined from the rms. voltage The rms. voltage has been calculated over a one-cycle sliding window:

$$\mathrm{Vrms}(k)=\sqrt{[\ 1/N \sum_{i=k-N+1}^{i=k} v(i)^2\ ]}$$

with N the number of samples per cycle, and v(i) the sampled voltage in time domain. The rms voltage as shown in Figure does not immediately drop to a lower value, but takes one cycle for the transition.This is due to the finite length of the window used to calculate the rms. value. We also see that the rms. value during the sag is not completely constant and that the voltage does not immediately recover after the fault.

2.1.3 Symptoms of dips, sags and surges

1. Variable speed drives close down to prevent damage.
2. Equipment does not operate correctly.
3. Dimming of lighting systems.
4. Production rates fluctuates.

5. Relays and contactors drop out.
6. Unreliable data in equipment test.

2.1.4 Causes of voltage sags

1. Unreliable grid system..
2. Long distance from a distribution transformer with interposed loads.
3. Rural location remote from power source
4. Power distributor tolerances not suitable for voltage sensitive equipment.
5. Switching of heavy loads.
6. Unbalanced load on a three phase system.
7. Equipment not suitable for local supply.

2.1.5 Voltage Sag Magnitude Calculation

In a radial system, to quantify sag magnitude, the voltage divider model can be used, where ZS is the source impedance at the point- of-common coupling and ZF is the impedance between the point-of-common coupling and the fault. The point-of-common coupling (pcc) is the point from which both the fault and the loadare fed. In other words, it is the place where the load current branches off from the fault current. In the voltage divider model, the load current before, as well as during the fault is neglected. The voltage at the pcc is found from:

$$\mathrm{Vsag} = \frac{\mathrm{ZF}}{\mathrm{ZS} + \mathrm{ZF}} \qquad \text{- - - - - - - - (eqn-1)}$$

Here it is assumed that the pre-event voltage is exactly 1 pu, thus E=1. The same expression can be derived for constant-impedance load, where E is the pre-event voltage at the pcc. We see before that the sag becomes deeper for faults electrically closer to the customer (when ZF becomes smaller), and for weaker systems (when ZS becomes larger).
Equation-1 can be used to calculate the sag magnitude as a function of the distance to the fault.

Therefore, we write ZF=zd, with z the impedance of the feeder per unit length and d the distance between the fault and the pcc, leading to:

$$\text{Vsag}=\frac{zd}{\text{ZS+zd}} \quad \text{- - - - - - - - - -(2)}$$

This expression has been used to calculate the sag magnitude as a function of the distance to the fault for a typical 11 kV overhead line, resulting in the following figure. For the calculations, a 150-mm2 overhead line was used and fault levels of 750 MVA, 200 MVA, and 75 MVA. The fault level is used to calculate the source impedance at the pcc and the feeder impedance is used to calculate the impedance between the pcc and the fault. It is assumed that the source impedance is purely reactive, thus ZS=j 0.161 V for the 750 MVA source. The impedance of the 150 mm2 overhead line is z=0.117þj 0.315 V=km.

2.1.6 Propagation of Voltage Sags

Calculation of the sag magnitude directly from fault levels at the pcc is also possible at the fault position. Let, SFLT be the fault level at the fault position and SPCC at the point-of-common coupling. The voltage at the pcc can be written as:

$$\text{Vsag} = 1\text{-}\frac{\text{SFLT}}{\text{SPCC}} \quad \text{- - - - - - - - - - - - - - (eqn -3)}$$

TABLE -2.1.1 Typical Fault Levels at Different Voltage Levels [29]

Voltage Level	Fault Level
400v	20MVA
11kv	200MVA
33kv	900MVA
132kv	3000MVA
400 kv	17000MVA

The given equation can be used to calculate the magnitude of sags due to faults at voltage levels other than the point-of-common coupling. Consider typical fault levels as shown in table . This data has been used to obtain table , showing the effect of a short circuit fault at a lower voltage level than the pcc. We can see that sags are significantly ‘‘damped’’ when they propagate upwards in the power system. In a sags study, we typically only have to take faults one voltage level down from the pcc into account. And even those are seldom of serious concern. However, that faults at a lower voltage level may be associated with a longer fault-clearing time and thus a longer sag duration. This especially holds for faults on distribution feeders, where fault-clearing times in excess of one second are possible.

2.1.7 Critical Distance

The voltage as a function of distance to the fault is given by eqn-4 . From this equation we can obtain the distance at which a fault will lead to a sag of a certain magnitude ,V. If we assume equal X=R ratio of source and feeder, we get the following equation:

$$\text{dcrit}=\frac{\text{Vnom}}{\text{zIflt}}\times\frac{V}{1-V} \text{ - - - - - - - - - (eqn-4)}$$

TABLE-2.1.2 : Propagation of Voltage Sags to Higher Voltage Levels[29]

Fault at	400V	11kV	33 kV	132kV	400kV
400v	-	90%	98%	99%	100%
11kV	-	-	78%	93%	99%
33kV	-	-	-	70%	95%
132kV	-	-	-		82%

TABLE -2.1.3 : Critical Distance for Faults at Different Voltage Levels[29]

Nominal Voltage	Short-Circuit Level	Feeder Impedance	Critical Distance
400V	20MVA	230mΩ/Km	35m
11kV	200MVA	310mΩ/Km	2km
33kV	900MVA	340mΩ/Km	4km
132kV	3000MVA	450mΩ/Km	13km
400kV	10000MVA	290mΩ/Km	55km

with Vnom the nominal voltage. As both z and Iflt are of similar magnitude for different voltage levels, one can conclude from Eq. -4 that the critical distance increases proportionally with the voltage level.

2.1.8 Voltage Sag Duration

The drop in voltage during a sag is due to a short circuit being present in the system .The voltage starts to return to its original value at the moment, the short circuit fault is cleared by the protection. Duration of a sag is thus determined by the fault-clearing time. However, the actual duration of a sag is normally longer than the fault-clearing time. Measurement of sag duration is less trivial than it might appear. From a recording the sag duration may be obvious, but to come up with an automatic way for a power quality monitor to obtain the sag duration is no longer straightforward. The commonly used definition of sag duration is the number of cycles during which the rms voltage is below a given threshold. This threshold will be somewhat different for each monitor but typical values are around 90% of the nominal voltage. A power quality monitor will typically calculate the rms value once every cycle.The main problem is that the so-called post-fault sag will affect the sag duration. When the fault is cleared, the voltage does not recover immediately. This is mainly due to the re-energizing and reacceleration of induction motor load . This post-fault sag can last several seconds, much longer than the actual sag. Therefore, the sag duration as defined before, is no longer equal to the fault clearing time. More seriously, different power quality monitors will give different values for the sag duration. As the r.m.s. voltage recovers slowly, a small difference in threshold setting may already lead to a serious difference in recorded sag duration .

Generally speaking, faults in transmission systems are cleared faster than faults in distribution systems. In transmission systems, the critical fault-clearing time is rather small. Thus, fast protection and fast circuit breakers are essential. Also, transmission and sub-transmission systems are normally operated as a grid, requiring distance protection or differential protection, both of which allow for fast clearing of the fault. The principal form of protection in distribution systems is over current protection.This requires a certain amount of time-grading, which increases the fault-clearing time. An exception is formed by systems in which current-limiting fuses are used. These have the ability to clear a fault within one half-cycle. In overhead distribution systems, the instantaneous trip of the re-closer will lead to a short sag duration, but the clearing of a permanent fault will give a sag of much longer duration. The so-called magnitude-duration plot is a common tool used to show the quality of supply at a certain location or the average quality of supply of a number of locations. Voltage sags due to faults can be shown in such a plot, as well as sags due to motor starting, and even long and short interruptions.

2.1.9 Methods of dealing with dips, sags and surges

1. Constant voltage (ferro-resonant) transformer.
2. Transformer with a tap changer.
3. Saturable reactor.
4. Switch mode power supply.
5. Servo controlled voltage stabilizer.
6. Soft starters on larger electrical equipment.
7. Connect larger loads to points of common coupling.
8. Choose equipment with dip resilience.

2.1.10 Equipment Voltage Tolerance

1. Voltage Tolerance Requirement :

Electrical equipment prefers a constant rms. voltage. That is what the equipment has been designed for and that is where it will operate the best. The other extreme is zero voltage for a longer period of time. In that case the equipment will simply stop operating completely. For each piece of equipment there is a maximum interruption duration, after which it will continue to operate correctly.

A simple test will give this duration. The same test can be done for a voltage of 10% (of nominal), for a voltage of 20%, etc. If the voltage becomes high enough, the equipment will be able to operate on it indefinitely. Connecting the points obtained by performing these tests results in the so-called ‘‘voltage tolerance curve’’.

The requirements for IT-equipment as recommended by the Information Technology Industry Council. Strictly speaking, one can claim that this is not a voltage-tolerance curve as described above, but a requirement for the voltage tolerance. One could refer to this as a voltage-tolerance requirement and to the result of equipment tests as a voltage-tolerance performance.

2. Voltage Tolerance Performance

Voltage-tolerance (performance) curves are the result of equipment tests performed in the U.S. (EPRI, 1994) and in Japan (Sekine et al., 1992). The shape of all the curves is close to rectangular. This is typical for many types of equipment, so that the voltage tolerance may be given by only two values, maximum duration and minimum voltage, instead of by a full curve.

From the tests summarized in it is found that the voltage tolerance of personal computers varies over a wide range: 30–170 ms, 50–70% being the range containing half of the models. The extreme values found are 8 ms, 88% and 210 ms, 30%. Voltage-tolerance tests have also been performed on process-control equipment: PLCs, monitoring relays, motor contactors. This equipment is even more sensitive to voltage sags than personal computers. The majority of devices tested tripped between one and three cycles. A small minority was able to tolerate sags up to 15 cycles in duration. The minimum voltage varies over a wider range: from 50% to 80% for most devices, with exceptions of 20% and 30%. Unfortunately, the latter two both tripped in three cycles. From performance testing of adjustable-speed drives, an ‘‘average voltage-tolerance curve’’ has been obtained . The sags for which the drive was tested are indicated as circles. It has further been assumed that the drives can operate indefinitely on 85% voltage. Voltage tolerance is defined here as ‘‘automatic speed recovery, without reaching zero speed.’’ For sensitive production processes, more strict requirements will hold .

2.1.11 Mitigation of Voltage Sags

Reducing the Number of Faults

Reducing the number of short-circuit faults in a system not only reduces the sag frequency, but also the frequency of long interruptions. This is thus a very effective way of improving the quality of supply and many customers suggest this as the obvious solution when a voltage sag or interruption problem occurs. Unfortunately, most of the time the solution is not that obvious. A short circuit not only leads to a

voltage sag or interruption at the customer interface, but may also cause damage to utility equipment and plant. Therefore, most utilities will already have reduced the fault frequency as far as economically feasible. In individual cases, there could still be room for improvement, e.g., when the majority of trips are due to faults on one or two distribution lines. Some examples of fault mitigation are:

- Replace overhead lines by underground cables.
- Use special wires for overhead lines.
- Implement a strict policy of tree trimming.
- Install additional shielding wires.
- Increase maintenance and inspection frequencies.

One has to keep in mind, however, that these measures can be very expensive, especially for transmission systems, and that their costs have to be weighted against the consequences of the equipment trips.

From Fault to Trip

To understand the various ways of mitigation, the mechanism leading to an equipment trip needs to be understood. The equipment trip is what makes the event a problem; if there are no equipment trips, there is no voltage sag problem. The underlying event of the equipment trip is a short-circuit fault. At the fault position, the voltage drops to zero, or to a very low value. This zero voltage is changed into an event of a certain magnitude and duration at the interface between the equipment and the power system. The short-circuit fault will always cause a voltage sag for some customers. If the fault takes place in a radial part of the system, the protection intervention clearing the fault will also lead to an interruption. If there is sufficient redundancy present, the short circuit will only lead to a voltage sag. If the resulting event exceeds a certain severity, it will cause an equipment trip. Based on this reasoning, it is possible to distinguish between the following mitigation methods:

. Reducing the number of short-circuit faults.

. Reducing the fault-clearing time.

. Changing the system such that short-circuit faults result in less severe events at the equipment terminals or at the customer interface.

. Connecting mitigation equipment between the sensitive equipment and the supply.

. Improving the immunity of the equipment.

3. Reducing the Fault-Clearing Time

Reducing the fault-clearing time does not reduce the number of events, but only their severity. It does not do anything to reduce to number of interruptions, but can significantly limit the sag duration. The ultimate reduction of fault-clearing time is achieved by using current-limiting fuses, able to clear a fault within one half-cycle. The recently introduced static circuit breaker has the same characteristics:

fault-clearing time within one half-cycle. Additionally, several types of fault-current limiters have been proposed that do not actually clear the fault, but significantly reduce the fault current magnitude within one or two cycles. One important restriction of all these devices is that they can only be used for low and medium-voltage systems. The maximum operating voltage is a few tens of kilovolts. But the fault-clearing time is not only the time needed to open the breaker, but also the time needed for the protection to make a decision. To achieve a serious reduction in fault-clearing time, it is necessary to reduce any grading margins, thereby possibly allowing for a certain loss of selectivity.

4. Changing the Power System

By implementing changes in the supply system, the severity of the event can be reduced. Here again, the costs may become very high, especially for transmission and sub-transmission voltage levels. In industrial systems, such improvements more often outweigh the costs, especially when already included in the design stage. Some examples of mitigation methods especially directed toward voltage sags are:

- Install a generator near the sensitive load. The generators will keep up the voltage during a remote sag. The reduction in voltage drop is equal to the percentage contribution of the generator station to the fault current. In case a combined-heat-and-power station is planned, it is worth it to consider the position of its electrical connection to the supply.
- Split buses or substations in the supply path to limit the number of feeders in the exposed area.
- Install current-limiting coils at strategic places in the system to increase the ‘‘electrical distance’’ to the fault. The drawback of this method is that this may make the event worse for other customers.
- Feed the bus with the sensitive equipment from two or more substations. A voltage sag in one substation will be mitigated by the infeed from the other substations. The more independent the substations are, the more the mitigation effect. The best mitigation effect is by feeding from two different transmission substations. Introducing the second infeed increases the number of sags, but reduces their severity.

5. Installing Mitigation Equipment

The most commonly applied method of mitigation is the installation of additional equipment at the system-equipment interface. Also recent developments point toward a continued interest in this way of mitigation. The popularity of mitigation equipment is explained by it being the only place where the customer has control over the situation. Both changes in the supply as well as improvement of the equipment are often completely outside of the control of the end user. Some examples of mitigation equipment are:

a. Uninterruptable power supply (UPS):

This is the most commonly used device to protect low power equipment (computers, etc.) against voltage sags and interruptions. During the sag or interruption, the power supply is taken over by an internal battery. The battery can supply the load for, typically, between 15 and 30 minutes.

b. Static transfer switch:

A static transfer switch switches the load from the supply with the sag to another supply within a few milliseconds. This limits the duration of a sag to less than one halfcycle, assuming that a suitable alternate supply is available.

c. Dynamic voltage restorer (DVR):

This device uses modern power electronic components to insert a series voltage source between the supply and the load. The voltage source compensates for the voltage drop due to the sag. Some devices use internal energy storage to make up for the drop in active power supplied by the system. They can only mitigate sags up to a maximum duration.

Other devices take the same amount of active power from the supply by increasing the current.These can only mitigate sags down to a minimum magnitude. The same holds for devices boosting the voltage through a transformer with static tap changer.

d. Motor-generator sets:

Motor-generator sets are the classical solution for sag and interruption mitigation with large equipment. They are obviously not suitable for an office environment but the noise and the maintenance requirements are often no problem in an industrial environment.

Some manufacturers combine the motor-generator set with a backup generator; others combine it with power-electronic converters to obtain a longer ride-through time. Improvement of equipment voltage tolerance is probably the most effective solution against equipment trips due to voltage sags. But as a short-time solution, it is often not suitable. In many cases, a customer only finds out about equipment performance after it has been installed. Even most adjustable-speed drives have become off-the-shelf equipment where the customer has no influence on the specifications.

Only large industrial equipment is custom-made for a certain application, which enables the incorporation of voltage-tolerance requirements in the specification.

Apart from improving large equipment (drives, process-control computers), a thorough inspection of the immunity of all contactors, relays, sensors, etc. can significantly improve the voltage tolerance of the process.

6. Different Events and Mitigation Methods:

Different mitigation strategies are applied for different events. Sags due to short-circuit faults in the transmission and sub-transmission system are characterized by a short duration, typically up to 100 ms. These sags are very hard to mitigate at the source and improvements in the system are seldom feasible. The only way of mitigating these events is by improvement of the equipment or, where this turns out to be unfeasible, installing mitigation equipment. For low-power equipment, a UPS is a straightforward solution; for high-power equipment and for complete installations, several competing tools are emerging .The duration of sags due to distribution system faults depends on the type of protection used—ranging from less than a cycle for current-limiting fuses up to several seconds for over-current relays in underground or industrial distribution systems.[3]

2.2 Voltage Swell

Voltage Swell is the increase of the RMS voltage amplitude to a level of 110% - 180% of nominalvoltage. The duration is of ½ cycles to one minute. It is classified as a short duration voltage variation phenomena, which is one of the general categories of problems mentioned in the second post of the power quality basics series of this site. Voltage swell is basically the opposite of Voltage sag or dip. [4]

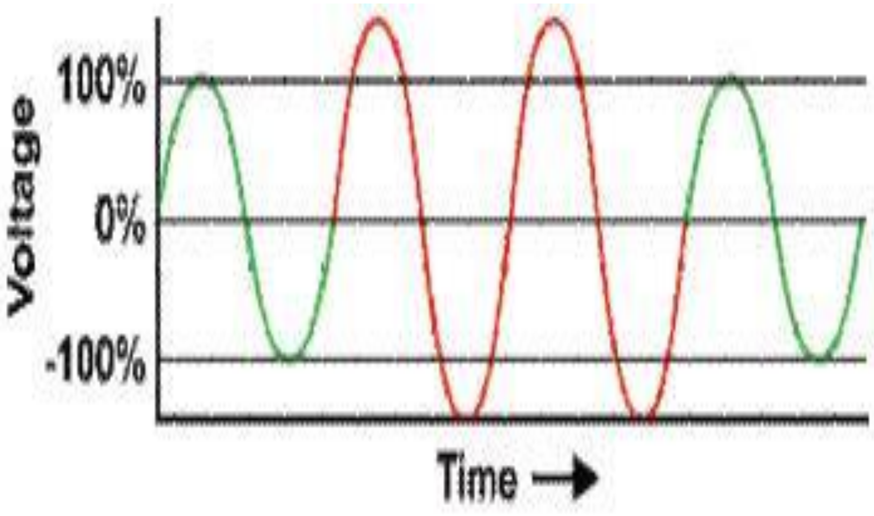

Figure-2.2.1 : Voltage Swell [5]

2.2.1 Causes and Effects of Voltage Swells

Just like voltage sags, voltage swells are usually associated with system fault conditions - but are much less common. This is particularly true for ungrounded or floating delta systems, where the sudden change in ground reference result in a voltage rise on the ungrounded phases. In the case of a voltage swell due to a single line-to-ground (SLG) fault on the system, the result is a temporary voltage rise on the un faulted phases, which last for the duration of the fault. This is shown in the figure below:

De-energization of a very large load is the cause of voltage swells. The abrupt interruption of current can generate a large voltage, per the formula: $V = L(di/dt)$, where L is the inductance of the line and di/dt is the change in current flow. Moreover, the energization of a large capacitor bank can also cause a voltage swell, though it more often causes an oscillatory transient. [6]

It may cause breakdown of components on the power supplies of the equipment, though the effect may be a gradual, accumulative effect. It can cause control problems and hardware failure in the equipment, due to overheating that could eventually result to shut down. Also, electronics and other sensitive equipment are prone to damage due to voltage swell. [7]

2.3 Harmonic Distortion

Waveforms in a non-sinusoidal wave having frequencies other than fundamental frequency are called harmonics. Harmonic component of current of order *n* can be represented as-

$$i_n = I_n \sin 2\pi nft \qquad n = 1, 2, 3, \ldots, \text{etc}$$

When the voltage or current wave shape is not sinusoidal, it is considered as distorted. Harmonic distortion implies that there are higher frequencies than standard frequency that define the power flow. These higher frequencies can disrupt, degrade and damage the equipment. Harmonic distortions mainly occur due to non-linear loads in electric power and distribution system. In non -linear devices, current is not proportional to applied voltage. Arc lighting, fluorescent lamps, electronic devices including convertors are other major sources of harmonic distortion in electric power distribution system .For uniform linearly increasing or decreasing load patterns of radial distribution feeder, permissible voltage distortion 3% nominal voltage and voltage harmonic magnitude 3% are considered to be tolerable. The total voltage distortion for distribution feeder having bus voltage below 69kV must not exceed 5.0%. Voltage distortion (Vh) caused to harmonic current is computed as follows:

$$Vh = \frac{R\ jwL}{(1-w^2\ LC+\ jwRC)} Ih$$

Where,

$W=2\pi(hf1)$

$h=2,3,4,5$………

f1=Fundamental frequency of power system.

2.3.1 Sources of Harmonics

- Loads that produce harmonics can be grouped into three main categories
    - arcing loads.
    - semiconductor converter loads.
    - loads with magnetic saturation of iron cores.

Arcing loads

- Electric arc furnaces, florescent lamps, electric welder.
- Produce harmonics across a wide range of frequencies.

Semiconductor loads

- Adjustable-speed motor drives, HVDC converter equipments, semiconductor based power supplies, phase controllers, reactors.
- Produce harmonic patterns with relatively predictable amplitudes at known harmonics.

Saturated magnetic elements

- Overexcited transformers, rotating machines.
- Produce certain ‘‘characteristic’’ harmonics.
- All three load types produce harmonics that generally decrease with frequency.

2.3.2 Effects of Harmonics

- Harmonics Can create resonance in power system network.
- Damping property may change due to presence of harmonics.
- Adverse effects on performance of rotating machines, transformers and transmission networks.
- Accuracy and operating characteristics of measuring instruments and protective devices may change.
- Performance of reactive power compensation devices may change.
- Harmonics have some adverse effects on different consumer equipment.

2.3.3 Harmonic Mitigation

Due to harmonic signal many problems arise. Two categories of solutions are available for this :

(1) Reduce the harmonics at their point of origin (before they enter the system).

(2) Apply filtering to reduce undesirable harmonics. There are many methods for reducing.

In most cases, reducing or eliminating harmonics at their origin is effective only in the design or expansion stage of a new facility. For existing facilities, harmonic filters often provide the least-cost solution. Harmonic filters can be subdivided into two types: active and passive. Active filters are only now becoming commercially viable products for high-power applications and operate as follows system to supply the power frequency current for the load. For high power applications or for applications where power factor correction capacitors already exist, it is typically more cost effective to use passive filtering. Passive filtering is based on the series resonance principle and can be easily implemented. Figure-2 shows a typical three-phase harmonic filter (many other designs are also used) that is commonly used to filter 5th or 7th harmonics. [8]

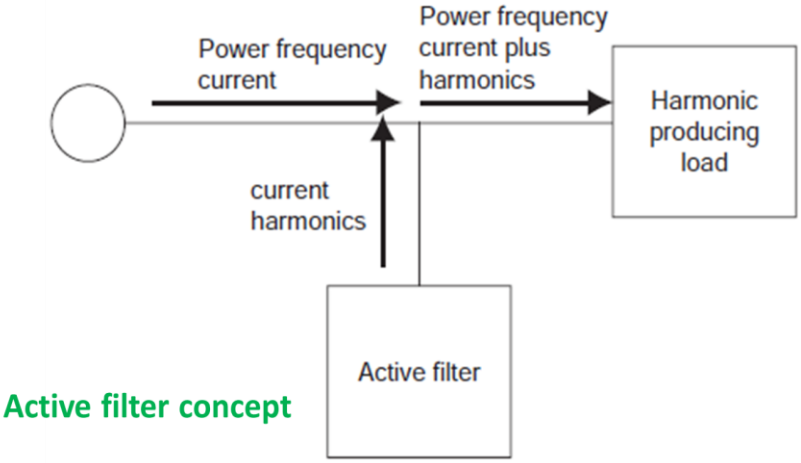

Figure-2.3.3 : Active Filter [9]

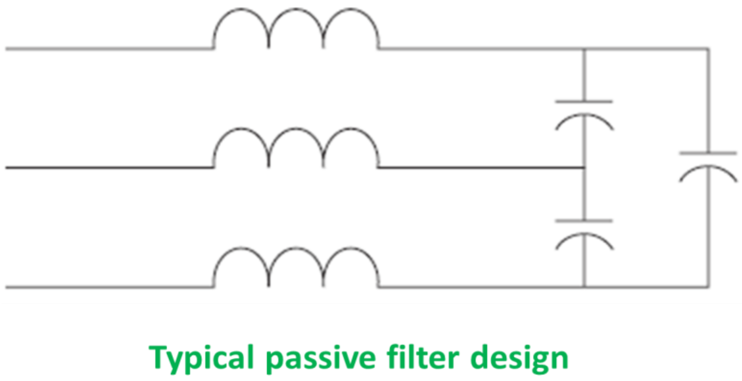

Figure-2.3.4 : Passive Filter [9]

Passive filtering cannot always make use of existing capacitor banks. In filter applications, the capacitors will typically be exposed continuously to voltages greater than their ratings (which were determined based on their original application). 600 V capacitors, for example, may be required for 480 V filter applications. Even with the potential cost of new capacitors, passive filtering still appears to offer the most cost effective solution to the harmonic problem at this time. In conclusion, power system harmonics have been carefully considered for many years and have received a significant increase in research and development activity as a direct result of the proliferation of high-power semiconductors. Fortunately, harmonic measurement equipment is readily available, and the underlying theory used to evaluate harmonics analytically (with computer assistance) is well understood. Limits for harmonic voltages and currents have been suggested by multiple standards making bodies, but care must be used because the suggested limits are not necessarily equivalent. Regardless of which limit numbers are appropriate for a given application, multiple options are available to help meet the levels required. As with all power quality problems, however, accurate study on the “front-end’’ usually will reveal possible problems in the design stage, and a lower-cost solution can be implemented before problems arise. The material presented here is not intended to be all-inclusive. The suggested reading provides further documents, including both IEEE and IEC standards, recommended practices, and technical papers and reports that provide the knowledge base required to apply the standards properly.

2.3.4 Harmonic Standard

- Different standards → IEEE 519, ANSI
- Harmonic standards mainly include following issues:
  1. Description and characterization of phenomenon .
  2. Major sources of harmonic problems.
  3. Impact on other equipment and on the power system.
  4. Indices and statistical analysis to provide a quantitative assessment and its significance .
  5. Measurement techniques and guidelines.
  6. Emission limits of quality degradation for different types and classes of equipment.
  7. Immunity or tolerance level of different types of equipment.
  8. Testing methods and procedures for compliance with limits.
  9. Mitigation guidelines.

2.4 Flicker

Modulation of voltage wave form frequencies of less than 25 Hz is called flicker signal. It is detectable to human eye as a variation in light output from standard bulbs.

Many types of end-use equipment can create voltage flicker, and many types of solution methods are available. In many cases, however, solutions can be expensive. To electric utility engineers, voltage flicker is considered in terms of magnitude and rate of change of voltage fluctuations. Voltage flicker is a problem that has existed in the power industry for many years.

Flicker can be divided in to two types, the cyclic flicker and the non-cyclic flicker. Cyclic flicker is created by periodic voltage fluctuation in the system whereas the non cyclic flicker is the result of occasional voltage fluctuation in the distribution system. Usually, the flicker signals are specified as percentage of the normal working voltage.

$$\%\text{ voltage modulation} = \frac{\text{Vmax}-\text{Vmin}}{\text{V0}} *100$$

Where,
V max =Maximum value of modulating signal.
V min =Minimum value of modulating signal.
V =Average value of normal operating voltage.

Flicker is the percent of total change in voltage with respect to average voltage over a certain period of time. The intensity of flicker can be determined by the frequency contents. Typical frequency range is from 0.5 to 30Hz, with observable magnitudes starting at less than 1.0 percent. According to IEEE standard 519TM-1992, flicker is considered objectionable when it either causes a modulation of the light level of lamps sufficient to be irritating to humans, or causes equipment miss-operation. Flicker level evaluation can be divided in to two types, short term evaluation of flicker severity and long term evaluation of flicker severity .

2.4.1 Causes of Flicker

Large electric loads like Electric furnaces, wielding plants, induction machines, etc are the main sources of flicker in electric power distribution system. A heavy electric load causes considerable variations in current over a short period of time, resulting in flicker. Sudden increase in load increases the current in the distribution line which, in turn, increases the voltage drop across the line. As a result the bus voltage reduces abruptly. This change in magnitude of voltage and frequency causes reasonable amount of flicker. Large industrial load located at the end of a weak distribution network can also be the source of flicker.

2.4.2 Mitigation Techniques

There are many options available to alleviate flicker problem. The application of Static capacitors, power electronic- based switching devices and enhancement in the system capacity are few out of them. Flicker effect can also be minimized by modifying the design of motors and using advance solid state technologies. The application of series reactors with heavy load minimizes flicker to considerable extent. Static VAR compensators can be used to eliminate the flicker and correct the power factor. Static VAR compensators are also very effective in controlling the voltage fluctuations at rapidly varying loads. Electronic-based thyristor switched capacitors are used to supply the reactive power to power system in a very short period of time which can minimize the effect of rapid load variations. [10]

2.5 Transients

In the analysis of power system variations, the term transient has long been used to denote an event that is undesirable and momentary in nature. The notion of a damped oscillatory transient due to an RLC network is probably what most power engineers think of when they hear the word transient.

A transient is “that part of the change in a variable that disappears during transition from one steady state operating condition to another. Unfortunately, this definition could be used to describe just about anything unusual that happens on the power system.

Figure-2.5.1 : Ligthening causes Transient [11]

Surge voltage is synonymous with transient. A utility engineer may think of a surge as the transient resulting from a lightning stroke for which a surge arrester is used for protection. End users frequently use the word indiscriminately to describe anything unusual that might be observed on the power supply ranging from sags to swells to interruptions. Because there are many potential ambiguities with this word in the power quality field, we will generally avoid using it unless we have specifically defined what it refers to.

Broadly speaking, transients can be classified into two categories, impulsive and oscillatory. These terms reflect the wave shape of a current or voltage transient. We will describe these two categories in more detail.

2.5.1 Impulsive transient

An impulsive transient is a non–power frequency change in the steady-state condition of voltage, current, or both that is unidirectional in polarity (primarily either positive or negative) that occurs suddenly.

Impulsive transients are normally characterized by their rise and decay times, which can also be revealed by their spectral content. Because of the high frequencies involved, the shape of impulsive transients can be changed quickly by circuit components and may have significantly different characteristics when viewed from different parts of the power system. They are generally not conducted far from the source of where they enter the power system, although they may, in some cases, be conducted for quite some distance along utility lines. Impulsive transients can excite the natural frequency of power system circuits and produce oscillatory transients.

2.5.2 Oscillatory transient

An oscillatory transient is a non–power frequency change in the steady-state condition of voltage, current, or both, that occurs suddenly, includes both positive and negative polarity values. An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content (predominate frequency), duration, and magnitude. The spectral content subclasses are high, medium, and low frequency.

The frequency ranges for these classifications are chosen to coincide with common types of power system oscillatory transient phenomena.

A transient with a primary frequency component between 5 and 500 kHz with duration measured in the tens of microseconds or several cycles of the principal frequency is termed a medium-frequency transient. Back-to-back capacitor energization results in oscillatory transient currents in the tens of kilohertz. Cable switching results in oscillatory voltage transients in the same frequency range. Medium-frequency transients can also be the result of a system response to an impulsive transient.

A transient with a primary frequency component less than 5 kHz, and a duration from 0.3 to 50 ms, is considered a low-frequency transient. This category of phenomena is frequently encountered on utility sub-transmission and distribution systems and is caused by many types of events. The most frequent is capacitor bank energization, which typically results in an oscillatory voltage transient with a primary frequency between 300 and 900 Hz. The peak magnitude can approach 2.0 pu, but is typically 1.3 to 1.5 pu with a duration of between 0.5 and 3 cycles depending on the system damping

Principal frequencies less than 300 Hz along with oscillatory transients can also be found on the distribution system. These are generally associated with ferro-resonance and transformer energization (Fig. 2.2.5). Transients involving series capacitors could also fall into this category. They occur when the system responds by resonating with low-frequency components in the transformer inrush current (second and third harmonic) or when unusual conditions result in ferro-resonance.

We can categorize transients as well as other disturbances according to their mode. Basically, a transient in a three-phase system with a separate neutral conductor can be either common mode or normal mode, depending on whether it appears between line or neutral and ground, or between line and neutral. [12]

2.5.3 Effects of Transient Activity

a) Electronic Equipment:

Electronic equipment could lock up or produced garbled results. These types of disruptions may be difficult to diagnose because improper specification and installation of transient voltage surge suppression equipment can actually increase the incidents of failure as described above.

Electronic devices may operate at decreased efficiencies. Damage is not readily seen and can result in early failure of affected devices. Unusually high frequency of failures in electronic power supplies are the most common symptoms.Integrated circuits (sometimes called "electronic chips") may fail immediately or fail prematurely. Most of the time, the failure is attributed to "age of the equipment". Modern electronic devices provided clean, filtered power should outlast the mechanical devices they control.

b) Motors:

Higher temperature is needed to run a motor, when transient voltages are present. Transients can interrupt the normal timing of the motor and result in "micro-jogging". This type of disruption produces motor vibration , noise, and excessive heat. Motor winding insulation is degraded and eventually fails. Motors can become degraded by transient activity to the point that they produce transients continually which accelerates the failure of other equipment that is commonly connected in the facility's electrical distribution system. Transients produce hysteresis losses in motors that increase the amount of current necessary to operate the motor. Transients can cause early failures of electronic motor drives and controls.

c)Lighting:

Early failure of all types of lights is caused by transient activity. Fluorescent systems suffer early failure of ballasts, reduced operating efficiencies, and early bulb failures. One of the most common indicators of transient activity is the premature appearance of black "rings" at the ends of the tubes. Transients that are of sufficient magnitude will cause a sputtering of the anodes-when these sputters deposit on the insides of the tube, the result is the black "ends" commonly seen. Incandescent lights fail because of premature filament failures. The same hysteresis losses produced in motors are reproduced in transformers. The results of these losses include hotter operating temperatures, and increased current draws.

d) Electrical Distribution Equipment:

The facility's electrical distribution system is also affected by transient activity. Transient degrade the contacting surfaces of switches, disconnects and circuit breakers. Intense transient activity can produce "nuisance tripping" of breakers by heating the breaker and "fooling" it into reacting to a non-existent current demand. Electrical transformers are forced to operate inefficiently because of the hysteresis losses produced by transients and can run hotter than normal. [13]

2.6 Interruptions

Normally “interruption” is referred to short-duration interruption, while the latter is preceded by the word “sustained” to indicate a long-duration. Interruptions are measured and described by their duration since the voltage magnitude is always less than 10% of nominal.

It is one of the general categories of power quality problems mentioned in the second post of the power quality basics series of this site.

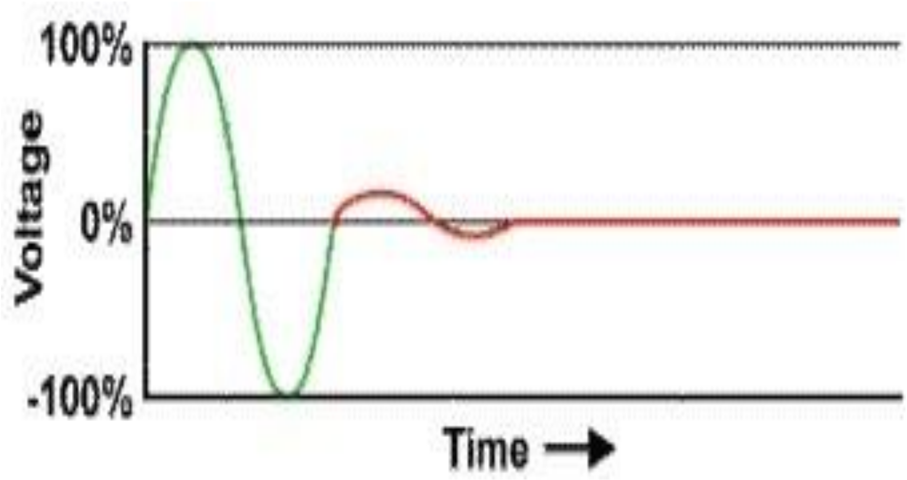

Figure-2.6.1 : Interruption [14]

Interruption is the most perceivable power quality problem. It generally affects the industrial sector, particularly the continuous process industry. In addition, the communication and information processing business is also significantly disturbed.

2.6.1 Short-duration Interruption

Interruptions are further subdivided into: Instantaneous (1/2 to 30 cycles), Momentary (30 cycles to 3 seconds) and Temporary (3 seconds to 1 minute).

Most of the interruptions result from reclosing circuit breakers or re-closers attempting to clear non-permanent faults, first opening and then reclosing after a short time delay. The devices are usually on the distribution system, but at some locations, momentary interruptions also occur for faults on the sub-transmission system. The extent of interruption will depend on the reclosing capability of the protective device. For example, instantaneous reclosing will limit the interruption caused by a temporary fault to less than 30 cycles. On the other hand, time delayed reclosing of the protective device may cause a momentary or temporary interruption.

Aside from system faults, interruptions can also be due to control malfunctions and equipment failures.[15]

2.6.2 Effects of Interruption

Consequences of short interruptions are similar to the effects of voltage sags. Interruptions may cause the following :

Stoppage of sensitive equipment (i.e. computers, PLC, ASD)
Unnecessary tripping of protective devices
Loss of data
Malfunction of data processing equipment.

2.6.3 Sustained Interruption

Sustained Interruption is defined as the decrease in the voltage supply level to zero for more than one minute. It is classified as a long duration voltage variation phenomena. Sustained interruptions are often permanent in nature and require manual intervention for restoration. In addition, they are specific power system phenomena and have no relation to the usage of the term outage. Outage does not refer to a specific phenomenon, but rather to the state of a system component that has failed to function. Furthermore, in the context of power quality monitoring, interruption has no relation to reliability or other continuity of service statistics.

Sustained interruptions are usually caused by permanent faults due to storms, trees striking lines or poles, utility or customer equipment failure in the power system or miss-coordination of protection devices. Consequently, such disturbances would result to a complete shutdown of the customer facility.

The effects of voltage sags are almost similar to interruptions. Yet, interruptions affect the majority of end-users, while voltage sags only impact the more sensitive end-users. In other words, if other customers on the same circuit are also affected, then, the probability is high that the disturbance is due to interruption and not voltage sag.

2.6.4 Interruption - Prevention and Protection

To prevent interruptions, the following works can be done :

1. Reduce incidents of system faults :
   - Includes arrester installation, feeder inspections, tree trimming and an animal guards

2. Limit the number of affected customers interrupted :
   - Improve selectivity through single-phase re closers and extra downstream re closers

3. Fast reclosing :
   - End-users may use Uninterruptible Power Supply (UPS) and other energy storage systems to protect equipment from interruptions. Back-up generator or Self-generation is necessary for sustained interruptions. Other solutions include the use of static transfer switch and dynamic voltage restorer with energy storage.[16]

2.6.5 Synopsis:

Magnitude:

Short Interruption - Less than 0.10 per unit

Sustained interruption – 0.0 pu

Duration:

Short Interruption - ½ cycle to 1 minute

Sustained interruption - More than 1 minute

Source: Utility or facility

Symptoms: Equipment Shutdown

Occurrence: Less than 2 interruptions/ year in the US

Protection: Uninterruptible Power Supply (UPS), Self-generation, Energy storage

2.7 Notching

A periodic voltage disturbance caused by electronic device, is called notching. The examples of notching are variable speed drives, light dimmers and arc welders under normal operation. This problem could be described as a transient impulse problem, but because the notches are periodic over each ½ cycle, notching is considered a waveform distortion problem. The usual consequences of notching are system halts, data loss, and data transmission problems. One solution to notching is to move the load away from the equipment causing the problem. UPSs and filter equipment are also viable solutions to notching if equipment cannot be relocated.[17]

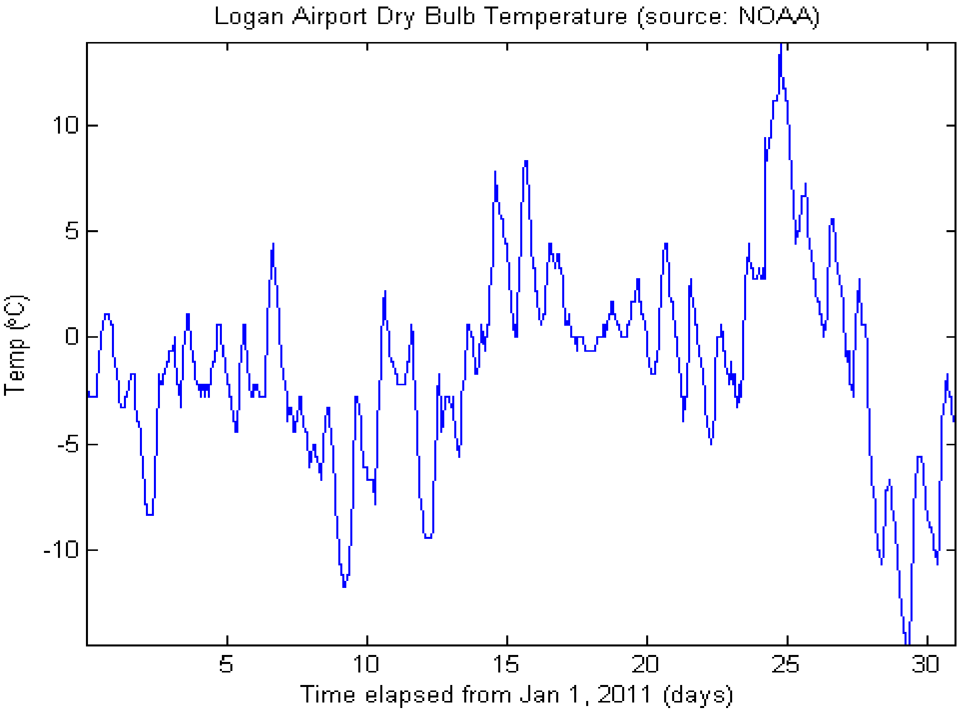

Figure-2.7.1 : Notch signal [18]

Chapter 3

Existing Methods

3.1 Support vector machines:

Unlike other learning machines, while classifying SVM shows a performance on training samples close to that on test samples by minimizing both structural and experimental risks. Structural risk is minimized by controlling the VC dimension of the approximation functions set. By means of this feature, SVM improves their ability of generalization and can learn with a small amount of data and can generally reach general optimum. SVM has a strong algorithmic substructure. SVM is used in classification which is known as support vector classification and in estimation which is known as support vector regression. SVM is also successful in data sets containing large size and little amount of data [19].

SVM is designed to carry data to a high-dimension space and constitute the plane defined in (1) on that space and carry out classification.

$$d(x) = w^T \phi(x) + b \qquad .... \quad (1)$$

Where $w \in \mathbf{R}^n$ and $b \in \mathbf{R}$ are the parameters that constitute the hyper-plane and $\phi(x)$ is the transformational function that is used to transform data from input space to high-dimension space [20].

SVM solves the primary optimization problem defined in (1). By minimizing the first term of (1) the complexity of the SVM is reduced, and by minimizing the second term the number of training errors is decreased.

$$\min_{w,b,\xi_i}\left\{\frac{1}{2}\|w\|^2+C\sum_{i=1}^{n}\xi_i\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$\text{subject to}\begin{cases} y_i(w'\phi(x_i)+b)\geq 1-\xi_i \\ \xi_i\geq 0, \quad i=1,\ldots,n \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where, ξ_i is slack variable and C is regularisation parameter. The minimization of the second term in (1) corresponds to the maximization of the distance between the hyper-plane and the closest points on the margins with the constraint that there are two margins on opposite sides of the hyper-plane. Since $\phi(x)$ which transforms data into a high-dimension space is generally not known, data are carried implicitly into high-dimension space by means of a kernel and without using this function. For this purpose, the primary optimisation problem is transformed into a secondary form by using the Lagrange method of multipliers.

$$L(\lambda)=-\frac{1}{2}\sum_{i,j=1}^{L}\lambda_i\lambda_j y y_j K(x^i,x^j)+\sum_{i=1}^{L}\lambda_i \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$\text{subject to: } \sum_{i=1}^{L}y_i\lambda_i=0, \quad 0\leq\lambda_i\leq\frac{C}{L}, \quad i=1,\ldots,L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where, λ_i represents Lagrange multipliers and $K(x_i, x_j)$ shows the inner product whose kernel is calculated with $K(x_i, x_j) = \varphi(x_i)^T \varphi(x_j)$. Thus, the final classification function can be represented as follows

$$d(x) = sign\left(\sum_i y_i \lambda_i K(x_i, x_j) + b \right) \qquad (6)$$

where support vectors represent xi values that correspond to Lagrange multipliers (li) . [21].

3.2 FkNN classifier:

To classify the PQ event classification problem, Machine learning techniques like support vector machines as well as various types of neural networks has been applied. This classifier called FkNN algorithm originally proposed by James M. Keller et al. [22]. It is a well-known classifier. The nearest neighbour algorithm is used to find a correlation between unknown samples and training samples. The training samples are denoted by 'n ' dimensional numeric attributes. The k-nearest neighbor (k-NN) algorithm searches the k training samples that are adjacent to the unknown sample given for the classification process. The closeness is measured in terms of Euclidean distances and can be calculated as-

$$D(X, Y) = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2} \qquad \text{--------} \quad (7)$$

The unknown sample is classified according to the most occurring class among the kNNs. It simply classifies the unknown sample to its nearest neighbor for a special case if k =1. The k values are chosen as odd numbers in the case of binary classification, so as to avoid the tied votes. The advantage of this algorithm over the neural-based classification schemes is that it does not generate the pre-defined model during training. But it will take more computation time if the number of training samples is much higher because each time it has to compute the distance vector. So it is better to use the k-NN algorithm when the number of training samples are less. The k-NN algorithm was modified using fuzzy logic in order to get better classification. The drawbacks in k-NN like precision and correctness during tie condition are overcome by FkNN algorithm. Moreover, this FkNN algorithm is getting idea from Bayes rule, which provides optimal solution to the classification problem, that is, it gives the highest assurance that the classification will be correct. The membership value of sample x in class i is given by

$$u_i(x) = \frac{\sum_{j=1}^{k} u_{ij}\left[1 \Big/ \left\| x - x_j \right\|^{2/(m-1)} \right]}{\sum_{j=1}^{k} \left[1 \Big/ \left\| x - x_j \right\|^{2/(m-1)} \right]} \quad \text{for all } i \quad \text{------} \quad (8)$$

Here, the denominator is a normalising factor. The value of scaling factor 'm' should be chosen in order to have better influence of distance samples. As the value of m approaches infinity, the result of the classification is same as that of the crisp k-NN algorithm result. Here in this paper, we used m = 2, so as to represents the Euclidean distance between the samples as used in [22].

3.3 Feature selection by GA:

To obtain optimal solution, GAs are stochastic search algorithm by which we can explore the search space. They operate on string structures called chromosomes, typically a concatenated list of binary digits representing the encoding of the control parameters of a given problem. It works with a population of individuals and the decisions taken are based on probabilistic rules. The PQ disturbance signal is decomposed up to fourth level using wavelet packet decomposition. The feature vector is formed by applying some of the statistical measures like energy, entropy, standard deviation and so on, the resulting WPT coefficients. The classification process using all 96 feature vectors may lead to less accuracy, since some of the features may have an overlapping nature between two classes, which leads to misclassification. In this work, we have tried to find the optimal feature vector by applying GA that leads to good classification accuracy. The GA encoding schema of chromosome is made up of a binary string, which represents the selection of one of the feature from the available six features in all 16 nodes.

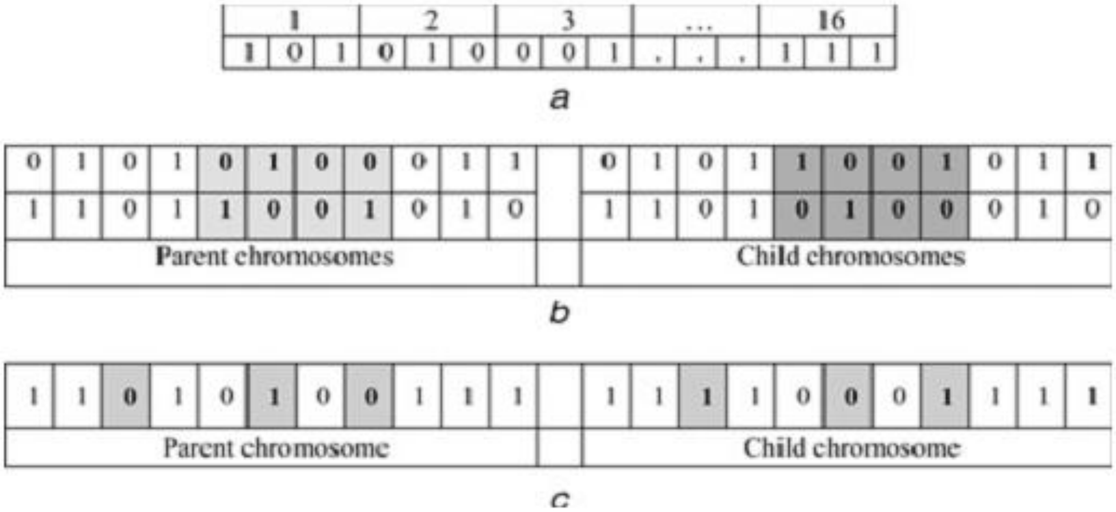

Figure-3.3.1 : Feature selection by GA

a) Chromosome structure for selecting the optimal features at fourth level.
b) Two point crossover operation.
c) Mutation operation.

This process, leads us to have 16 control parameters in the chromosome string with each parameter represented by 3 bits as shown in Fig. 1a. While decoding of these chromosome structures, we employed discrete type of decoding schema as mentioned in [23]. During the search process, the fitness of each chromosome is evaluated using FkNN classification accuracy so that our objective, become maximization of classification accuracy.

GA consists of three basic operations, namely reproduction, crossover and mutation. Reproduction comprises forming a new population, usually with the same total number of chromosomes, by selecting from members of the current population following a particular scheme. The higher the fitness, the more likely it is that the chromosome will be selected for the next generation. There are several strategies for selecting the individuals, example roulette-wheel selection, ranking methods and tournament selection. Here we use tournament selection. In tournament selection, the size of the participant in the tournament ‘n ’ is chosen first. The ‘n’ individuals are selected at random from the current population and the better solution among the ‘n ’is selected and inserted into the new population. Then another ‘n’ individual is selected randomly and the better one is inserted into the new population. This procedure is repeated until the mating pool is filled. The best solution in the current population may be inserted more than once. Similarly, the worst solution in the current population may have disappeared. In this manner, any solution in the current population may have zero, one, two or many copies in the new population.

The crossover and mutation operations are performed after reproduction. The crossover operator is mainly responsible for the global search property of the GA. There are many ways to do the crossover operation, like single point crossover, two point crossover and uniform crossover. In this work two point crossover is considered. Two parent strings are selected from the population at random. In the two-point crossover the crossover points are generated randomly between string lengths. The information between these two crossover points is exchanged and thus the two child strings are created. This is shown in Fig. 1b. Two child strings are then generated from the parent strings in the process of crossover by complementing the child strings at selected bit positions in order to exchange the already existing information.

To introduce new information in the mating pool, with small probability as shown in Fig.1c. mutation is then applied on some of the strings The bitwise mutation operator changes from 1 to 0 and vice versa. The mutation operation helps to keep the diversity in the population. In order to maintain better solutions during the crossover and mutation process, there is some probability called crossover probability and mutation probability. Usually, crossover probability is chosen between 0.6 and 0.9 and mutation probability is taken between 0.001 and 0.1. In order to maintain the best chromosomes elitism is performed. It always maintains the best chromosome called elites in the mating pool.

3.4 Wavelet Transform:

In order to obtain a low data size and distinctive feature vector for power system event signals, a Wavelet Transform signal processing method has been applied for all the event signals. WT is a very convenient signal processing method which has acquired a central position in pattern recognition systems in recent years. [24]

As like as Fourier transform, WT divides a signal into small pieces. However, while Fourier transform uses regular sine waves, assumed to be of infinite length, of various frequencies, WT uses the scaled and offset forms of limited duration, irregular and asymmetric signal pieces, which is called the mother wavelet. The short time and abrupt changes in the signals can be analysed better with an irregular wavelet rather than a smooth wavelet. Therefore WT provides better time – frequency localisation. By using WT, both time and frequency resolution of a given signal is accomplished. WT performs this task by using mother wavelet functions. The unique property of the mother wavelets is that for high-frequency components, the time intervals would be short whereas for low-frequency components, the time intervals would be longer. The WT can be carried out with either continuous WT (CWT) or discrete WT (DWT). The definition of CWT for a given signal x(t) with respect to a mother wavelet $\psi(t)$ is given by

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi\left(\frac{t-b}{a}\right)dt \qquad (9)$$

where, b is the translation factor and defines the decomposition filters at different frequency levels and a is the scaling parameter and scales decomposition filters for each level. CWT's working load and the data size it uses to realise a transform is considerably substantial. Since it requires an infinite number of inputs, CWT is not suitable for computer analysis. DWT in (10) is used for computer analysis.

$$DWT(m,n) = \frac{1}{\sqrt{a_0{}^m}} \sum_k x(k)\psi\left(\frac{n-kb_0a^m{}_0}{a^m{}_0}\right) \qquad (10)$$

Where, the parameters a and b in (9) are changed to be the functions of integers and $m\,,n$ and $x(k)$ is the sequence of samples from the continuous time function $x(t)$. In (10), a_0 and b_0 are the discrete scale and translation factor, respectively. An efficient way to realize this process was developed by Mallat in 1989 by using filters [25].

a classic method named Mallat algorithm is known as a two-channel lower band coder. This is a very convenient filter algorithm that can perform WT very fast. The approximation coefficients in this filter algorithm are high- scale and low-frequency components. Detailed coefficients, on the other hand, represent low-scale and high-frequency components. Thus, a signal is passed through complementary low-pass and high-pass filters and separated into its low- frequency and high-frequency components.

Into more than two lower frequency bands decomposition of a signal can be realized. This process is called multi-resolution analysis. Thus, the signal to be studied can be decomposed into its many components with less resolution. The WT multi-resolution analysis is based on decomposition of the original signal into different signals at various levels of resolution. At first, the original signal is passed through the two filters producing the detail (D1) and approximate coefficients (A1) for level 1. After the down-sampling by a factor of 2, the approximate coefficients (A1) are passed through the same filters to obtain the coefficients for level 2 again. After another down-sampling, the approximate coefficients (A2) are then filtered again to obtain the next level of coefficients. This filtering operation continues according to this way.

Chapter 4

Proposed Method

From many of the power quality disturbance classification methods, we have used the Discrete Cosine Transform (DCT), because of it’s fame as a powerful system for the linear processing technique of power signals corrupted by various disturbances. Here, from the distorted waveforms using this method important temporal information are extracted and it has been the better feature extraction method at power quality classification. It has s comparative high accurate results, when signal is in heavy noises. DCT can provide a significantly higher energy compaction compared to the FT. DCT has higher spectral resolution than the FT for the same window size.

4.1 Comparison in between the disturbance signals & normal signal:

In our experiment, at first we compared the wave-shapes of the disturbance signals with a normal sine wave as we use a.c. signal of sinusoidal waveform. We have seen the difference in between the sine wave and the disturbance signals. Here, the differences in between the disturbance signals and the normal signal are given below-

4.1.1 Difference in between sag & normal wave

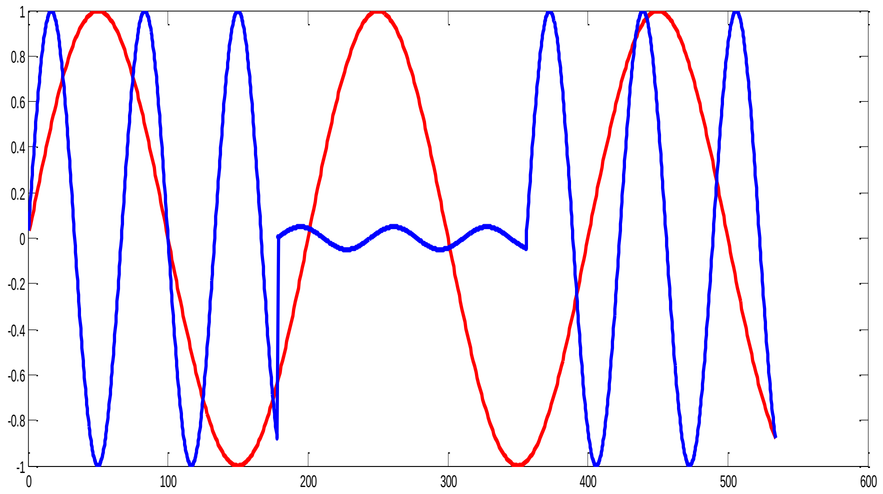

Figure-4.1.1 : voltage sag along with sine wave

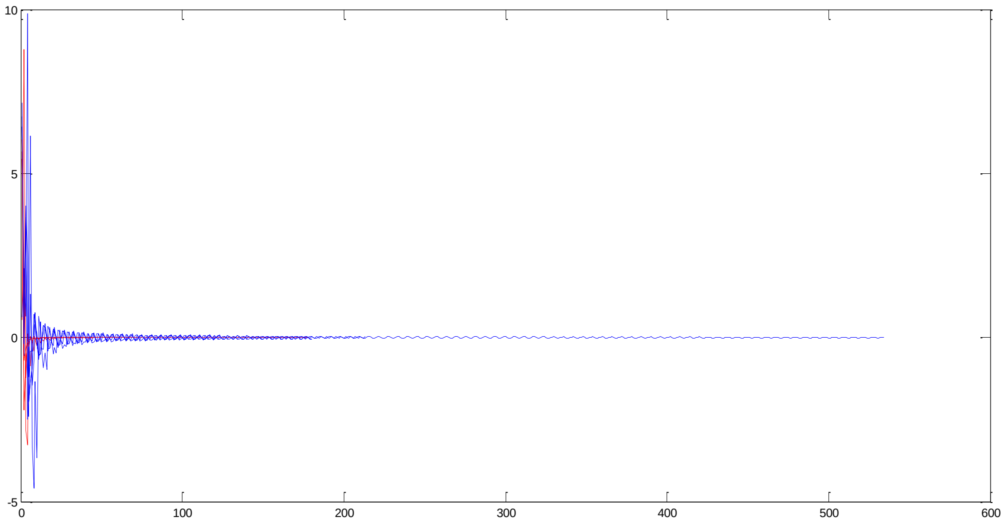

Figure-4.1.2 : DCT of voltage sag along with sine wave

From the figures, we see that the magnitude of sag wave is smaller than the supply voltage wave for 2.5 cycles. This happens for a short time period . But the effect of this wave is more disastrous.

4.1.2 Difference in between swell & Normal signal

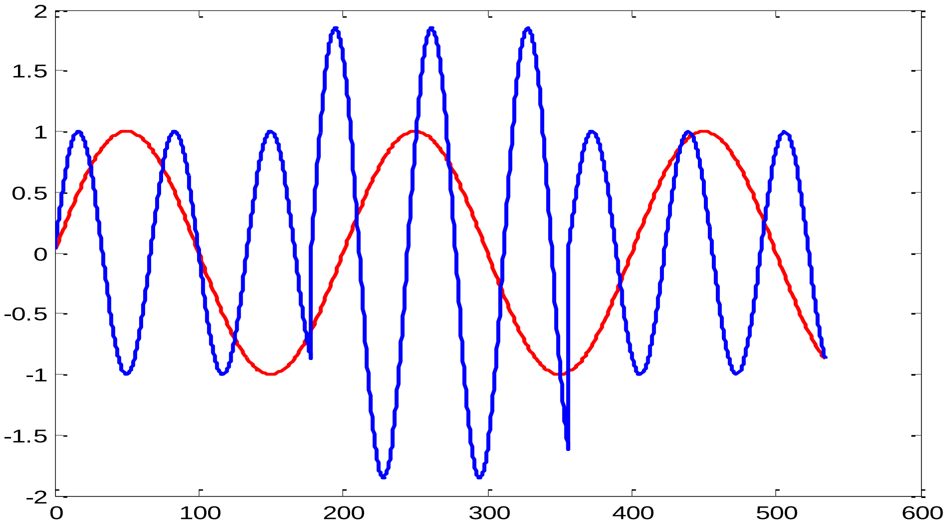

Figure-4.1.3 : voltage swell along with sine wave

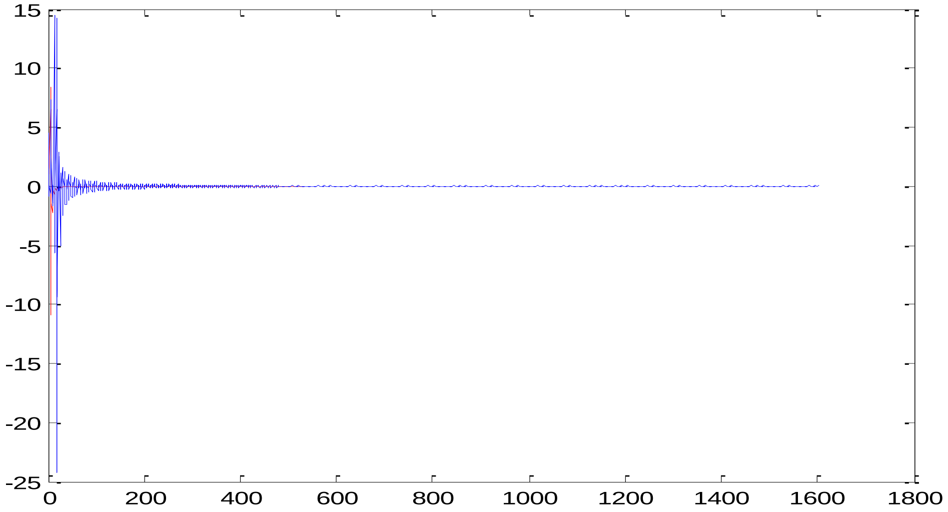

Figure-4.1.4 : DCT of swell along with sine wave

From the figure above, we see the voltage swell curve with normal sine wave. We see that the magnitude of swell wave is larger than the supply voltage. It, sometimes causes over-voltage.

4.1.3 Difference in between Harmonics & Normal signal

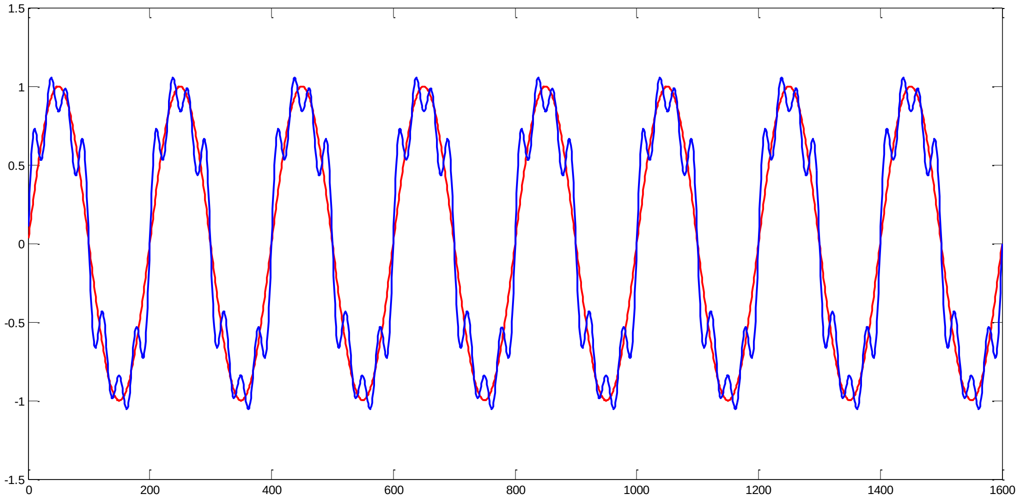

Figure-4.1.5 : Harmonic signal with sine wave

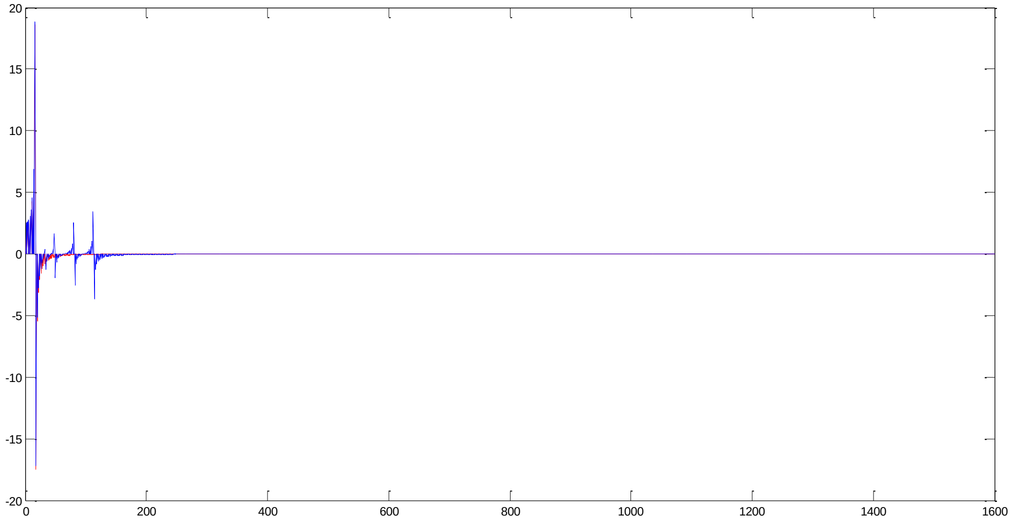

Figure-4.1.6 : DCT of Harmonic with sine wave

From the figure above, we see the curve of harmonic signal with normal sine wave. Harmonics are most dangerous types of disturbance.

4.1.4 Difference in between Flicker & Normal signal:

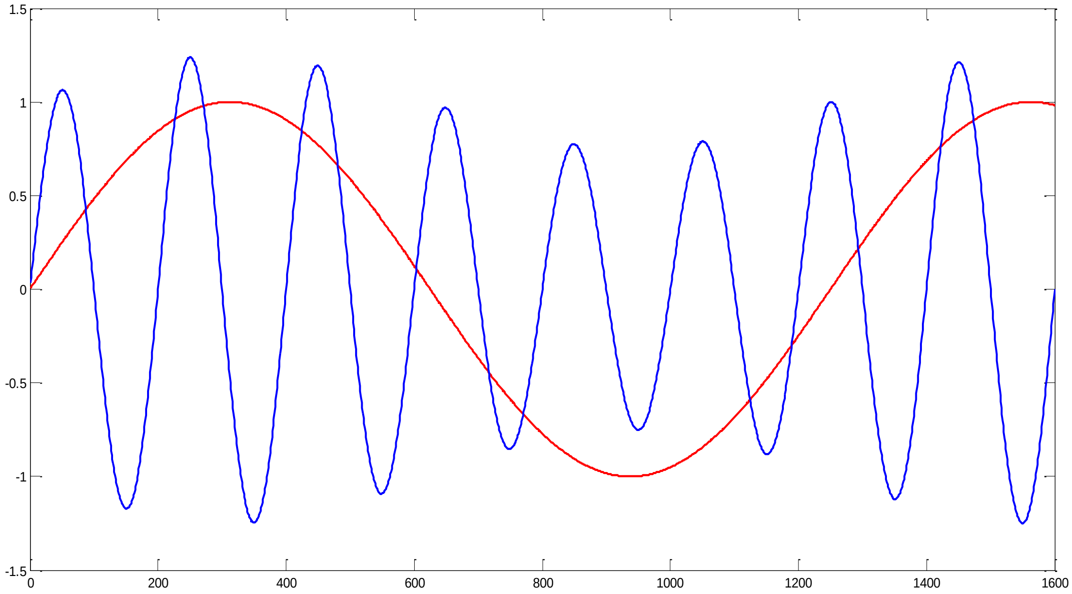

Figure-4.1.7 : Flicker signal along with sine wave

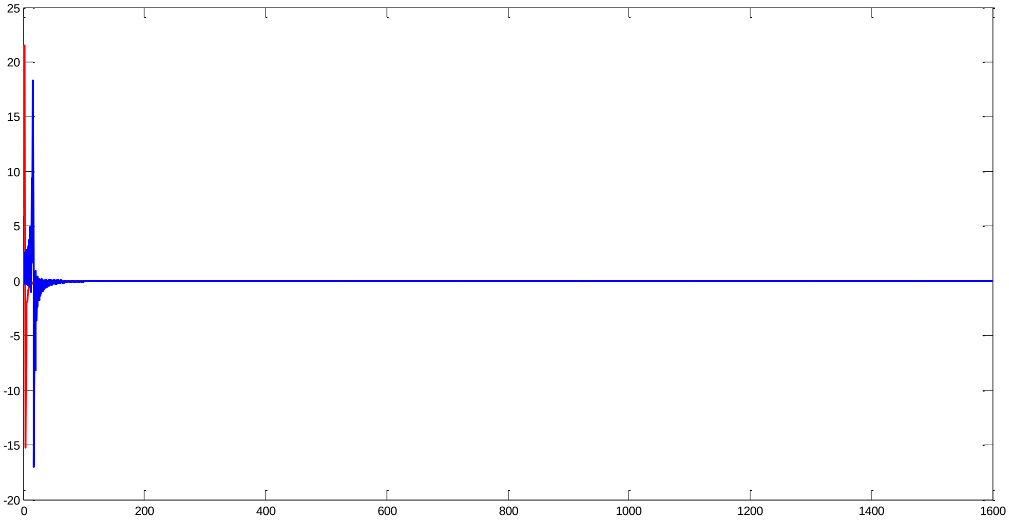

Figure-4.1.8 : DCT of Flicker signal with DCT of sine wave

Flicker signal is one type of modulated signal. It is also harmful for the equipments.

4.1.5 Difference in between Transient & Normal signal :

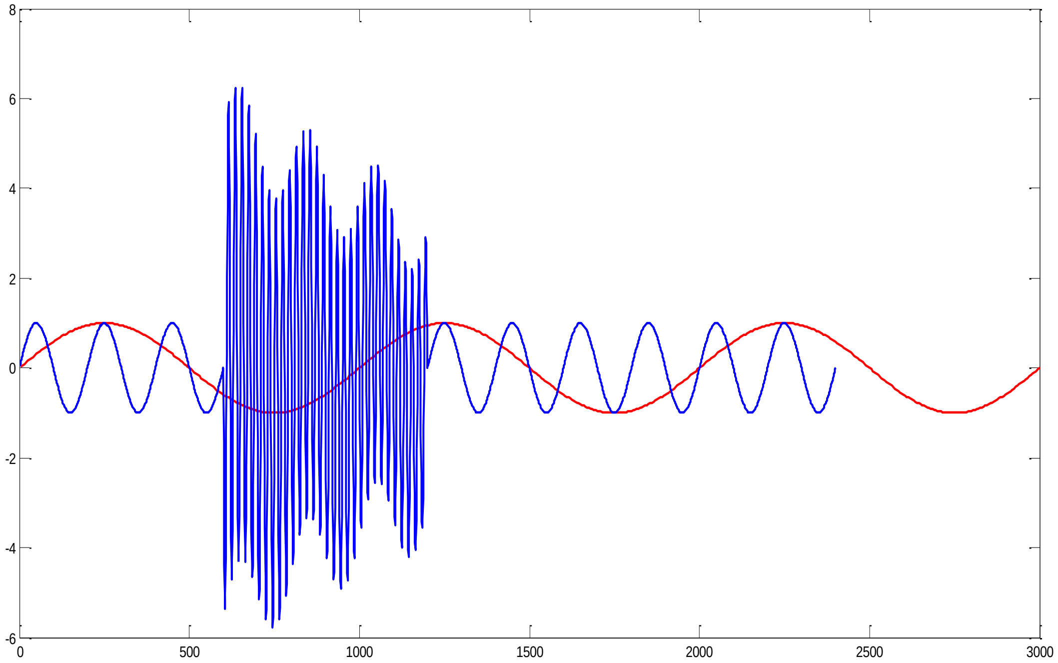

Figure-4.1.9 : Transient signal with sine wave.

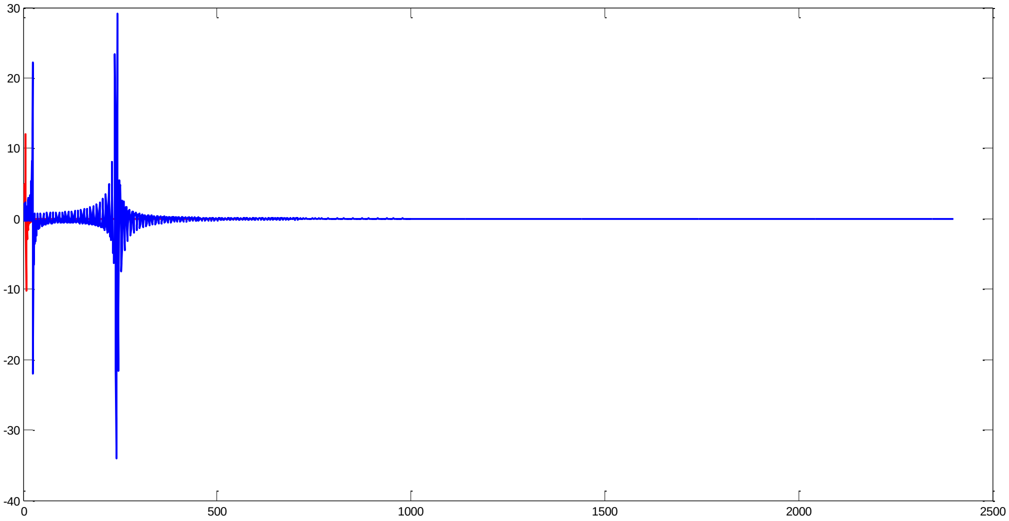

Figure-4.1.10 : DCT of Transient signal with sine wave

4.1.6 Difference in between Interruption & Normal signal

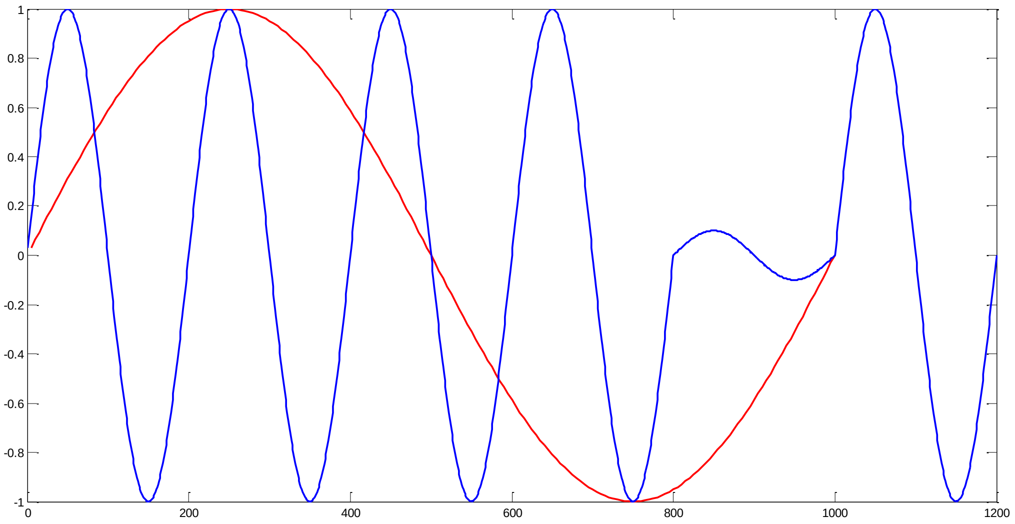

Figure-4.1.11: Interruption with sine wave

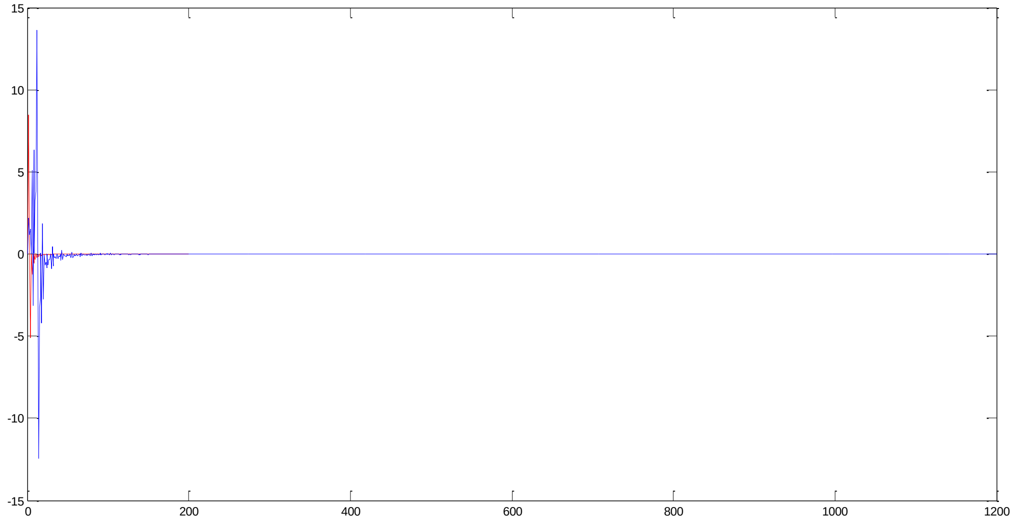

Figure-4.1.12 : DCT of interruption with DCT of sine wave

4.1.7 Difference in between Sag with harmonics & Normal signal

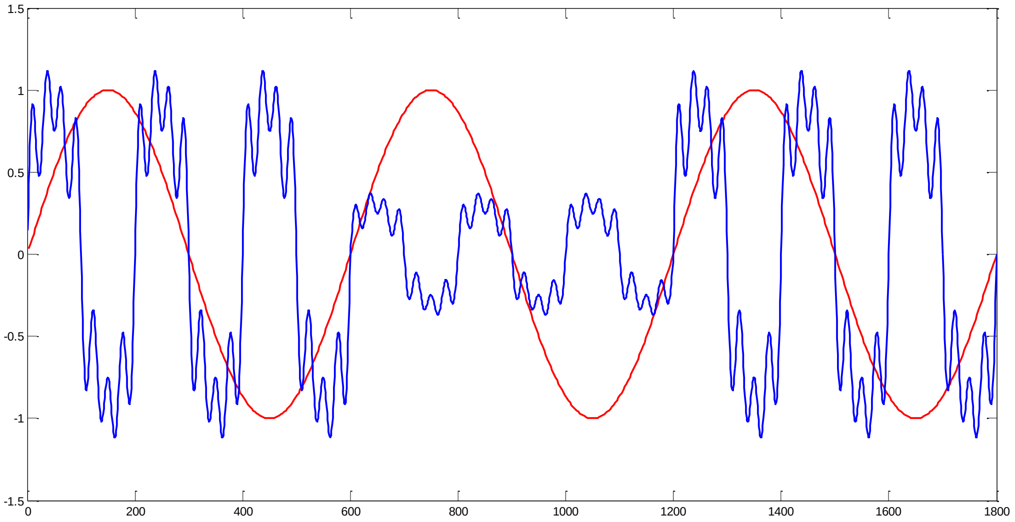

Figure-4.1.13 : Sag with harmonis along with sine wave

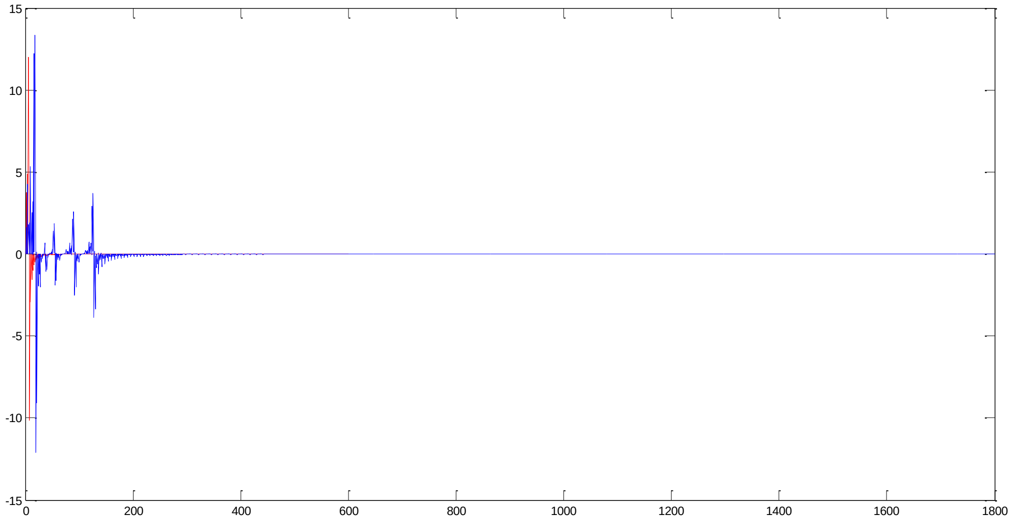

Figure-4.1.14 : DCT of sag with harmonics with DCT of sine wave

Sometimes, harmonics occur with voltage sag. This most dangerous disturbance that can occur.

4.1.8 Difference in between Swell with harmonics & Normal signal

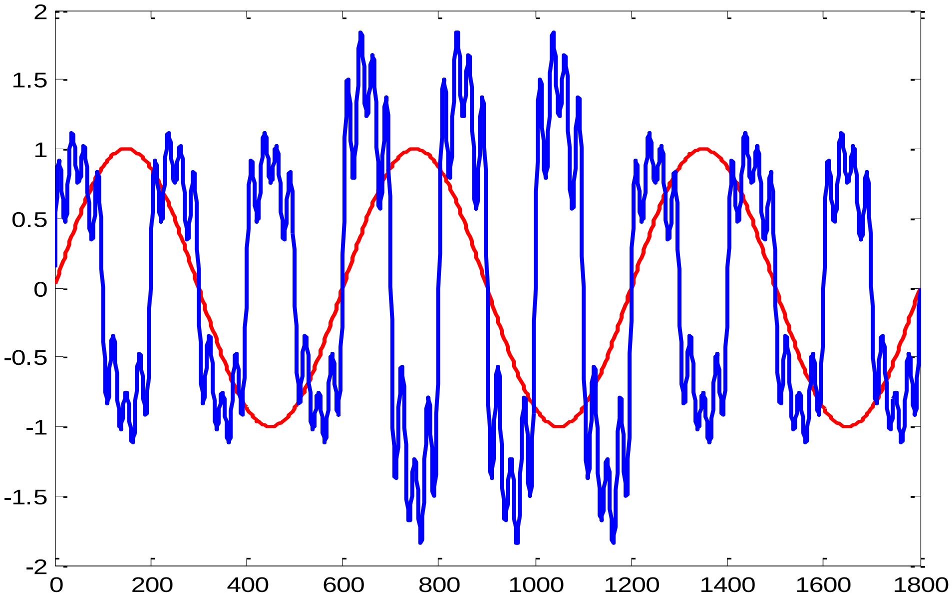

Figure-4.1.15 : Swell with harmonis along with sine wave

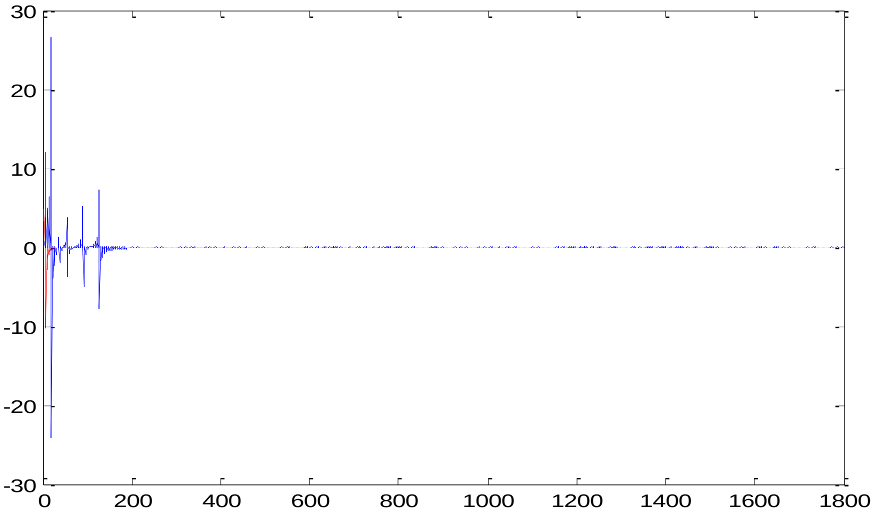

Figure-4.1.16 : DCT of swell with harmonics with DCT of sine wave

Harmonics can also occur with voltage swell.

4.2 Solution for extraction of disturbance signals

There are many types of feature extraction process like FkNN, Wavelet Transform (WT) and Genetic Algorithm (GA). But here we will propose the best solution for feature extraction. The best feature extraction process is DCT domain feature.

4.2.1 Proposed Feature Extraction by DCT-domain

The proposed PQ disturbance classification method has two steps : training and classification.. If the different types of disturbance signals can be represented in multiple sample signals and the classification stage compares an unknown disturbance signal against the set of trained signals, the training stage selects features taking into account a set of pre-classified training Power Quality disturbance signals DCT-domain by means of the selected features

In the proposed method, the disturbance signal classification task is defined as the distance between the feature vectors of the training signals and the test signal based on a similarity measure, which is given by the N-dimensional feature vector of the $j{-}th$ sample signal of the k-th PQ disturbance class is { γjk (1), γjk(2), ..., γjk(N)} and the feature vector of a test signal x is {vx (1), vx (2), ..., vx (N)}, the similarity between the test signal x and the k-th disturbance class is obtained as -

$$(Dk)\hat{}x = \sum_{j=1}^{q} \sum_{i=1}^{N} |\gamma jk(i) - vx(i)|^{2} \text{ - - - - - - - - - } (1)$$

Where, a certain class represents a PQ disturbance type with q number of sample signals. A total p number of classes are considered. Therefore, according to (1), the test signal x is classified as the $k - th$ class among the p number of classes . [26]

4.3 Advantages

In our proposed method effective spectral domain feature selection is done from discrete cosine transform instead of selecting from the time-domain, coefficients. The proposed feature extraction method has two advantages-

1. For the classification, our proposed method uses a very low dimensional feature space. This advantage saves us from large computational burden.
2. The classification accuracy will vary with respect to the variation of our selected signal. Now, if we check the classification accuracy, we will see that our proposed feature will offer the best classification accuracy.[27]

Chapter 5

Experimental Results

We have experimented with some of the power quality disturbance signals. Such as –

1. Voltage sag.
2. Voltage swell.
3. Harmonics.
4. Interruption.
5. Oscillatory transient.
6. Flicker.
7. Sag with harmonics.
8. Swell with harmonics.

5.1 Proposed Process

- We used DCT feature extraction method for classification of various disturbance signals. By DCT feature at first we identified the disturbance signal from a subjected signal. Here, we wanted to find out the selected main signal from the disturbance signals.
- From the curves of the mixed signal, we find out the disturbance signal.
- Then we used Discrete Cosine Transform of the corrupted mixed signal.

- There we got the DCT coefficients of the signals.
- DCT co-efficient has an important role in our feature extraction method.
- For higher value of DCT coefficients, the accuracy of finding our subjected signal is higher.
- Using the DCT coefficients, we have got a feature matrix of length 1602.
- We consider 100 signals for our feature extraction.so, the size of combined feature matrix becomes 100 × 1602 .
- After that we find out the mean of the feature matrix, whose length was 1×1602.
- Then after sorting the 1×1602 matrix, we used the first 50 values of DCT coefficient.
- Using these 50 values, we have got the position of our target signals' DCT values in the 1×1602 mean matrix.
- Then using the positions of the mean matrix, we have got the positions of DCT values in our preferred signals.
- From those of the DCT values of each signal, we have got the accurate subjected signal.

5.2 Result

After all these process, we have got our main subjected signal. And we see that, the accuracy of extraction of the disturbance signal is effectively high. We have extracted the noises as well as the disturbance signals from our subjected main signal. Then we have found out our expected signal more accurately.

5.3 Comparison of accuracy with other methods

Though our proposed DCT domain feature extraction method is in the initial stage, it has higher accuracy compared to the other feature extraction method. The following table will show the comparison of accuracy in between our proposed DCT domain feature and other recognized features.

TABLE-5.3.1 : Comparison of Classification Accuracies

Method	**Classification accuracy**
Proposed method	88.5%
Method [30]	98.51%
Method [31]	97.22%
Method [32]	95.00%
Method [33]	98.70%

From the table we see that, our proposed method has also a greater accuracy of extraction of the disturbance signal. So, it is clear that, our proposed method is more accurate for disturbance signal extraction.

Chapter 6

Conclusion

The discrete cosine transform (DCT) has been mainly used for image processing. It allows the use of a window length of a fundamental semi-period. Recursive filters have larger quantization errors when implemented in fixed-point devices. Moreover, FIR filters are based on constant multipliers, which are efficient and flexible. In this paper, the DCT was compared with various implementations. .

A novel algorithm for disturbance identification has been presented which is based on the DCT technique. It's main advantages are its simplicity, accuracy, frequency adaptation effectiveness, low calculation burden and fast transient. The proposed method was validated by both simulated and experimental results. The high performance and robustness of it has been demonstrated in steady state and under transients including frequency steps and load changes. This paper introduces DCT into detection of power quality disturbances. This method realizes characteristic detection of disturbances in strong signal noises through DCT coefficients and the difference sequence extracted from corresponding DCT sequence, which make use of linearity and orthogonal of DCT and noises robustness of DCT coefficients. The advantage of this method is that it can realize short time power quality disturbances detection in strong noises, and detection accuracy is higher than DB1 wavelet analysis, and it can get good accuracy of finding the original signal from most of the disturbances characteristic. Furthermore, as data size of DCT coefficients is small.

Our work in the proposed method of feature extraction is in the primary stage. But at this stage, we have got the feature extraction accuracy much better. We have further work to improve the accuracy into a high level. It will be a unique method of disturbance feature extraction.

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Appendix

Active filter

Any of a number of sophisticated power electronic devices for eliminating harmonic distortion.

Crest factor

A value reported by many power quality monitoring instruments representing the ratio of the crest value of the measured waveform to the rms value of the waveform.

Current distortion

Distortion (deviation from the normal sine wave) in the ac line current.

Fast tripping

Refers to the common utility protection relaying practice in which the circuit breaker or line recloser operates faster than a fuse can blow. Effective for clearing transient faults without a sustained interruption, but is somewhat controversial because industrial loads are subjected to a momentary or temporary interruption.

Fault

Generally refers to a short circuit on the power system.

Fault, transient

A short circuit on the power system usually induced by lightning, tree branches, or which can be cleared by momentarily interrupting the current.

Flicker

Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Ground

A connecting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of the earth.

Ground loop

A potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential.

Harmonic content

The quantity obtained by subtracting the fundamental component from an alternating quantity.

Harmonic distortion

Power system frequencies that are multiples of the fundamental frequency. The frequencies involved are created by nonlinear loads, or loads in which the current waveform does not conform to the waveform of the supply voltage.

Harmonic filter

On power systems, a device for filtering one or more harmonics from the power system. Most are passive combinations of inductance, capacitance, and resistance.

Harmonic resonance

A condition in which the power system is resonating near one of the major harmonics being harmonics being produced by nonlinear elements in the system, thus exacerbating the harmonic distortion.

Impulse transient

A sudden non power frequency change in the steady-state condition of voltage or current that is unidirectional in polarity.

Inter-harmonic (component)

A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is designed to operate.

Interruption, momentary

A type of short-duration variation. The complete loss of voltage on one or more phase conductors for a time period between 30 cycles and 3 seconds.

Interruption, sustained

A type of long-duration variation. The complete loss of voltage on one or more phase conductors for a time period between 3 seconds and l minute.

Linear load

An electrical load device, which, in steady-state operation, presents an essentially constant load impedance to the power source throughout the cycle of, applied voltage.

Noise

Unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur.

Non-linear load

Electrical load which draws current discontinuously or whose impedance varies throughout the cycle of the input ac voltage waveform.

Outage

A complete loss of power lasting from several milliseconds to several hours. Outages affect all electrical equipment, but some particularly sensitive equipment may be disrupted by outages as short as 15 seconds.

Passive filter

A combination of inductors, capacitors, and resistors designed to eliminate one or more harmonics. The most common variety is simply an inductor in series with a shunt capacitor, which short-circuits the major distorting harmonic component from the system.

Phase shift

The displacement in time of one voltage-waveform relative to another.

Power factor

The ratio of active power (watts) to apparent power (volt-amperes).

Spikes

It is also called impulses, switching surges or lightning surges, are high voltage transients of very short duration (typically a microsecond to a millisecond) with high amplitudes.

Total harmonic distortion

The ratio of the root mean squared (rms) of the harmonic content to the rms of the fundamental quantity, expressed as a percent of the fundamental.

Transient

Pertaining to or designating a phenomenon or a quantity, which varies between two consecutive steady states during a time interval that is short, compared to the time scale of interest. A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave from the first peak occurring in either polarity.

Under voltage or overvoltage

Abnormally high or low voltage conditions lasting for more than a few seconds. These conditions are caused by circuit overloads, poor voltage regulation, and intentional reduction in voltage by the utility.

Voltage sags and swells

Momentary (generally less than two seconds) deviations from the standard voltage levels for which electronic devices are equipped.

Voltage unbalance

A condition in which the three phase voltages differ in amplitude or are displaced from their normal 120 degree phase relationship or both.

Waveform distortion

A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.