Power Quality Improvement by BFO-Fuzz Controlled DVR

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Abstract: Power quality is the one of the major concern in the present era. It has become important, with the introduction of power sensitive devices, whose performance is very sensitive to the quality of power supply.

Power quality distortion occurrence results in failure of end user equipment. Voltage sags and swells in the medium and low voltage distribution grid are considered to be the most frequent type of power quality problems based on recent power quality studies. Their impact on sensitive loads is severe. The impact ranges from load disruptions to substantial economic losses up to millions of dollars. Different solutions have been developed to protect sensitive loads against such disturbances but the DVR is considered to be the most efficient and effective solution.

Its appeal includes lower cost, smaller size and its dynamic response to the disturbance. This research described DVR principles and voltage restoration methods for balanced and/or unbalanced voltage sags and swells in a distribution system. Simulation results were presented to illustrate and understand the performances of DVR under voltage sags/swells conditions. The controlling of DVR is done by controlling the duty cycle of pulse width modulator (PWM). For this, in this thesis bacterial foraging optimization along with fuzzy logic is used.

Membership functions of fuzzy logic are optimized by bacterial foraging optimization which is a bio inspired optimization technique and based on the behavior of E. Coli bacteria. Reduction in total harmonic distortion (THD) is compared with PI controller and fuzzy controlled DVR and it has been found that firefly optimized fuzzy logic reduces THD up to a good value.

INTRODUCTION:

Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage. Power Quality has now become an issue of great interest for research and analysis in the area of power system and other areas where better power quality is concerned. With the increase in the use of sensitive equipment’s and non-linear loads in the domestic as well as industrial area, an enhanced awareness of power quality is developed amongst electricity consumers. A sinusoidal voltage waveform having constant magnitude and frequency represents the best form of electrical supply.

However presence of non-linear loads and non-zero impedance of the supply system may generate a large number of inequalities and disturbances in the system which ultimately leads to a poor power quality. These disturbances create situations in which the waveform of the supply voltage (voltage quality) or load current (current quality) deviate from the sinusoidal waveform for all three phases of a three-phase structure at rated frequency with amplitude corresponding to the rated Root Mean Square (RMS) value. A number of power quality disturbances may encountered in the system. The adequate range of power quality disturbances covers sudden, short duration variations viz. impulsive and oscillatory transients, voltage sags, short interruptions, as well as steady state deviations, such as harmonics and flicker.

Among various power quality problems, the voltage sag, usually results from the faults on parallel transmission feeders is attracting a big amount of attention of researchers from industry. If the power quality of a system is good then any loads connected to it will run efficiently and on the other hand if power quality of a system is bad then loads connected to it will fail or will have reduced lifetime. One can also differentiate, based on the
cause, between disturbances associated to the quality of the supply voltage and those interrelated to the quality of the current taken by the load. Though the impact of power quality disturbances presents less financial severity in case of residential areas but when we talk about industries, impact of these disturbances is very much severe.

Power quality problems have increasingly become a substantial concern over the last decade. Power quality problem is defined as any undesired thing or unwanted occurrence appears in the voltage, current and frequency deviations that ultimately leads to the failure or disoperation of the system or end user utility. Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as “the conception of powering and grounding sensitive electronic equipment in a manner suitable for the equipment.” All the power quality issues are closely related with power electronics in case of residential, domestic and industrial applications. There are large numbers of equipment’s that use power electronic devices and are concerned with power quality problems.

The category includes residential appliances like TVs, PCs etc. business and office equipment’s like printers, copiers etc. industrial equipment’s like programmable logic controllers (PLCs), rectifiers, inverters and so on. We may mention some more devices like a transformer, electric motor, a generator and any communication equipment. All electrical devices are prone to failure or breakdown when exposed to one or more power quality problems. All of these devices and others react undesirably to power quality issues, depending on the severity of problems.

There are some issues that are related with the detection of power quality problems. These issues are:-

1. Frequent blackouts
2. Sensitive equipment frequent dropouts
3. Lamp flicker
4. Overheated elements and equipment’s
5. Communications interference

However, we can say nearly everybody accepts that it is a very important aspect of power systems and electric machinery with direct impacts on efficiency, security and reliability. The term “power quality” stands different meaning to different sources. There are some other terms that are synonymous to the term “power quality” These terms include “supply reliability,” “service quality,” “voltage quality,” “current quality,” “quality of supply” and “quality of consumption.”

While a domestic customer with low power consumption gets a single-phase supply, both industrial and commercial consumers get three phase supplies not only because their consumption is high but also because many of them use three-phase motors. For example, the use of induction motor is very common amongst industrial customers who run pumps, compressors, rolling mills etc.

It is to be noted that the voltage levels quoted above are not standard and vary from one country to another. Let us consider for example the Indian power system in which the generation level varies between 11 kV to 25 kV. The domestic customers get supply at 415 V (line-to-line) or 240 V (line-to-neutral). The distribution side voltages are either 11 kV or 33 kV. In some places the distribution voltage is 22 kV or even 6.6 kV. The sub transmission voltages are either 66 kV or 110 kV or

Fig . A typical power system
132 kV and the transmission voltages are 220 kV or 400 kV. A new 800 kV line has also been installed recently. It can therefore be seen that there are various stages between the points of power generation to the stage when electric power is delivered to the end users. The correct operation of all components of a power system is absolutely critical for a reliable power delivery. There are many issues involved here such as the maintenance of power apparatus and system, the stability of the system operation, the operation of power distribution system, faults etc. Some of these problems are power transmission related - a subject matter that is not treated here, as this book deals exclusively with problems related to power distribution systems and their solutions.

**ELECTRIC POWER QUALITY:**

These days, quality too is very important to them. For example, a consumer that is connected to the same bus that supplies a large motor load may have to face a severe dip in his supply voltage every time the motor load is switched on. In some extreme cases, he may have to bear with blackouts. This may be quite unacceptable to most customers. There are also very sensitive loads such as hospitals (life support, operation theatre, and patient database system), processing plants (semiconductor, food, rayon and fabrics), air traffic control, financial institutions and numerous other data processing and service providers that require clean and uninterrupted power.

In several processes such as semiconductor manufacturing or food processing plants, a batch of product can be ruined by a voltage dip of very short duration. Such customers are very wary of such dips since each such interruption cost them a substantial amount of money. Even short dips are sufficient to cause contactors on motor drives to drop out. Stoppage in a portion of a process can destroy the conditions for quality control of the product and require restarting of production. Thus in this changed scenario in which the customers increasingly demand quality power, the term power quality (PQ) attains increased significance. Transmission lines are exposed to the forces of nature. Furthermore, each transmission line has its load ability limit that is often determined by either stability considerations or by thermal limits. Even though the power quality problem is a distribution side problem, transmission lines often have an impact on the quality of power supplied. It is however to be noted that while most problems associated with transmission systems arise due to the forces of nature or due to the interconnection of power systems, individual customers are responsible for a more substantial fraction of the problems of power distribution systems.

**IMPACTS OF POWER QUALITY PROBLEMS ON END USERS:**

The causes of power quality problems are generally complex and difficult to detect. Technically speaking, the ideal ac line supply by the utility system should be a pure sine wave of fundamental frequency (50/60 Hz). In addition, the peak of the voltage should be of rated value. Unfortunately the actual ac line supply that we receive everyday departs from the ideal specifications.

There are many ways in which the lack of quality power affects customers. Impulsive transients do not travel very far from their point of entry. However an impulsive transient can give rise to an oscillatory transient. The oscillatory transient can lead to transient overvoltage and consequent damage to the power line insulators. Impulsive transients are usually suppressed by surge arresters. Short duration voltage variations have varied effects on consumers. Voltage sags (also known as dips) can cause loss of production in automated processes since voltage sag can trip a motor or cause its controller to malfunction for semiconductor manufacturing industries such a loss can be substantial. Voltage sag can also force a computer system or data processing system to crash. To prevent such a crash, an uninterruptible power supply (UPS) is often used, which, in turn, may generate harmonics. The protective circuit of an adjustable speed drive (ASD) can trip the system during a voltage swell. Also voltage swells can put stress on computers and many home appliances, thereby shortening their lives. A temporary interruption lasting a few seconds can cause a loss of production, erasing of computer data etc. The cost of such an interruption during peak hours can be hundreds of thousands of dollars.

**USE OF POWER ELECTRONICS IN DISTRIBUTION SYSTEMS**

At distribution level, power electronic controllers, also called custom power devices, have been established to pick up the quality of power distribution in industrial plants, in retort to growing demand from industries reporting production stops due to voltage disturbances, like short interruptions and voltage dips. These power quality phenomena are generally caused by clearing short-circuit faults in the power system and in spite of their very short duration, can impact the operation of low-power electronic devices, motor contactors and drive systems, where the sensitivity of electronic equipment to voltage disturbances can cause the stoppage of the whole facility. To solve this
problem, different custom power devices have been proposed, many of which have at their heart a Voltage Source Converter (VSC) connected to the grid. One way to mitigate voltage dips is to install a VSC connected to the system in shunt. This device, also known under the name of distribution STATCOM or DSTATCOM, injects a controllable current in the grid.

Table 1.1 Lists Various Power Quality Problems, Their Characterization Methods Possible Causes.

<table>
<thead>
<tr>
<th>Broad Categories</th>
<th>Specific Categories</th>
<th>Method of Characterization</th>
<th>Typical Causes</th>
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<tbody>
<tr>
<td>Transients</td>
<td>Impulsive</td>
<td>Peak magnitude, rise time and duration</td>
<td>Lightning, strike, transformer, capacitor switching</td>
</tr>
<tr>
<td></td>
<td>Oscillatory</td>
<td>Peak magnitude, frequency components</td>
<td>Line or capacitor or load switching</td>
</tr>
<tr>
<td>Short duration voltage variation</td>
<td>Sag</td>
<td>Magnitude, duration</td>
<td>Ferro-resonant transformers, single line-to-ground faults</td>
</tr>
<tr>
<td></td>
<td>Swell</td>
<td>Magnitude, duration</td>
<td>Ferro-resonant transformers, single line-to-ground faults</td>
</tr>
<tr>
<td></td>
<td>Interruption</td>
<td>Duration</td>
<td>Temporary (self-clearing) faults</td>
</tr>
<tr>
<td>Long duration voltage variation</td>
<td>Under voltage</td>
<td>Magnitude, duration</td>
<td>Switching on loads, capacitor de-energization</td>
</tr>
<tr>
<td></td>
<td>Overvoltage</td>
<td>Magnitude, duration</td>
<td>Switching on loads, capacitor de-energization</td>
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<td></td>
<td>Sustained interruptions</td>
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<td>Voltage imbalance</td>
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<td>Symmetrical components</td>
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<tr>
<td></td>
<td>Notching</td>
<td>THD, Harmonic spectrum</td>
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</tr>
<tr>
<td></td>
<td>DC offset</td>
<td>Volts, Amp, Frequency current</td>
<td>Geo-magnetic, half wave rectification</td>
</tr>
</tbody>
</table>

The device named as Dynamic Voltage Restorer, which is connected in series with the line. The DVR is a Power Quality device which can protect sensitive loads against the disturbances i.e., voltage sags and swells related to remote system faults.

**IMPORTANCE OF POWER QUALITY**

Power quality as we all know has become an important aspect which is concerned with system performance. A power quality problem is defined as "an incidence manifested in voltage, current or frequency deviations, which results in failure or disoperation of end-use equipment". Commercial customers have become more exacting in their command for relative 'quality' of power they purchase, variations in flow or voltage can actually damage and disrupt sensitive electronics equipment like computers and microprocessors.

Poor power quality always imparts harmful effect on system under consideration. The main reasons or we can say main contributors to low voltage poor power quality are given below:-

1. Reactive power, as it puts unnecessary loads on system.
2. Harmonic pollution, as it puts extra stress on the networks and makes installations run less efficiently.
3. Load imbalance, specifically in office building applications because the unbalance loads may result in excessive voltage imbalance causing stress on other loads connected to the same network.
4. Long and fast voltage variations which ultimately leads to voltage flicker.

The entire above listed phenomenon potentially lead to inefficient running of installations, reduced equipment life and consequently high installation costs.

Customers and utilities have a shared responsibility in the mitigation of voltage variation. Mitigation of the effects on consumer devices from voltage variations can be achieved only if utilities work with manufacturers in the design of consumer products so that the products function during normal utility operation. Different types of power quality problems, customer load profiles and power quality improvement techniques are discussed in this.

POWER QUALITY PROBLEMS

Power quality is influenced among other factors by utility operations, customer load types and equipment designs. Distribution utilities and their customers, along with their engineering equipment manufacturers and vendors, generate, propagate and receive power quality problems. Electrical disturbances can develop from problems within the customer's facility, even though the supply voltage is constant. Achieving power quality demands a united effort between the utility and the customer.

1. Interruption
An interruption is defined as the complete loss of supply voltage or load current. It may be defined as a large decrease in the RMS voltage or a complete loss of voltage. Refer to Fig 3.1 and 3.2 for an illustration of an interruption. Within this definition there are three types of interruptions which are characterized by their duration. The momentary interruption is defined as the complete loss of supply voltage or load current having duration between 0.5 cycles and 3 seconds.

![Fig. 3.1 Very Short Interruptions.](image-url)

The temporary interruption is the complete loss lasting between 3 seconds and 1 minute and the long term interruption or outage is an interruption which has duration of more than 1 minute. The main cause of voltage interruption includes accidents like faults and component malfunctions e.g., a fuse or automatic breaker, which is utilized to isolate the source of the system fault. Common sources of interruptions include lightning, animals, trees, vehicle accidents and equipment failure.

2. Sags
Voltage sags (dips) are short-duration reductions in RMS voltage caused by short-duration increases of the current, typically at another location than where the voltage sag is measured. Voltage sag is also called a voltage dip. It may also be defined as a decrease in the RMS voltage below nominal voltage. The most common causes of over currents leading to voltage sags are motor starting and...
transformer energizing. Also the faults on electrical power system cause voltage dips.

Fig. 3.3 Voltage Sag or Dip.

Voltage sags have been mainly associated with short circuit incidences. Fault occurrences elsewhere can generate voltage sags affecting consumers differently according to their location in the electrical system. Starting large motors can also generate voltage sags, although usually not so severe.

3. Swells
A voltage swell is an increase in the RMS voltage above nominal voltage or sliding reference voltage. Swell may also be defined as an RMS increase in the AC Voltage, at the power frequency, for duration from a half a cycle to a few seconds. Voltage can rise above normal level for several cycles to seconds. The causes of voltage swell include switching off large loads, capacitor bank energizing and transfer of loads from one power source to another. Voltage swells can originate internally in building wiring or externally on power lines. Voltage swells are the least frequent of the power line problems representing only about 2 to 3% of all power problems occurring to industry studies.

Fig. 3.4 Voltage Swell.

Voltage swells will normally cause damage to lighting, motor and electronic loads and will also cause shutdown to equipment. With electronically controlled equipment, voltage above 6 to 10% above normal may result in damage.

Solutions to voltage swells for motor loads include motor phase protectors, electronically controlled devices that shutdown motors before damage occurs. For sensitive computer and electronic loads, solutions include Uninterruptible Power Supplies, Voltage Regulators, Power Conditioners, Energy Storage Devices and Static Switches.

4. Voltage Flicker
Voltage flicker is a phenomenon that is different from other power quality distortions because it deals with the effect of power quality on humans rather than on equipment’s. Flicker is a very specific problem related to human perception and incandescent light bulbs. Flicker may be termed as a fundamental frequency effect. It is not a general term for voltage variations. Humans can be very sensitive to light flicker that is caused by voltage fluctuations. Human perception of light flicker is almost always the limiting criteria for controlling small voltage fluctuations. The sensitivity is a function of the frequency of the fluctuations and it is also dependent on the voltage level of the lighting. Flicker may leads to headaches and eye fatigue in human.
5. Harmonics
A harmonic of a wave is a component frequency of the signal that is an integer multiple of the fundamental frequency. For example, if the fundamental frequency is f, the harmonics have frequencies 2f, 3f, 4f, … etc. When electronic power converters first became commonplace in the late 1970s, many utility engineers became quite concerned about the ability of the power system to accommodate the harmonic distortion. Many dire predictions were made about the fate of power systems if these devices were permitted to exist. To some, harmonic distortion is still the most significant power quality problem. It is not hard to understand how an engineer faced with a difficult harmonics problem can come to hold that opinion. Harmonics problems counter many of the conventional rules of power system design and operation that consider only the fundamental frequency.

6. Harmonic Distortion
It is generally a periodic distortion of sine wave. Harmonic distortion is caused by nonlinear devices in the power system. A nonlinear device is one in which the current is not proportional to the applied voltage. While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a different wave shape. This is the source of most harmonic distortion in a power system.

7. Harmonic Sources from Commercial Loads
Commercial facilities such as office complexes, department stores, hospitals and Internet data centers are dominated with high-efficiency fluorescent lighting with electronic ballasts, adjustable-speed drives for the heating, ventilation and air conditioning loads, elevator drives and sensitive electronic equipment supplied by single-phase switch-mode power supplies. Commercial loads are characterized by a large number of small harmonic-producing loads. Depending on the diversity of the different load types, these small harmonic currents may add in phase or cancel each other. The voltage distortion levels depend on both the circuit impedances and the overall harmonic current distortion.

8. Harmonic Sources from Industrial Loads
Modern industrial facilities are characterized by the widespread application of nonlinear loads. These loads can make up a significant portion of the total facility loads and inject harmonic currents into the power system, causing harmonic distortion in the voltage. This harmonic problem is compounded by the fact that these nonlinear loads have a relatively low power factor.

9. Transients
An electrical transient is a momentary excess of voltage and/or current in an electrical circuit which has been perturbed. Transients are small-duration events, and may be called as a short lived burst of energy in a system caused by a sudden change of state, typically lasting from a small number of thousandths of a second (milliseconds) to billions of a second (nanoseconds) and they are found on all types of electrical, information data and communications circuits. The source of transient energy may be an internal event or a nearby event.

SOURCES OF POWER QUALITY PROBLEMS

1. Power Electronic Devices
Power electronics started with the development of mercury arc rectifier. Power electronic devices viz. Rectifiers, Inverters, Choppers etc. are nonlinear loads that produce harmonic distortion and can be vulnerable to voltage sags if not sufficiently protected.

2. IT and Office Equipment
IT equipment power provisions consist of a switched mode power supply (SMPS) and are the reason of a significant increase in the level of 3rd, 5th and 7th harmonic voltage distortion in current years. Because the third harmonic is a ‘triplen’ harmonic it is of zero order phase sequence and therefore adds in the neutral of a balanced three-phase system. The increasing use of IT equipment has led to concern of the increased overloading of neutral conductors and also overheating of transformers.

3. Arcing Devices
Electric arc furnaces, arc welders and electric discharge lamps are all forms of electric arcing devices. These devices are highly non-linear loads. The results of arc furnaces are difficult to mitigate, balancing the phases with other furnaces will not always be effective as arc furnaces are operated in various modes, leading to phase imbalance. Arc welders normally cause transients in the local network due to the intermittent switching and therefore some electronic equipment may necessitate safeguard from the impulsive spikes generated.

4. Load Switching
The result of load switching on the voltage is normally encountered in the form of transient
activity. This kind of transient might occur as the effect of switching in a heavy single-phase load [10]. Other apparatus can be protected from these switching transients by electrically isolating them from the affecting apparatus.

5. Large Motor Starting

The energetic nature of induction machines means that they draw current depending on the mode of operation, during starting this current can be as high as six times the standard rated current. This increased loading on the local network has the effect of causing voltage sag, the magnitude of which is reliant on the system impedance.

6. Sensitive Equipment

Equipment manufacturers are planning and manufacturing ever more complicated equipment, much of which is increasingly vulnerable to variations in power quality. There are many concerns relating to the subject of equipment sensitivity and the effect of power quality occurrences on perceptive equipment.

POWER QUALITY ENHANCEMENT USING DVR

1. Power Quality Enhancement

Among the power quality problems like sag, swell, harmonic etc., voltage sag and harmonic are the most severe disturbances in the distribution system. To overcome these problems the concept of custom power devices is introduced lately. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. The first DVR was installed in North America in 1996, a 12.47 kV system located in Anderson, South Carolina. Since then DVRs have been applied to protect critical loads in utilities, semiconductor and food processing. Today the dynamic voltage restorer is one of the most effective power quality devices. DVR is a series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is generally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and swells compensation, DVR can also added other features like line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.

DVR can compensate voltage at both transmission and distribution side. During the normal operating condition (without sag condition), DVR operates in a low loss standby mode. During this condition the DVR is said to be in steady state. When a disturbance occurs (abnormal condition) and supply voltage deviates from nominal value, DVR supplies voltage for compensation of sag and is said to be in transient state.

At present, modern industrial devices are typically based on power electronic devices such as programmable logic controllers and adjustable speed drives. The electronic devices are very responsive to disturbances and become less tolerant to power quality problems such as voltage sags, swells and harmonics.

The basic principle of the DVR is to inject an appropriate voltage in series with the supply through injection transformer whenever any disturbance like voltage sag or voltage swell is encountered. DVRs are a class of custom power devices for providing consistent distribution power quality. They use a series of voltage boost technology using solid state switches for compensating voltage sags/swells.

The DVR applications are mostly for sensitive loads that may be considerably affected by fluctuations in system voltage. Overcome these problems from the concept of custom power devices, DVR is the most efficient and advantageous modern custom power device used. It is usually installed in a distribution system between the utility and the critical load feeder at the point of common coupling. DVR has been modeled with PI Controller and Fuzzy Logic Controllers to enhance the performance of the system. The main objective of the above model is to improve the power quality of the system during fault conditions and to compare two different control techniques namely Fuzzy Logic Control and PI control.

Basic Configuration of DVR

The common configuration of the DVR consists of the following necessary units.

- An Injection/ Booster transformer
- A Harmonic filter
- A Storage Device
- A Voltage Source Converter
- DC Charging Circuit
- A Control and Protection System

1. Injection/ Booster Transformer

The injection transformer used in a Dynamic Voltage Restorer plays an important role in the reliability and effectiveness of the scheme. The Injection / Booster transformer is a particularly designed transformer that attempts to limit the coupling of noise and transient energy from the primary side to the secondary side.
It is a special type of transformer that is connected between a network analyzer and a voltage regulator in order to inject a perturbing signal into the control loop and to record the response of the loop over a wide frequency range. Its major tasks are given below.

1. It connects the DVR to the distribution network using the HV-winding of the transformer and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage.

2. The Injection / Booster transformer serves the function of isolating the load from the system (VSC and control mechanism).

2. Voltage Source Converter

Voltage Source Converters have been used for the time for HVDC transmission in a real network. A Voltage Source Converter is a power electronic system consists of a storage device and switching equipment, which can produce a sinusoidal voltage at any necessary frequency, magnitude and phase angle. In the DVR application, the VSC is used to momentarily replace the supply voltage or to produce the part of the supply voltage which is missing. The purpose of storage devices is to supply the necessary energy to the VSC using a DC Link for the generation of injected voltages. The different kinds of energy storage devices are superconductive magnetic energy storage batteries and capacitance.

3. DC Charging Circuit

The dc charging circuit has two main tasks.

1. The first task is to charge the energy source after a sag compensation event.
2. The second task is to maintain DC Link voltage at the nominal DC Link voltage.

4. Equations related to DVR

The load impedance $Z_{th}$ depends on the fault level of the load bus. When the system voltage ($V_{th}$) drops, the DVR injects a series voltage $V_{DVR}$ through the injection transformer so that the desired load voltage magnitude $V_{L}$ can be maintained. The series injected voltage of the DVR can be written as
Fig. 3.9 Equivalent Circuit Diagram of DVR.

\[ V_{DVR} = V_L + Z_{TH} I_L - V_{TH} \]

Where

- \( V_L \): The desired load voltage magnitude
- \( Z_{TH} \): The load impedance.
- \( I_L \): The load current
- \( V_{TH} \): The system voltage during fault condition

The load current \( I_L \) is given by,

\[ I_L = \left[ \frac{P_L + j Q_L}{V_L} \right] \]

When \( V_L \) is considered as a reference equation can be rewritten as,

\[ V_{DVR} = V_L + Z_{TH} \alpha + Z_{TH} (\beta - \delta) - V_{TH} \delta \]

\( \alpha, \beta, \delta \) are angles of \( V_{DVR}, Z_{TH}, V_{TH} \) respectively and \( \theta \) is Load power angle. The complex power injection of the DVR can be written as,

\[ S_{DVR} = V_{DVR} I_L^* \]

It requires the injection of only reactive power and the DVR itself is capable of generating the reactive power.

**Proposed Architecture**

DVR is used to control injected voltage into transmission line to compensate faults whether sag or swell. For this purpose IGBT controlled by pulse width modulator is used. The pulse width of PWM can be controlled and for this purpose some controllers like PI, fuzzy logic and BFO optimized fuzzy logic, are used here. Fuzzy logic algorithm’s performance depends upon its membership functions and rule sets. When rules and membership functions are designed for a specific task then these are considered to be fixed. But due to change in system conditions steady state error changes. So to minimize steady state errors, membership function should be continuously changing with initial condition change. So position of membership functions is optimized. In our work this is done by bacterial foraging optimization (BFO). BFO is discussed later in this paper. Time consumed in iterations to minimize the steady state error can be set by iteration number and number of bacteria’s considered. Total number of positions in membership functions, decides searching space dimensions. In this work as shown in figure 4.1, 7 membership functions for each input and output are used. Positions of these are fixed initially. Two types of membership functions are used: trapezoidal and triangular. In error input, either one or two position vector of function coincides, this reduces the dimension of searching space to a great extent. Triangular function has three positions \([x_1, x_2, x_3]\), satisfying condition \(x_1<x_2<x_3\). As is seen in figure 4.1, the middle position of NM coincides with starting position of NS and similar other membership functions also have some common positions, reducing total of 4 positions to be optimized to minimize the steady state error for single input.

**Bacterial Foraging Optimization**

Bacteria Foraging Optimization Algorithm (BFOA), is a new comer to the family of nature-inspired optimization algorithms. For over the last five decades, optimization algorithms like Genetic
Algorithms (GAs), Evolutionary Programming (EP), Evolutionary Strategies (ES), which draw their inspiration from evolution and natural genetics, have been dominating the realm of optimization algorithms. Recently natural swarm inspired algorithms like Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) have found their way into this domain and proved their effectiveness. Application of group foraging strategy of a swarm of E.coli bacteria in multi-optimal function optimization is the key idea of the new algorithm. Bacteria search for nutrients in a manner to maximize energy obtained per unit time. Individual bacterium also communicates with others by sending signals.

Fig.4.2. Swim and tumble of a bacterium
Define fuzzy logic rule set

Define fuzzy logic rule set

Initialize BFO parameters like number of bacteria, searching space, elimination, dispersal steps etc.

Assign random position to each bacteria that position constitute the position of membership function of fuzzy logic

Call objective function

Output_{object}(t) <

Increment the position of bacteria

End

End

Sort the bacteria position in descending order

Read defined fuzzy logic

Assign bacteria positions to membership function which are not fixed

If for each member hip

Evaluate new ‘fis’ structure and pass the value to the main function

Decrease the position by a step size of 0.5

Yes

no

Yes

no
MATLAB Simulink Model Description

A model for simulation of DVR with PI Controller and Fuzzy Logic Controller is shown in fig 5.6. In this model a three phase star ground connected source of 50 Hz is connected to three phase transformer having winding connections star ground, delta and delta for winding 1, 2 and 3 respectively. Winding 2 terminals of transformer is connected to a three phase series RLC branch through a transmission line and winding 3 terminals are connected to another three phase RLC branch having inductance of 0.005H and resistance of 0.001 Ohms. Output of these RLC branches are directly connected to two different three phase transformers (2 windings). On the upper side transformer, a three phase fault having fault resistance 0.001 Ohms and ground resistance 0.001 Ohms has been put. And on the below side transformer a three phase fault having fault resistance 0.66 Ohms and ground resistance 0.001 Ohms has been put. Now a DVR system consisting of a 3 arm universal bridge (which actually implements a three phase power converter consisting of six power switches connected into the bridge configuration) having snubber resistance 1e5 Ohms and forward voltage [0 0] along with a unit delay and a discrete pulse width modulated generator having carrier frequency 1080 Hz is connected to the fuzzy logic controller. Scopes have been connected appropriately to check the performance of the system without DVR and after DVR’s action. A three phase breaker is also used to test the system in case of unbalance loading. Output of three phase breaker is directly connected to secondary windings of 3 linear two windings transformers having a nominal power of 250e6 VA and frequency of 50Hz each. Fuzzy logic controller is connected to a subtractor of constant 1 and then to a 3 phase sequence analyzer of fundamental frequency 50 Hz which outputs the magnitude and phase of positive, negative and zero sequence components. Output of T2 which is coupled with output of sequence analyzer is connected to three phase parallel RLC load and three voltage measurement blocks are connected to measure the instantaneous voltages. After introduction of DVR with Fuzzy Logic Controller, we see that fault condition is improved to normal condition and in the same manner output of DVR system connected with PI controller is also studied and introduction of PI controller connected with DVR has shown in the same model. Scope in the model shows the combine output of the whole system i.e. output without DVR, output with DVR connected with Fuzzy Logic Controller and output with DVR connected with PI controller. Further fuzzy logic is optimized by bacterial foraging optimization (BFO) and results will be compared also as above. The complete model is shown in figure 5.6 below. This model has been subdivided into DVR and transmission part. The internal structure of DVR block is shown in figure 5.7. For comparison of DVR controlling by different technologies is, all functions are included in the model and their selection is done by a switch. Selection of 1 runs the simulink model for only fuzzy logic, 2 for BFO fuzzy logic and 3 for only PI controller.
Figure Simulink model of complete model

1. Fuzzy Control
2. BFO - Fuzzy Control
3. PI Controlled Breaker

Note: 1. For Sag--- Breaker 1 is open and Breaker 2 is closed
2. For Swell--- Breaker 2 is open and Breaker 1 is closed

Discrete, Ts = 0.0001 s.

Breaker 1
Breaker 2

Voltage Swell
Voltage Swell1

Three-Phase Source

DVR

Line Feeder 1

Line Feeder 2

Control_Selection
Goto

BFO

Double click on this to run optimisation

In11-12-13-1
1-22-23-2

Scope

Out11-1-2
2-12-2

Scope

Scope

Scope

Scope

Scope

Scope

Scope

Scope

Scope
Figure DVR simulink model
Scope used at the output will always show the comparison of controlled value and uncontrolled output.

To measure the total harmonic distortion fast fourier transform is used. It measures the power spectrum of signal. For improvement in controlling of DVR THD(%) should be less than previous method used.

**Discussion of Results**

Results have been categorized into two categories. Since in above chapters it has been stated that sags and swells are two main problems, so, these problems are mitigated by proposed method separately and makes two categories also.

1. **Voltage Sag Mitigation**

In main simulink model as shown in figure 5.6 three phase faults are used along with two breakers. For introducing sag in the model breaker 2 should be closed and breaker 1 should be open. Timing for fault introduction can be controlled also. In our experiment it has been taken from 0.1-0.3 sec. Initially PI controller is selected for DVR controlling. Figure shows th result.

By just looking at above figure, it is visible that a perfect sag compensation is obtained by PI controller but if figure is zoomed then some distortions in the output are visible as shown in figure 5.9. this figure shown is zoomed in simulink window and direct taken from there.

So because of these distortions total harmonic distortions are measured by FFT analysis. For this, FFT analysis from 'powergui' block is used which is placed in model to set the environment for simpower toolbox in simulink. The THD calculated by that is shown in figure 5.10. The THD in this case is 1.46%.
Figure Distortions in the PI compensated waveform

Figure THD of uncompensated output
Figure Compensated output’s THD = 0.24%

Voltage Sag in the interval 0.1-0.3

Compensated Voltage Sag in the interval 0.1-0.3
Figure distortions in fuzzy logic compensated output

References


