FUZZY PI CONTROL BASED CUSTOM POWER DEVICES FOR POWER QUALITY IMPROVEMENT

Nikhil Kumar Chaudhary, PG scholar
Vignana Bharathi Institute of Technology

Abstract- During last decade power quality problems has become more complex at all level of power systems. Recently, the Power electronics controllers are gaining concern to provide the quality of power for both power suppliers and consumers. Various power filtering technology i.e. passive filters, active power filters, hybrid filters have been applied from time to time for giving the solution of power quality problems to users, but could not fully satisfy them. Nowadays, a new concept of custom power is used for consumer’s satisfaction. This paper presents a review on the performance of four series and parallel custom power devices (CPDs) including active voltage conditioner (AVC), active power conditioner (APC), dynamic voltage restorer (DVR), and distribution static synchronous compensator (D-STATCOM). The CPDs are controlled by using fuzzy PI hybrid control logic, simulated on the modified 16-bus radial distribution system using Matlab/Simulink software to investigate performance efficacy of each device under various power quality (PQ) disturbances including voltage sags, voltage interruptions, and harmonic distortions. The simulation results demonstrate that the effectiveness of each device to compensate different types of power quality disturbances toughly depends on the device’s arrangement and characteristics during PQ disturbances.

Index Terms-- Active voltage conditioner; active power conditioner; power quality; DVR; D-STATCOM; Fuzzy Control, PI Control, Fuzzy PI Hybrid Control, power quality disturbance.

I. INTRODUCTION

Power quality problems have become important issues for electricity consumers at all the levels of usage. The deregulation of electric power energy has boosted the public awareness toward power quality among the different categories of users. The subject power quality and its problems related to electric power network have been discussed in many publications. To provide an active & flexible solution for power quality problems, various efforts have been done from time to time. Among these power quality solutions, lossless passive filters consisting of L-C tuned components have been widely used to suppress harmonic. Passive filters are advantageous as their initial cost is low and are highly efficient. On the other hand, they do have various drawbacks like instability, fixed compensation, resonance with supply as well as loads and utility impedance. To overcome these limitations, active power filters have been used. Active power filter has various configurations: shunt, series and hybrid. Hybrid is the combination of series and shunt types. Shunt APF is used for compensating current based distortions while series APF compensates voltage based distortions. Hybrid APF is applied for filtering higher order harmonics. However, they have a problem, their rating is sometimes very close to load (up to load 80 %) in typical applications. Due to this reason, power quality level is not obtained. This causes power disturbances and customer dissatisfaction. To increase the reliability of the distribution system and face the power disturbance problems, advanced power electronic control devices have been launched over the last decades. The evolution of power electronic controller devices has given birth to the term, custom power.

Custom power is a strategy, which is intended principally to convene the requirements of industrial and commercial consumers. The concept of the custom power is in tools of application of power electronic controller devices into power distribution system to supply a quality of power, demanded by the sensitive users. These power electronic controller devices are also called custom power devices because through these only, the valuable power is supplied to the consumers. They have good performance at medium distribution levels and most are available as commercial products. For the generation of custom
power devices, VSI is generally used, due to self-supporting characteristic of dc bus voltage with a large dc capacitor. The custom power devices are mainly divided into two groups: network reconfiguring type and compensating type. The complete classification of custom power devices is shown in the figure.

Fig 1. Custom power devices

This paper presents a review on the performance of the most renowned CPDs including active voltage conditioner (AVC), active power conditioner (APC), dynamic voltage restorer (DVR), and distribution static synchronous compensator (D-STATCOM), under different PQ disturbances. Each device is modeled on the modified IEEE 16-bus radial distribution system using Matlab/Simulink software. Several PQ disturbances including voltage sag, momentary voltage interruption, and voltage and current harmonic distortions, are generated to investigate the advantages and limitations of CPDs.

II. POWER QUALITY PROBLEMS

Power quality (PQ) related issues are of most concern nowadays. The widespread use of electronic equipments, such as information technology equipment, power electronics such as adjustable speed drives (ASD), programmable logic controllers (PLC), energy-efficient lighting, led to a complete change of electric loads nature. These loads are simultaneously the major causers and the major victims of power quality problems. Due to their non-linearity, all these loads cause disturbances in the voltage waveform. Electrical supply is designed to operate under constant magnitude and frequency of sinusoidal voltage waveform. Any deviation from these predesigned magnitude and frequency can be interpreted as PQ problem. Power quality problems are usually due to inappropriate interactions between the utility grids and the consumer equipment, and these disturbances can result in serious technical and financial problems for the system components. For example, voltage sags down to 80% of nominal voltage with a few tens of millisecond duration can cause interruption in processing plants, resulting in hours of downtime and more turnover losses. The most regular and important PQ issues that require practical solutions are as follows:

A. Voltage interruption

A voltage interruption is a large decrease in RMS voltage to less than a small percentile of the nominal voltage, or a complete loss of voltage. Voltage interruptions may come from accidents like faults and component malfunctions, or from scheduled downtime. Short voltage interruptions are typically the result of malfunction of a switching device or a deliberate or inadvertent operation of a fuse, circuit breaker, or recloser in response to faults and disturbances. Long interruptions are usually the result of scheduled downtime, where part of an electrical power system is disconnected in order to perform maintenance or repairs. A voltage interruption can be defined as the complete loss of a supply voltage for a specific time, which can be categorized into momentary interruption (duration, between 0.5 cycles and 3 s), temporary interruption (lasting between 3 s to 1 min), and long voltage interruption (duration, more than 1 min). These disturbances occur due to the normal or false operation of protection system and isolation of the power source from the loads which may cause severe financial losses due to the decrease in the operational life of the equipment such as transformers or equipment downtime in processing plants.

B. Voltage sag

Voltage sags are short-term reductions in the rms voltage to a value between 10% and 90% for duration of 1 min (0.5 cycle). These voltage reductions are caused by motor starting, transformer energizing, or faults. Voltage sags are characterized by magnitude and duration. Analyzing voltage sags is a complicated task which requires considering a large variety of random factors, such as type of short circuits, location of faults, and protective system performance. Voltage sags can be harmful to equipment with insufficient internal energy storage for riding through sags or sensitive semiconductor-based devices that may cause shut down, lock up, or garble data.

C. Harmonic distortions
Generally, a voltage waveform generated in the AC generators under constant frequency is pure sinusoidal. However, when a nonlinear load is fed by a pure sinusoidal voltage, the resulting current is not completely sinusoidal. The current drawn by the nonlinear load produces voltage distortion at the load terminal under the effect of system impedance. The distorted voltage contains harmonic which is defined as a perfectly sinusoidal component of a periodic waveform that has a frequency equal to an integer multiple of the fundamental frequency. Voltage and current harmonic distortions may increase losses in transformers and electromotors, overheating of equipment, and mis-operation of protective devices.

III. CUSTOM POWER DEVICES

A. Active voltage conditioner

The AVC is an IGBT-based series CPD which is used to protect sensitive loads from the most common PQ disturbances in the utility grid. AVC can effectively mitigate voltage sags down to 70% and also voltage imbalance for critical loads with a very fast response to meet most PQ standard requirements. The AVC structure is based on a direct AC/AC converter, to supply the required compensation power from the grid, an LC low-pass filter with damping resistor (R), an injection transformer, and a bypass switch as shown in Fig. 2.

Fig 2. Single-line diagram of AVC

This topology allows AVC to provide long-duration compensation using a DC-link. From the figure, the terminal voltage of the converter, \(v_C(t)\), can be defined as

\[
v_C(t) = \frac{t_1 \cdot v_{PCC}(t)}{T_2} + v_{Eff}(t)
\]

where,

\[
T_2 = t_1 + t_2
\]

\(t_1\) and \(t_2\) are the sampling period time intervals between 0 to \(T_s\), and \(v_{PCC}(t)\) is the measured voltage at the point of common coupling (PCC). To compensate voltage sags and swells, the nominal load voltage, \(v_L(t)\) can be expressed as

\[
v_L(t) = v_{PCC}(t) + v_{Eff}(t)
\]

Where,

\[
v_{Eff}(t) = \frac{v_C(t)}{N}
\]

\(N\) is the turn ratio of the injection transformer.

B. Dynamic voltage restorer

The DVR is a solid-state power electronic-based compensator which is connected in series to the utility’s primary distribution system. The DVR is able to inject a three-phase voltage with a controllable magnitude and phase to recover the load voltage at the point of common coupling. The main components of DVR are very similar to those in AVC, but the main difference is the presence of DC energy storage unit in DVR to provide the required power for correcting voltage disturbances as shown in Fig. 3.

Fig 3. Single-line diagram of DVR

C. Active power conditioner

The APC is known as a parallel CPD with voltage source inverter (VSI) topology which can be used in the utility’s distribution systems to regulate voltage variations and mitigate PQ disturbances. The main components of APC are a buffer capacitor, an AC/DC, and a DC/AC power converter, where the AC/DC unit provides the required DC compensation power for APC and the DC/AC unit injects the required current to compensate PQ disturbances as shown in Fig. 4. From the figure, the instantaneous loadcurrent, \(i_{Load}(t)\), and the PCC voltage, \(v_{PCC}(t)\), shown in Fig. 4 can be defined as

\[
i_{Load}(t) = I_1 \sin(\omega t + \phi_1) + \sum_{k=2}^{n} I_k \sin(k\omega t + \phi_k)
\]
Where, $\omega$, $h$, and $\phi$ are radial frequency, harmonic order, and phase angles of the load current and the PCC voltage, respectively.

The source current supplied by the PCC, $i_{pcc}(t)$, after compensation should be purely sinusoidal as

$$i_{pcc}'(t) = p_f(t)/V_{pcc}(t) = I_1 \cos(\omega t) \sin(\omega t)$$

Where, $p_f(t)$ is the fundamental components of power. If the APC compensates the total reactive and harmonic power, then the PCC current, $i_{pcc}'(t)$, can be in phase with the PCC voltage. Therefore, the injected compensation current, $i_{comp}(t)$, can be expressed as,

$$i_{comp}(t) = i_{Load}(t) - i_{pcc}'(t)$$

**D. Distribution static synchronous compensator**

D-STATCOM is a shunt-connected CPD which can be used to regulate voltage variations resulting from the motor starting condition or in-rush current and to mitigate current harmonic distortions [20, 21]. The structure of D-STATCOM is similar to that of the APC but without the AC/DC converter, as shown in Fig. 5. Thus, the required power for recovering PQ disturbances should be directly provided through CD energy storage.

**IV. FUZZY INFERENCE SYSTEM (FIS)**

Fuzzy inference systems (FIS) are one of the most famous applications of fuzzy logic and fuzzy set theory. They can be helpful to achieve classification tasks, offline process simulation and diagnosis, online decision support tools and process control. The strength of FIS relies on their two fold identity. On one hand, they are able to handle linguistic concepts and on the other hand, they are universal approximates able to perform nonlinear mappings between inputs and outputs. These two characteristics have been used to design two kinds of FIS. The first kind of FIS to appear, focused on the ability of fuzzy logic to model natural language. These FIS contain fuzzy rules built from expert knowledge and they are called fuzzy expert systems or fuzzy controllers, depending on their final use. Prior to FIS, expert knowledge was already used to build expert systems for simulation purposes.

These expert systems were based on classical Boolean logic and were not well suited to managing the progressiveness in the underlying process phenomena. Fuzzy logic allows grading rules to be introduced into expert knowledge based simulators. It also points out the limitations of human knowledge, particularly the difficulties in formalizing interactions in complex processes. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping, then provides a basis from which decisions can be made, or patterns discerned. The fuzzy inference system is shown in Fig 6.

**Error Calculation**

The error is calculated from the difference between supply voltage data and the reference voltage data. The error rate is the rate of change of error. The error and error rate are defined as

$$\text{Error} = V_{ref} - V_S$$

$$\text{Error rate} = \text{error} (n) - \text{error} (n-1)$$

Where,

$V_{ref}$ is voltage References.

$V_S$ is voltage Source.
Error is Error supply.
Error rate is Error rate supply.

**Fig 7. Fuzzy Logic Controller**
The aim of the control system is to maintain voltage magnitude at the point where a sensitive load is connected under system disturbances. Voltage sag is created at the load terminals via a three-phase fault. The above voltage problems are sensed separately and passed through the sequence analyzer. The control system of the general configuration typically consists of a voltage correction method which determines the reference voltage injected.

**Fig 8. Input and output variables of FIS with 7 membership functions**
FIS has two inputs and one output, as shown in fig 8, the inputs consisting of 7 membership functions and output fuzzy consists of 7 membership functions. Where, the input variables are in the range [-1 1], and the output variables are in the range [-1 1].

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**Fig 9. Rule Based Fuzzy Controller**
A process for constructing a FIS can be summarized as follows:
Fuzzification is an important concept in the fuzzy logic theory. Fuzzification is the process where the crisp quantities are converted to fuzzy. Thus Fuzzification process may involve assigning membership values for the given crisp quantities. This unit transforms the non-fuzzy (numeric) input variable measurements into the fuzzy set (linguistic) variable that is a clearly defined boundary, without a crisp (answer). In this simulation study, the error and error rate are defined by linguistic variables such as negative big (NB), negative medium (NM), zero (Z), positive medium (PM) and positive big (PB) characterized by membership functions given in Fig 9.

**Fuzzy PI hybrid control logic**

**PI control**
- Design a proportional controller to meet the transient response specifications, i.e. place the dominant closed-loop system poles at a desired location
- Add a PI controller with a zero
- Tune the gain of the system to move the closed-loop pole closer
- Check the time response and modify the design until it is acceptable.

**Fig 10. Fuzzy PI hybrid control**

**V. SIMULATION RESULTS**
To investigate the performance of CPDs on distribution systems under different PQ disturbances, a modified 16-bus test system is considered as shown in Fig. 11. Each CPD is individually planned to be placed at bus 11 to compensate PQ issues seen by loads L6 and L7. To investigate the performance of CPDs, voltage sag with depths of 0.6 p.u. followed by a voltage interruption are created. The measured rms value of voltage waveform at bus 11, shows that parallel devices cannot accurately mitigate voltage sag when the depth of sag increases. This restriction occurs given the limitation of the DC-link storage in D-STATCOM (capacitor rapid discharge) or inverter limitations in APC. In addition, parallel devices are advised to be disconnected from the protection system to prevent them from feeding upstream faults. In case of series compensators, the results show that these devices have better performance for PQ improvements.

DVR is able to recover accurately all the voltage sags and voltage interruptions that occurred. However, limited DC-link storage may limit DVR as to cost of device and duration of voltage sag compensation, although not as much as D-STATCOM. To illustrate the limitations of the devices better, the injected voltages and currents are shown in 10.
V. CONCLUSIONS

Fuzzy PI control logic based CPDs are implemented for harmonic and reactive power compensation of the non-linear load, voltage sag compensation. In this work the sag of the load voltage has been compensated by using the CPDs with minimum VA loading. And the total harmonic distortion of the source current has been reduced with the improved power factor. The CPDs including AVC, APC, DVR, and D-STATCOM are modeled on a 16-bus test system with nonlinear loads using Matlab/Simulink software, and a voltage interruption and voltage sag with a depth of 0.6 p.u., are created to test the performance of each device. The simulation results showed that the performance and effectiveness of each device depends on the device’s structure and characteristic during the duration of PQ disturbances.

REFERENCES


Nikhil Kumar Chaudhary, received the Bachelor's degree in Electrical & Electronics Engineering from Geethanjali College of Engineering & Technology, Hyderabad. He is pursuing his Master's Degree in Power Electronics & Electrical Drives from Vignana Bharathi Institute of Technology, Hyderabad, expected to receive in 2016. His current research interests include custom power devices, power quality improvement.

M. Sharanya, M.Tech., (Ph.D), received the Bachelor’s degrees in Electrical and Electronics Engineering and Master’s degree in Power electronics and electrical drives from Jawaharlal Nehru Technological University, Hyderabad. She is pursuing the...
Ph.D. degree at Jawaharlal Nehru technological university, Hyderabad. She is currently working as Associate Professor in Electrical and Electronics Engineering Department in Vignana Bharathi institute of technology, since 2007. She has a teaching experience of 14 years. Her areas of interest are power electronics, electrical drives, power quality and electrical machines.