METHODS FOR INCREASING THE QUALITY AND RELIABILITY OF POWER SYSTEM USING FACTS DEVICES

BY

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Author Biography

I am Dr. Hidaia Mahmoud Mohamed Alassouli. I completed my PhD degree in Electrical Engineering from Czech Technical University by February 2003, and my M. Sc. degree in n Electrical Engineering from Bahrain University by June 1995. I covered most subjects in Electrical Engineering, Computer Engineering and Telecommunications Engineering during my study. My nationality is Palestinian from gaza strip.

I was working also as a computer networking administrator in government computer center at Palestine Ministry of Telecommunication and Information Technology. I worked also as electrical engineer trainee in Bahrain Ministry of Power & Water, Bahrain. I worked also as electrical and telecommunication engineer trainee in Bahrain Telecommunication Company, Batelco.

I had considerable undergraduate teaching experience in several types of courses in many universities. I handled teaching the most important subjects in Electrical and Telecommunication and Computer Engineering.

I could publish 5 papers in a top-tier journals, and 25 papers in conference proceedings besides a lot of published books in Lulu.com book store.

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Preface

FACTS are one aspect of power electronics revolution that is taking place in all areas of electrical energy. A variable of powerful semiconductor devices not only offer the advantage of high speed and reliability of switching but, more importantly, the opportunity offered by a variety of innovative circuit concepts based on these power devices enhance the value of electric energy.

In generation area, the potential application of power electronics is largely in renewable generation. Photovoltaic and fuel cells requires conversion of dc to ac. Generation with variable speed is necessary for economic viability of wind and small hydro generators. Variable-speed wind generators and small hydro generators requires conversion of variable frequency ac to power system frequency. These applications of power electronics in renewable generation area require converter sizes in the range of few kilowatts to few megawatts.

In coming decades, electrical energy storage is expected to be widely used in power systems as capacitor, battery and superconducting magnet technologies move forward. Batteries are widely used already for emergency power supplies. These require ac/dc/ac converters in the range of a few kilowatts to a few tens of megawatts. On the other hand, variable speed hydro storage requires converters of up to a few hundred megawatts.

In transmission area, application of power electronics consists of High Voltage Direct Current (HVDC) power transmission and FACTS. HVDC is often an economical way to interconnect certain power systems, which are suited in different regions separated by long distances or those have different frequencies or incompatible frequency control.

HVDC involves conversion of ac to dc at one end and conversion of dc to ac at the other end.

What is most interesting for transmission planners is that FACTS opens up new opportunities for controlling power and enhancing the usable capacity of the lines. The possibility that current through a line can be controlled at reasonable cost enables a large potential of increasing the capacity of the existing lines with larger conductors, and use one of the FACTS controllers to enable corresponding power to flow through lines under normal and contingency conditions. These opportunities arise through the ability of FACTS controllers to control the interrelated parameters that govern the operation of transmission line including series impedance, shunt impedance, current, voltage, phase angle, and the damping of oscillations at various frequencies below the rated frequency.
In distribution area, an exciting opportunity called Custom Power. The custom power concept incorporates power electronics controllers and switching equipment, one or more of which can be used to provide a value-added service to the customers. In general, these custom service applications represent power electronics in the range of few tens of kilowatts to few ten of megawatts of conversion or switching equipment between the utility supply and customer.

On the end-user side, power electronics conversion and switching technology has been fast growing area. Complementing the Custom Power technology is the whole area of power conditioning technology used by customers, under the term Power Quality. Uninterruptible power supplies (UPS) and voltage regulators represent the major growth area in power electronics. In end use, the converter sizes range from a few watts to ten of megawatts.

The term active filter is a general one and is applied to a group of power electronic circuits incorporating power switching devices and passive energy storage circuit elements such as inductors and capacitors. The functions of these circuits vary depending on the applications. They are generally used for controlling current harmonics in supply networks at the low and medium voltage distribution level or for reactive power and/or voltage control at high voltage distribution level. These functions may be combined in a single circuit or in separate active filters.

Thesis Objective

The thesis will try to summarise the major power system problems and the important role of the FACTS devices to enhance the power system quality. Then, it will give a brief description for various FACTS and Active Filters controllers as mentioned on the existing publications.

Most of the control schemes introduced in the existing papers were designed either for eliminating current harmonics or eliminating voltage flickers or for load flow control. So, this work is devoted to find a proper optimal control schemes for a system with series or shunt or series and shunt converters that can provide all functions together.

Various optimal control schemes will be designed for systems with series, shunt and series-shunt converters with the objective to control the load flow through a lines and to eliminate current harmonics and voltage flickers with different strategies for tracking.

- **Chapter 1:** Gives a general description of most power system problems and the basic techniques used to improve the power system quality. It also gives idea about basic objectives from the FACTS devices.
- **Chapter 2:** Offers detailed description for the basic types of FACTS devices and active filters existing in power industry.
- **Chapter 3:** Describes various shunt controllers for control of the Static Compensator (STATCOM) and various series controllers for the control of the Static Synchronous Series Compensator (SSSC) and various

Unified Power Flow Controllers (UPFC) as covered in most existing papers.

- **Chapter 4:** Describes the major control schemes for the shunt active filter as covered by most existing papers.
- **Chapter 5:** Describes the major control schemes for the other types of active filters as covered by most existing papers.
- **Chapter 6:** Gives description for optimal control design.
- **Chapter 7:** Case studies to design different optimal control schemes for system with UPFC unit to control the power flow, eliminate voltage flicker and eliminate current harmonics. The case studies were repeated for system with only series or shunt converters.

Chapter 1: Basic Power System Quality Problems

The information given in this chapter are based on Ref. [1], Ref. [2] and Ref. [3].

1 Basic Power System Problems

1.1 Transient

An undesirable event that is undesirable and momentary in mature.

1.1.1 Impulsive Transient

Sudden non power frequency change in steady state conditions of voltage or current (i.e. lightening is impulsive transient).

1.1.2 Oscillatory Transient

Consists of voltage and currents whose instantaneous value changes polarity rapidly. It is defined by its spectral content, duration and magnitude. The spectral contents subclasses are high, medium and low frequency. The oscillatory transients with frequency greater than 500 kHz and duration measured in microseconds are high frequency oscillatory transients. The oscillatory transient with frequency 5-500 kHz and duration 10 microseconds are medium frequency oscillatory transients. Back to back eneregization of capacitor results in oscillatory transient currents in 10 kHz. Transient with frequency components less than 5 kHz and (0.3 to 0.5 ms) is low frequency transient. Oscillatory transients with principal frequencies less than 300 Hz can also be found in distribution system.

These are generally associated with ferroresonance and transformer energization.

1.1.3 Principe of Overvoltage Protection

The main sources of the transient over voltage protection are capacitor switching, magnification of capacitor switching transients and lightening.

The fundamental principles of overvoltage protection of load equipment are:

1. Limit the voltage across sensitive insulation.
2. Divert the surge current a way from the load.
3. Block the surge current from entering the load.
4. Bond ground references together at the equipment.
5. Reduce or prevent surge current from flowing between grounds.
6. Create a low pass filter using blocking or limiting principles.

The surge arresters and transient voltage surge supressors are widely used. Their main function is to limit the voltage that can appear between two points in the circuit.

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1.2 Long Duration Voltage Variation

1.2.1 Overvoltages

Increase in rms. ac voltage greater than 110% at the power frequency for longer than 1 min. It results from load switching (e.g. switching off large load or energising large capacitor). It results because the system is too week for voltage regulation or voltage control is inadequate.

1.2.2 Undervoltages

Decrease in voltage less than 90% at the power frequency for duration longer than 1 min. A load switching on or a capacitor bank switching off can cause an undervoltage until the voltage equipment on system can bring voltage back to within tolerances.

1.2.3 Sustained Interruption

When supply voltage has been zero for longer time than 1 min, the long duration voltage variation is considered as sustained interruption.

1.2.4 Protection against Long Duration Voltage Variations

The root cause of most voltage regulation problems is that there is too much impedance in the power system to properly supply the load. Therefore, the voltage drops too low under heavy load. Conversely, when the source voltage is boosted to overcome the impedance, there can be an overvoltage condition when the load drops too low. The corrective measures usually involve either compensation for the impedance or compensation for the voltage drops caused by the impedance.

The options for improving the voltage regulation are

1. Add voltage regulators, which boosts the apparent .
2. Add shunt capacitors to reduce the current and shift it to be more in phase with the voltage.
3. Add series capacitors to cancel the inductive impedance drop ()
4. Reconducor lines to change to a larger size to reduce the impedance .
5. Change the service transformer to larger size to reduce the impedance .
6. Add static var. compensators, which serve the same purpose as capacitors for rapidly changing loads.

There are a variety of voltage regulation devices in use on utility and industrial power systems. We divide them into three major classes:

1. Tap changing transformers.
2. Isolation devices with separate voltage regulators.
3. Impedance compensation devices, such as capacitors.

Isolation devices include UPS systems, ferroresonant transformers, M-G sets, and the like. These are devices that isolate the load from power source by performing some sort of energy conversion. Therefore, the load side of the device can be separately regulated and can maintain constant voltage regardless of what is occurring at the power supply. The downside of using such devices is that they introduce more losses and may also cause harmonics problems on the power supply system.

Shunt capacitors help maintain the voltage by reducing the current in the lines. To maintain a more constant voltage, the capacitors can be switched in conjunction with the load, usually in small incremental steps to follow the load more closely.

Series capacitors are rare because of the extra care in engineering required for the series capacitor installation. The series capacitors compensate for most of the inductance in the system up to the load. If the system is highly inductive, this represents a significant reduction in impedance.

Another approach to flicker-causing loads is to apply static var. compensators. These can react within few cycles to maintain a fairly constant voltage by controlling the reactive power production. Such devices are commonly used on arc furnaces and other randomly varying loads where the system is weak and the resulting flicker is affecting nearby customers.

1.3 Short Duration Voltage Variation

1.3.1 Interruption

Occurs when supply voltage or load currents decrease to less than 0.1 pu for period of time not greater than 1 min. It results of the power system faults and equipment failure.

1.3.2 Sags

A decrease to between 0.1 to 0.9 in rms. voltage or current for duration from 0.5 cycle to 1 min. They are caused by energization of heavy load or starting of large motors i.e. typical voltage sag can be associated with SLG fault on another feeder or substation.

1.3.3 Swell

Increase between 1.1 and 1.8 p.u. in rms. voltage or current of power frequency for duration from 0.5 cycles to 1 min. It is associated with system faults. One way when the voltage sag can occur for temporary voltage rise on unfaulted phase during SLG and also can be caused by switching off large load or energising large capacitor.

1.3.4 Protection against Voltage Sags and Interruption

As we entertain solutions at higher levels, solution is more costly. The solution close to the load is cheaper. The least cost solution is often for the end user to specify to the supplier that the machine is able to ride through sags of a designated duration. Many suppliers can provide the necessary capability if it is specified at the time quotations are requested. At the next higher level, it may be possible to apply an uninterruptible power supply (UPS) system or some other type of power conditioning to the machine control. At higher level 3 some sort of backup power supply with the capability to support the load for brief period is required. Higher level 4 represents alterations to the utility power system to significantly reduce the number of sags and interruptions.

Fig. 1. Approaches for voltage sag ride-through

1.4 Voltage Imbalance

Voltage imbalance is defined as maximum deviation from average of 3 phase voltages or currents divided by average of the three phase voltages or currents expressed in percentage.

Imbalance can be defined using symmetrical components. The ratio of either negative or zero components to the positive sequence component equal = percentage imbalance. Sources of voltage imbalance are single-phase loads on three-phase circuit. It can be also the result of blown fuses in one phase of three-phase capacitor bank.

1.5 Waveform Distortion

1.5.1 Dc Offset

Presence of dc voltage or current in ac power system. Occur due to result from geometric disturbance or effect of half wave rectification.

1.5.2 Harmonics

Sinusoidal voltages and currents having frequencies are integer multiples of frequency at which the power system designed. Harmonics distortion originates due to the non-linear characteristics of devices and loads in power system.

There are several measures commonly used for indicating the harmonic content of the waveform. One of the most common is total harmonic distortion (THD), which can be calculated for either voltage or current:
=

THD is a measure of the effective value of the harmonic components of a distorted waveform, that is, the potential heating value of the harmonics relative to the fundamental.

The rms. value of the total waveform is not the sum of the individual components, but the square root of the sum of the squares. THD is related to the rms value of the waveform as follows:

All circuits containing both capacitances and inductances have one or more natrual frequencies. When one of those frequencies lines up with a frequency that being produced on the power system, resonance can develop in which the voltages and current at that frequency continue to persist at high values.

Fig. 2. Effect of capacitor size on the parallel resonant frequency.

1.5.3 Interharmonics

Voltages or currents having frequency components not integer multiples of frequency at which supply system designed to operate. Sources are i.e. static converters, cycloconverters and induction motors.

1.5.4 Principles for Controlling Harmonics

When the harmonics problem occurs, the basic options for controlling harmonics:

1- **Reduce the harmonics currents produced by the load:** For example adding a line reactor in series with PWM drives will significantly reduce harmonic. Transformer connections can be employed to reduce harmonic in three phase systems. Phase shifting half of the six pulse power converters in a plant by 30 degrees can approximate the benefits of 12-pulse loads by dramatically reducing the fifth and seventh harmonics. Delta connected transformers can block the flow of the zero sequence harmonics from the line. Zigzag and grounding transformers can shunt the triples off the line.

2- **Add the filters to either siphon the harmonic currents off the system, block the currents from entering the system, or supply the harmonics currents locally:** The shunt filter works by short circuiting the harmonics currents close to the source of distortion. This keeps the currents out of supply system. Another approach is to apply a series filter that blocks the harmonic currents. This is a parallel tuned circuit that offers high impedance to harmonic currents. One common application is in the neutral of the grounded wye capacitor to block the flow of triplen harmonics while still retaining a good ground at fundamental frequency.

3- **Modifying the system frequency response:** Adverse system responses to harmonics can be modified by a number of methods: adding a shunt filter, adding a reactor to detune the system, changing the size of the capacitor, moving a capacitor to a point on the system with different short impedance or high losses, removing the capacitor and simply accepting the higher losses.

1.5.4.1 Filtering

There are two general classes of filters: Passive filters and Active filters

1. Passive filters: Passive filters are made of inductance, capacitance and resistance elements. They are relatively inexpensive compared to other means for eliminating harmonic distortion, but they have the disadvantage of potential adverse with the power system. They are employed either to shunt the harmonic currents off the line or block their flow between parts of the system by tuning the elements to create resonance at the selected frequency. The most common type is the notch series filter. An example of common 480 V arrangement is shown in Fig. 3. One important side effect of adding a filter is that it creates sharp parallel resonance with power system at a frequency below the notch frequency. This resonant frequency must be safely away from any significant harmonic.

Fig. 3. Creating a fifth-harmonic notch filter and its effect on system response.

2. Active filters: Active filters are based on sophisticated power electronics and are much more expensive than passive filters. However they have distinct advantage that they dont resonate with the system. The basic idea is to replace the portion of the sine wave that is missing in the current in the non-linear load.

Fig. 4. Application of an active filter at a load.

1.6 Stability

As the load demand and the generation change continuously, the system must automatically adjust to the new conditions. Power system stability is the ability to keep the generators in synchronism, and to keep a desired voltage and frequency in the presence of load and generation variations and disturbances.

Power systems are large, complex and highly non-linear systems. Stability analysis has to be performed with simplified models. Depending on the nature of the potential instability, the size of the disturbance, and the time scale, different approaches to modelling and system analysis are used. This leads to a classification of power system stability. This classification is well known to power engineers, and can be found in any book on power system stability. Based on the nature of the potential instability the following classification is made:

1. Angle stability: Is the ability to keep the generators in synchronism. This is a problem of balancing active power, as imbalance in mechanical torque and electrical torque makes a generator accelerate or decelerate. If the generator speeds up, the load angle is increased, and the machine automatically takes a larger part of the load. This increases the electric torque and decelerates the machine. If this increase in electric torque is enough to stop the acceleration, the system remains in synchronism.

2. Voltage stability: Is the ability to supply the load with a high enough voltage. This is a problem of balancing reactive power. An inductive load supplied via a weak line leads to a large voltage drop across the line. The load voltage will then be low. Since many loads aim to draw constant power, a low voltage implies an increased current, which further increases the voltage drop. If the voltage drop cannot be compensated for by reactive power injection, the result may be a voltage collapse.

3. Frequency stability: Is the ability to keep the frequency steady at the reference frequency, for instances 50 or 60 Hz under continuous load variations.

Any disturbance small or large can affect the synchronous operation of the system. For example, there can be sudden increase in load or loss of generation. Another type of disturbance which may occur due to overloading or fault. The stability of the system determines whether the system can settle down to new original steady state
The disturbance can be divided into two categories (a) small or (b) large. A small disturbance is one for which the system dynamics can be analysed from linearised equations. The small changes in load or generation can be termed as small disturbance. However, faults which result in a sudden dip in the bus voltages are large disturbances and require remedial action in the form clearing of the fault. The duration of the fault has a critical influence on system stability. System stability can be divided in the following categories:

1. Steady state or small signal stability: A power system is steady state stable for particular steady state operating condition if, following any disturbance, it reaches a steady state operating condition which is close to or identical to the pre-disturbance operating condition.

2. Transient stability: A power system is transient stable for a particular steady-state operating condition and for a particular large disturbance or sequence of disturbances if, following that disturbances, it reaches an acceptable steady state condition.