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Power Quality Enhancement Using Active Filters

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***Abstract*- Use of nonlinear loads and devices in the power systems is expected to grow rapidly. These loads inject harmonic currents into the power system. Active filtering of electric power has now become a mature technology for harmonic and reactive power compensation in two- wire (single phase), three-wire (three phase without neutral), and four-wire (three phase with neutral) ac networks with nonlinear loads. Current harmonics are one of the most common power quality problems and are usually solved by the use of shunt active and passive filters. Harmonic standards are prescribed by various agencies (IEC & IEEE) to keep harmonics within prescribed limits.**

Keywords - Active power filters, Active power line conditioners, power quality, harmonics and reactive power compensations, control strategies

I. Introduction

In recent years, the electrical power quality is a more and more important issue. The main problems are stationary and transient distortions in the line voltage such as harmonics, flicker, swells and sags and voltage asymmetries. With the significant development of power electronics technology, especially static power converters (well known as non-linear loads), voltage harmonics resulting from current harmonics produced by the non-linear loads have become a serious problem. Paradoxically, static power converters, the source of most of the perturbations, could also be used efficiently as active power filters in order to cancel or mitigate the above mentioned power quality problems as other power systems troubles such as damping of voltage oscillations.The proposals to use static power converters for active harmonic filtering have came into view around 1970 [1].

The active filter technology is now mature for providing compensation for harmonics, reactive power and neutral current in ac networks.Active filters are also used to eliminate voltage harmonics, to regulate voltage terminal voltage, to suppress voltage flicker, and to improve voltage balance in three phase systems.

Advantages of active filters over conventional means (passive filters, special transformer connections and special transformers) are mainly: Flexibility in defining and implementing the functions of the filter, a very fast response, and no additional problems caused by possible resonant frequencies or network configuration.

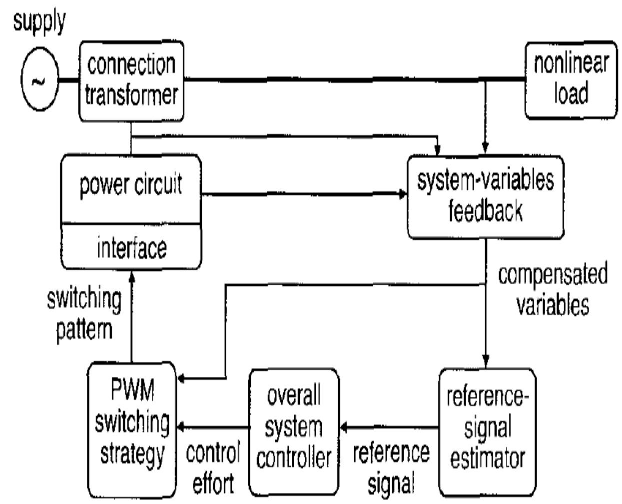

Fig.1 Generalized block diagram of Active Filter

II. Classification Of Active Filters

They can be classified on the basis of:

A. Power rating and speed of response required in compensated systems;
B. Power circuit configuration and connections;
C. System parameters to be compensated (e.g. current harmonics, power factor, unbalanced three- phase system etc.);
D. Control techniques employed; and
E. Technique used for estimating the reference current / voltage.

A. Classification according to power rating and speed of response required in compensated system

The power rating of the compensated system and its speed of response play a major role in deciding the control philosophy to implement the required filter.These two factors follow a reciprocal relationship. In general the cost of any particular system is proportional to the required speed of response.

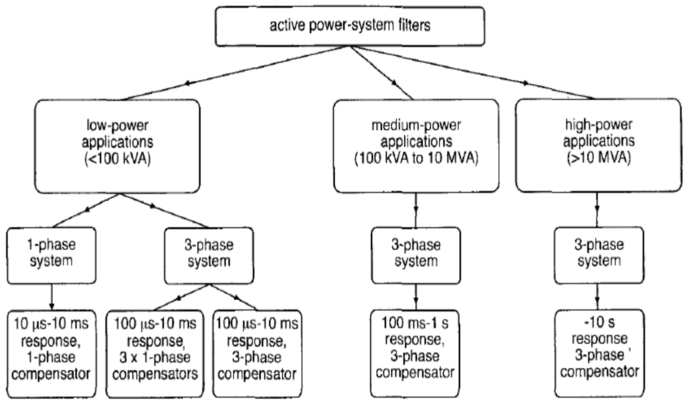

Fig.2 Classification according to Power rating and speed of Reponse

B. Classification according to the power-circuit configuration and connection

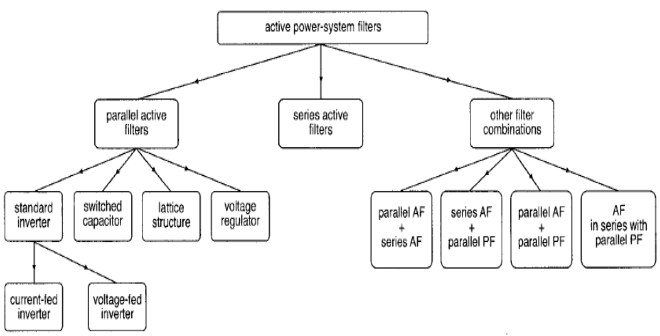

Fig.3 Classification according to Power-circuit configuration

C. Classification according to compensated variables

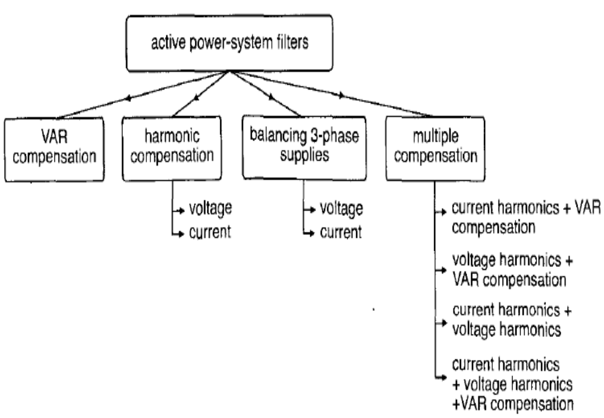

Fig. 4 Classification according to Compensated variables

D. Classification based on control technique

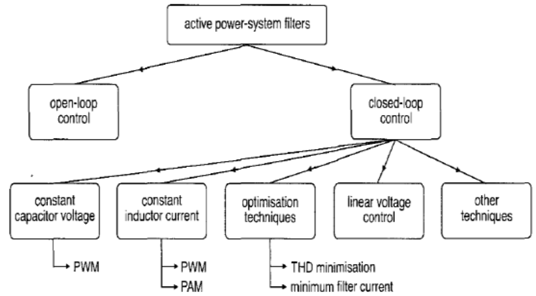

Fig. 5 Classification according to Control Techniques

The control strategy of active filters has great impact not only on the compensation objective and required kVA rating of active filters, but also on the filtering Characteristics in transient state as well as in steady state.

1) Frequency-Domain and Time- domain

There are mainly two kinds of control strategies for extracting current or voltage harmonics from the corresponding distorted current or voltage; one as based on the Fourier analysis in the frequency domain and other is based on the theory of instantaneous reactive power, which is called the "p-q theory".

2) *Harmonic Detection Methods-*

Three kinds of harmonic detection methods in the time-domain have been proposed for shunt active filters acting as a current source.

a) Load current detection
b) Supply current detection
c) Voltage detection

E. Classification according to current/voltage-reference-estimation Technique

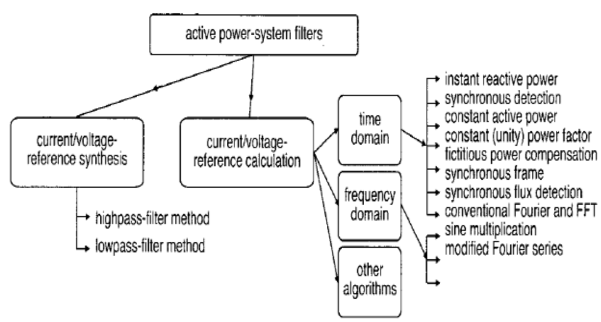

Fig. 6 Classification according to Current/Voltage-reference estimation

Load current detection and supply current detection are suitable for shunt active filters installed in the vicinity of one or more harmonic-producing loads by individual high-power consumers. Voltage detection is suitable for a shunt active filter to be used as the shunt device of the "unified power quality conditioner" which will be concentrated installed in primary distribution substations by utilities.

III. POWER QUALITY & THEIR PROBLEMS

The term Electric Power Quality broadly refers to maintaining a near sinusoidal power distribution bus voltage at rated magnitude and frequency. In addition, the energy supplied to a customer must be uninterrupted from the reliability point of view. It is to be noted that even though power quality (PQ) is mainly a distribution system problem, power transmission systems may also have an impact on the quality of power.

A power quality problems exists if any voltage or current or frequency deviation results in a failure or in a bad operation of customer's equipment.However, quality of power supply implies basically voltage quality and supply reliability.

TABLE I. PQ PROBLEMS AND THEIR CAUSES

Broad Categories	Specific Categories	Methods of Characterization	Typical Causes
Transients	Impulsive	Peak magnitude, rise time and duration	Lightning strike, transformer energization, capacitor switching
	Oscillatory	Peak magnitude, frequency components	Line or capacitor or load switching.
Short duration voltage variation	Sag	Magnitude, duration	Ferroresonant transformers, single line-to-ground faults
	Swell	Magnitude, duration	Ferroresonant transformers, single line-to-ground faults
	Interruption	Duration	Temporary (self-clearing) faults
Long duration voltage variation	Undervoltage	Magnitude, duration	Switching on loads, capacitor deenergization
	Overvoltage	Magnitude, duration	Switching off loads, capacitor energization
	Sustained interruptions	Duration	Faults
Voltage imbalance		Symmetrical components	Single-phase loads, single-phasing condition
Waveform distortion	Harmonics	THD, Harmonic spectrum	Adjustable speed drives and other nonlinear loads
	Notching	THD, Harmonic spectrum	Power electronic converters
	DC offset	Volts, Amps	Geo-magnetic disturbance, half-wave rectification
Voltage flicker		Frequency of occurrence, modulating frequency	Arc furnace, arc lamps

TABLE II. POWER QUALITY STANDARDS

Topic	Standards
Classification of power quality	IEC 61000-2-5: 1995, IEC 61000-2-1: 1990 IEEE 1159: 1995
Transients	IEC 61000-2-1: 1990, IEEE c62.41: (1991) IEEE 1159: 1995, IEC 816: 1984
Voltage sag/swell and interruptions	IEC 61009-2-1: 1990, IEEE 1159: 1995
Harmonics	IEC 61000-2-1: 1990, IEEE 519: 1992 IEC 61000-4-7: 1991
Voltage flicker	IEC 61000-4-15: 1997

A. *Poor load power factor:*

Reason is use of more lagging reactive loads. This results in large voltage drop, heat dissipation & reduced life span of feeder.

B. *Transients*- Classified into two categories:

1) Impulse transients
2) Oscillatory transients

Impulse transients are mainly caused by lightning stroke, whereas oscillatory transientsare caused by capacitor or transformer energization and converter switching.

C. *Short duration voltage variation (for less than one minute)-*

1) Voltage sag: Decrease in supply voltage up to 0.75 p.u. and less. Reason is mainly system faults and energization of heavy loads.

2) *Voltage swell*: Increase of supply voltage up to 1.25 p.u and more. One possible reason is LG-fault.

3) Interruption-Supply: voltage is around 0.1 p.u. & below. Mainly due to system faults, equipment failure and control malfunction.

D. *Long duration voltage variation (for more than one minute)-*

1) *Over voltage*- Supply voltage is 1.1p.u and more. Due to switching off of large load or energization of a large capacitor banks.

2) *Under voltage*- Supply voltage is 0.9 p.u and less. Reason is switching of a large load or de energization of a capacitor banks.

3) *Sustained interruption*- supply voltage is zero.

E. *Voltage fluctuation-*

It is Systematic random variation of supply voltage. When fluctuation is rapid, it is called flicker. One of the reasons is arc furnaces.

F. *Voltage Imbalance-*

Due to single phase loads.

G. Waveform distortion-

Steady state deviation in the voltage and current waveform from an ideal sine wave

1) *DC offsets*- Due to poor grounding, half wave rectification. Results in saturation of distribution transformer, so heating.

2) *Notches*- It is a periodic voltage distortion due to the operation of power electronic converters when current commutates from one phase to another, resulted in PCC voltage distortion

3) Harmonics- Presence of **integral-multiple, inter-harmonic and sub-harmonic** components. Reason is mainly use of power electronics loads. Results in malfunction of traffic control systems, losses & heating in transformer, interference with communication lines.

H. Harmonic Sources-

In recent years, more and more diode rectifiers with smoothing dc capacitors are used in electronic equipment, household applications, and ac drives. Harmonics generated by these loads have become a major issue.
Types of Harmonic Sources:

1) Current –Source Nonlinear Loads (CSNLs): Thyristor converters are a common and typical source of harmonic currents.The current waveform distortion (i.e.,the generation of harmonics) results from switching operation.Because the harmonic current contents and characteristics are less dependent on the ac side, this nonlinear load behaves like a current source.

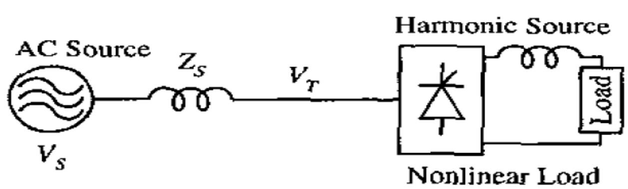

Fig.7 Current Source Nonlinear Loads (CSNL)

2) Voltage –Source Nonlinear Loads (VSNLs)- Another common type of harmonic source is a diode rectifier with smoothing dc capacitors.Although the current is highly distorted, its harmonic amplitude is greatly affected by the ac side impedance and source voltage unbalance .Therefore, the diode rectifier behaves like a voltage source.

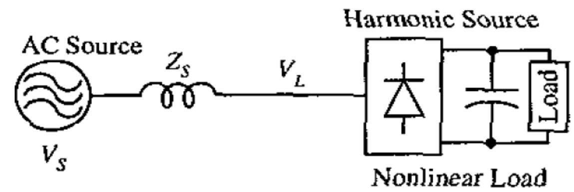

Fig.8 Voltage Source Nonlinear Loads (VSNL)

a) *Passive Filter*- This is also called traps, which provide low impedance paths to divert harmonics to ground and devices that create a higher -impedance path to discourage the flow of harmonics. A weakness of passive harmonic filter is that, as their name implies, they cannot adapt to changes in the electrical system in which they operate.This means that changes to the electrical system (for example, the addition or removal of power factor-correction capacitors or the addition of more nonlinear loads) could cause them to be overloaded or to create " resonances " that could actually amplify, rather than diminish, harmonics.

a) Active harmonic filters- In contrast, continuously adjust their behavior in response to the harmonic current content of the monitored circuit, and they will not cause resonance. Like an automatic transmission in a car, active filters are designed to accommodate a full range of expected operating conditions upon installation, without requiring further adjustments by the operator.

b) *Isolation transformers*- are filtering devices that segregate harmonics in the circuit in which they are created, protecting upstream equipment from the effects of harmonics. These transformers do not remove the problem in the circuit generating the harmonics, but they can prevent the harmonics from affecting more sensitive equipment elsewhere within the facility.

c) *Harmonic mitigating transformers (HMT)*- actually do relieve problematic harmonics. The right application includes transformers that are heavily or moderately loaded and where high levels of harmonic currents are present. In addition, HMTs are very effective in supporting critical loads that are backed up by a UPS.UPSs and backup generators tend to have high impedance, which results in high voltage distortion under nonlinear loading. Because of this, equipment that operates flawlessly when supplied by utility power may malfunction when the backup system engages during a utility outage.

d) *Harmonic Suppression System (HSS)*- Harmonic suppression system is a unique solution for single -phase loads that is designed to suppress the third harmonic. An HSS is generally more expensive than an HMT, but it is designed to attenuate the harmonic problems throughout the entire distribution system not just upstream of the transformer. The type of facilities that present the best opportunities for HSS installation are those that place a very high premium on power quality and reliability such as server farms, radio and television broadcast studios, and hospitals.

IV. CONTROL STRATEGIES FOR ACTIVE FILTERS

Active power filter appears to be a viable solution for power quality conditioning. With the emergence of fast computing devices, control strategies for active filters are continually changing aiming at near perfect compensation. Control strategy plays a vital role on the overall performance of the power conditioner. Rapid detection of disturbance signal with high accuracy, fast processing of the reference signal and high dynamic response of the controller are the prime requirements for desired compensation.
Types of Control Strategy:

A. *Frequency-Domain Approaches:*

1. Conventional Fourier technique
2. Modified-Fourier series technique

B. *Time-Domain Approaches*

1. Instantaneous Reactive-Power Theory or ‘p-q’ Theory
2. Synchronous‘d-q’ Reference-frame based Algorithm
3. Instantaneous Power Balance Method
4. Energy Balanced (EB) Method
5. Synchronous Detection Algorithm
6. Direct-Detection Method
7. Notch-Filter based Method
8. Unity Power Factor Method
9. Sine –Multiplication Technique
10. Flux-Based Controller
11. Adaptive –Detection Technique
12. Fictitious Power Compensation Technique

C. *Other Control Techniques*

1. The hysteresis-band current control
2. Sliding mode control
3. Negative sequence current component control
4. Deadbeat control
5. Predictive control
6. Space vector control

V. ACTUAL STATUS OF ACTIVE FILTERS

Solid state power devices- Active power filters are implemented by using self-commutated semiconductor devices.For high power applications thyristor type devices are used.

TABLE III. AVAILABLE SELF-COMMUTATED SEMICONDUCTOR DEVICES:

Thyristors	**Transistors**
GTO	BPT
MCT	MOSFET
FCTh	FCT
SITh	SIT
MTO	DBPT
EST	IEGT
IGT	IGBT

A. *Commercial Implementations-*

There is available a large variety of technical options to mitigate and correct power quality problems.The choice of which one has to be used, as well as who is responsible for installing, largely depends on specific circumstances; the selection of equipment for improvement of power quality basically depends on the perturbation source or type.
There are briefly presented **three** types of active power filters, available in the market, in use to compensate power disturbances problems, and considered as representative for the actual stage.

B. *Static Compensators (STATCOM) and Distribution Static Compensators (DSTATCOM)-*

The STATCOM is a solid -state synchronous voltage generator, which consists of a multiphase, voltage-source inverter connected in shunt with the transmission line.It can counteract both voltage depression and voltage rises.The STATCOM is superior in that it provides greater speed of response, does not increase short circuit current in the system and can provide symmetrical leading or lagging reactive current.The smooth continuous control of the STATCOM minimizes the possibility of large voltage fluctuations which may occur with passive devices.The development efforts of advanced static compensation technology at the power delivery level have resulted in a distribution STATCOM (DSTATCOM) that exhibits high-speed control of reactive power to provide harmonics suppression voltage stabilization, flicker suppression, and other types of system control.The DSTATCOM utilizes a design consisting of a voltage -source converter connected to the power system via a multi-stage converter transformer.

C. *Static Synchronous Series Compensator (SSSC)-*

The SSSC is a solid -state voltage source inverter connected in series with the transmission line through an insertion transformer.This connection allows the SSSC to precisely control power flow in the line with a wide range of system conditions.Although the SSSC can be compared to variable series capacitors in that they both insert a voltage in quadrature with the line current, the SSSC is considerably more power powerful.In addition to advancing power flow, the SSSC can operate inductively to retard power flow.Another advantage of the SSSC over passive components (whether fixed or switched) is that the full compensating voltage of a series reactive element is directly proportional to the current flow.Using active control, the SSSC has the ability to damp system oscillations over a wide range of frequencies including those associated with sub-synchronous resonance (SSR) phenomena that involves series capacitors.

D. Unified Power Flow Controller (UPFC)-

The UPFC gives power system operators the flexibility to overcome many of the transmission restraints facing the industry today. A UPFC-equipped transmission line can independently control real and reactive flow to maximize line utilization and system capability .It also can be used to minimize reactive current flow, enabling users to reduce system losses.The UPFC provides simultaneous ,real-time control of all three basic power transfer parameters (voltage, impedance and phase angle) in any combination to optimize the transmitted power.The UPFC allows the power delivery system operator to set and independently control the real and reactive flow on a specific power transmission line.

VI. SELECTION OF COMPONENTS AND SPECIAL FEATURES OF ACTIVE FILTERS

The selection of components of the active filters is an important factor to achieve improved performance.The main component of the active filters is the solid-state device.Nowadays, the IGBT is an ideal choice up to medium ratings,and GTO's are used in higher ratings.A series inductor L at the input of a VSI bridge working as an active filter is normally used as the buffer between supply terminal voltage and PWM voltage generated by the active filter.The value of this inductor is very crucial in the performance of the active filters.If a small value of L is selected, then large switching ripples are injected into the supply currents, and a large value of L does not allows proper tracking of the compensating currents close to the desired values.An optimum value of L is essential to obtain satisfactory performance of the active filter.Generally, a passive ripple filter is used at the terminal of the supply system,which compensates for switching harmonics and improves the THD of the supply voltage and current.The design of the passive ripple is also important, because source impedance can cause an interaction with its components.The dc-bus capacitor value C_{dc} of the active filter is another important parameter.With a small value of C_{dc}, large ripples in the steady state and wide fluctuations in the dc - bus voltage under transients are observed. A higher value of C_{dc} reduces ripples and fluctuations in the dc-bus voltage, but increases the cost and size of the system.

In general active filters are used to compensates current and voltage harmonics, but in most cases, they also have additional functions, such as compensation for reactive power current and voltage unbalance, neutral current, voltage flicker, voltage spikes and for voltage regulation.

VII. TECHNICAL AND ECONOMIC CONSIDERATION

Technical literature on the active filters has been reported since 1971 and, in the last two decades, has boomed.Around 1990, many commercial development projects were completed and put into practice.Initially reported configurations were quite general and the rating of the solid-state devices involved was substantial, which resulted in high cost. Due to these reasons ,the technology could not translated to field applications.Moreover,modern active filter are capable of compensating quite high orders of harmonics (typically, the 25 th) dynamically.

Economic considerations were the hindrance at the initial stages of active filter development, but now they are becoming affordable due to a reduction in the cost of devices used.With the harmonic pollution in present-day power systems, the demand for the active filter is increasing.Recommended standard such as IEEE-519 will result in the increased use of active filter in the coming years.

VIII. APPLICATIONS OF ACTIVE FILTERS

Selection of the active filters for a particular application is an important task for application engineers.There are widely varying applications requirements, such as single phase or three - phase, three wire or four wire systems, requiring currentorvoltagebasedcompensations.Moreover,
there is a number of active filters configurations which may cater to the needs of individual users.

TABLE IV. APPLICATION OF ACTIVE FILTERS

Components for specific application	Active series	Active shunt	Hybrid of active series and passive shunt
Current Harmonics			Prefer
Reactive Power		Prefer	
Load Balancing		Prefer	
Neutral Current		Prefer	
Voltage Harmonics	Prefer		
Voltage Regulation	Prefer		
Voltage Balancing	Prefer		
Voltage Flicker		Prefer	

Voltage sags and Dips	Prefer		
(Current Harmonics +Reactive power)		Prefer	
(Current Harmonics +Reactive power + Load balancing)		Prefer	
(Current Harmonics +Reactive power + Load balancing +Neutral current)		Prefer	
(Voltage Harmonics + Voltage Regulation)	Prefer		
(Voltage Harmonics+ Voltage regulation +Voltage Flicker +Voltage sags and Dips)	Prefer		
(Current Harmonics+ Load balancing)		Prefer	

IX. CONCLUSIONS

An extensive review of active filter has been presented to provide a clear perspective on various aspects of active filters.The substantial increase in the use of solid -state power control results in harmonic pollution to the tolerable limits.Utilities are finding it difficult to maintain the power quality at the consumers end and consumers are paying the penalty indirectly in the form of increased plant downtimes.At present active filter technology is well developed and many manufacturers are are fabricating active filters with large capacities.The utilities in the long will induce the consumers with nonlinear loads to use the active filter for maintaining the power quality at acceptable limits. A large number of active filter configurations are available to compensate harmonic current, reactive power, neutral current, unbalance current, and harmonics.The consumers can select the active filter with the required features.

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