J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*


# POWER SYSTEM HARMONIC CONTROL

A main objective of modern industry is to achieve an acceptable quality in its manufacturing products. Electricity nowadays has been considered as such a product. The distributor sells electric energy, which is expressed in kilowatt hours, and is characterized by a sinusoidal voltage. However, electricity is a product that cannot be fully controlled by the manufacturer because customers may affect the power and voltage qualities as well. Therefore electricity is basically different from other manufactured products. Power quality issues have always been a significant topic in power engineering. But recently, due to excessive use of susceptible loads, especially high-performance electronic devices (e.g., computers, communication equipment), the quality of delivered power and the voltage waveshape has drawn special attention to this matter. On the other hand, the increasing use of power electronic equipment, generating harmonics, has aggravated this situation. This article introduces the main sources of disturbance in electric networks such as static power converters, arc furnaces, saturated magnetic devices, and effects of harmonics on power systems. Lowering efficiency in electromagnetic equipment, generating oscillatory torque in rotating machinery, decreasing power factor, derating of power cables, and generating disturbances in communication systems are the most common effects caused by these sources of disturbance. Solutions to improve the power quality will also be presented. These solutions include passive and active methods and using higher-order pulse converters. Harmonics and power factor, two important issues in power quality, will be introduced in the following two paragraphs.

## Harmonics

The voltage waveform delivered by an ac generator is almost perfectly sinusoidal except for slot harmonics caused by winding structure of machine. During its transport and distribution, this voltage wave is distorted by a number of imperfections, some of which occur in customers' installations connected to the supply system. In recent years some electric distributors have been affected regarding the increase in harmonic pollution on their systems. Since the beginning of the 1970s, electromechanical systems have been gradually replaced by power electronics. At the same time, new generations of appliances, generating harmonics, were increasingly produced. This was due to the application of power electronics in the domestic and service-industry areas (TV sets, microcomputers and air-conditioning units) and purely industrial applications. So it was decided to limit rapidly the emission levels of mass-produced appliances. This is why standards dealing with limits for harmonic currents for household appliances were prepared and published (1,2,3,4).

The amounts of these harmonics are related to many factors as

- Number of domestic customers
- Time of day
- Season
- Cultural considerations

Harmonics generated by household appliances usually follow a statistical distribution. These domestic user disturbances are injected at the distribution voltage level while those generated by industrial loads are generated at the subtransmission or distribution voltage levels. High voltage dc (*HVDC*) and static var compensator (*SVC*) systems are the main sources of harmonics at transmission voltage level. High-power rectifiers have the most significant role in producing harmonics of industrial nature. Current harmonics cause higher temperature in the various conductors, as rotors of electrical drives. Local overvoltage is another effect of current harmonics, which occur in presence of capacitors, when there is a resonance phenomenon. This phenomenon will be discussed later. Current harmonics also cause malfunctions in electric equipment, for example, unreliable operation of electronic equipment and incorrect switching.

## Power Factor

Power factor is a measure of the match between the waveforms of voltage and current in an energy transmission circuit. The definitions regarding power factor, which are given in the next paragraph, indicate that power factor can be expressed as the ratio of active power to apparent power of an electric device. Active power is the component of apparent power that can be usefully converted to other forms of energy, while reactive power is a circulating power between source and load, with no contribution to energy conversion. In the ideal case of a resistive load where the current and voltage are fully in phase and have proportional waveforms, the resulting power factor will be maximum and equal to unity. Unity power factor implies that the reactive component of power equals zero. Flow of reactive power in an electric network is due either to linear energy-storage components such as unsaturated reactors and capacitors or to harmonics generated by nonlinear loads. Load compensation has always dealt with power factor correction, which is the practice of generating reactive power as close as possible to the load rather than supplying it from a remote source. Most industrial loads have lagging power factor; that is to say, they absorb reactive power. The load current therefore tends to be larger than the current, which is required to supply the real power. This situation can cause greater energy loss in line and a waste in line capacity. Power factor correction can make the load resemble an ideal resistance as seen from the network side.

## Definitions

Harmonics, as explained, are produced when the voltage or current waveforms deviate from a pure sinusoidal shape. To analyze these waveforms, engineers use the concept known as Fourier series, which allows any periodic function $s(t)$ to be described as a series of sinusoidal functions with multiple frequencies as

$$s(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left[a_n \cos\left(\frac{2n\pi t}{T}\right) + b_n \sin\left(\frac{2n\pi t}{T}\right)\right] \qquad (1)$$

where

$T$ = period of the wave

$a_0/2$ = dc component

$n$ = order of harmonic

$a_n, b_n$ = Fourier coefficients

The values of $a_n$ and $b_n$ can be calculated by integration as:

$$a_n = \frac{2}{T}\int_0^T s(t)\cos\left(\frac{2\pi n}{T}\right)dt \qquad (2)$$

$$b_n = \frac{2}{T}\int_0^T s(t)\sin\left(\frac{2\pi n}{T}\right)dt \qquad (3)$$

According to Eq. (1), harmonic components are introduced having frequencies that are multiples of the fundamental frequency $f = 1/T$. The amplitude of $n$th order harmonic can be defined as

$$c_n = \sqrt{a_n^2 + b_n^2} \qquad (4)$$

The total harmonic distortion (*THD*) of a periodic wave is defined as the ratio of the root-mean-square (*rms*) of the harmonic content to the value of the fundamental quantity and is usually expressed as a percent of the fundamental:

$$\text{THD} = \frac{\left(\sum_{n=2}^{\infty} c_n^2\right)^{1/2}}{c_1}\cdot 100\% \qquad (5)$$

Another important definition regarding harmonics is distortion factor:

$$\text{Distortion factor} = \frac{c_1}{\left(c_1^2 + \sum_{n=2}^{\infty} c_n^2\right)^{1/2}} \qquad (6)$$

In a general case, namely nonsinusoidal voltage and current, power factor and displacement factor are defined in terms of average input power and values of voltage and current as follows:

$$\text{Displacement factor} = \frac{\text{Average input power}}{(\text{rms fundamental voltage})(\text{rms fundamental current})} \qquad (7)$$

$$\text{Power factor} = \frac{\text{Average input power}}{(\text{rms supply voltage})(\text{rms supply current})} \qquad (8)$$

In the particular case of sinusoidal voltage and nonsinusoidal current, for example, in ac/dc converters, the power factor and displacement factor can be written as:

$$\text{Displacement factor} = \frac{P_1}{VI_1} = \frac{VI_1\cos\varphi}{VI_1} = \cos\varphi \qquad (9)$$

$$\text{Power factor} = \frac{P_1}{V(I_1^2 + \sum_{n=2}^{\infty} I_n^2)^{1/2}} = \frac{VI_1 \cos\varphi}{V(I_1^2 + \sum_{n=2}^{\infty} I_n^2)^{1/2}}$$
$$= \frac{I_1}{(I_1^2 + \sum_{n=2}^{\infty} I_n^2)^{1/2}} \cdot \cos\varphi \qquad (10)$$

where

$P_1$ = average power
$V$ = input sinusoidal voltage (rms)
$I_1$ = fundamental harmonic current (rms)
$I_n$ = $n$th harmonic current (rms)
$\phi$ = phase angle between fundamental line current and line voltage

In Eq. (10) the power factor is seen as a product of two terms. The first is related to harmonic content of the current wave, and the second is the displacement factor. The poor power factor for different types of load such as fractional horsepower induction motors, arc furnaces, and induction heaters ($Pf < 0.8$) implies that power factor correction is needed (5). The technical performance and economic benefits of improving the power factor will be discussed later in this article.

## Standardization Policy

In previous sections the necessity to limit the generation of harmonic currents was explained. The first step to implement such a limitation consists of setting the maximum threshold on the magnitudes of harmonic currents and voltages at various frequencies and various power system short-circuit ratios. Thus international and national standards have come into force to limit the level of harmonic injection into the system and to maintain good power quality.

European standards concerning harmonics (IEC 1000-3-2) and those concerning voltage variations (IEC 1000-3-3) in low-voltage networks by domestic appliances were published in 1995 and 1994, respectively (1,2). Standard 1000-3-2 is intended to be a specification concerning the emission of harmonics, complying with the EEC directives concerning electromagnetic compatibility. There are also German standards VDE 0838, VDE 0160, and VDE 0712, for household appliances, converters, and fluorescent lamp ballast, respectively (4,6,7).

The revised IEEE Std 519-1992 is another standard, which describes distortion limits that apply to the individual consumers of electrical energy as well as utilities. These limits for individual users consist of:

- Depth of notches, total notch area, and distortion of bus voltage caused by commutation process
- Individual and total voltage distortion
- Individual and total current distortion
- Voltage flicker

For utilities, this standard defines limits, which include:

- Voltage distortion limits expressed as maximum *THD*
- Limits of interference with communication circuits expressed as a factor called telephone influence factor (*TIF*) which is defined as

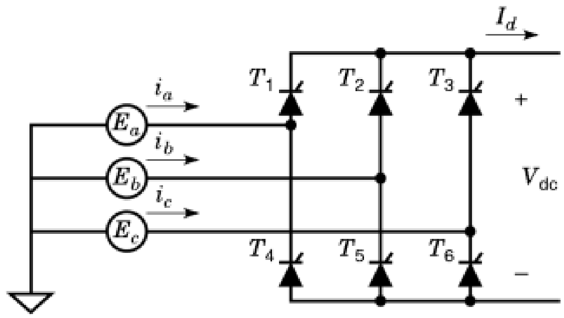


**Fig. 1.** Three-phase thyristor bridge fed from an infinite bus. $T_1 \ldots T_6$ are successively triggered every 60° to produce a dc output voltage $V_{dc}$.

$$\mathrm{TIF} = \frac{\left(\sum_{h=1}^{\infty}(X_h \cdot T_h)^2\right)^{1/2}}{X} \tag{11}$$

where

$X_h$ = Single frequency rms current or voltage at $h$th-order harmonic
$T_h$ = single frequency *TIF* weighting factor
$X$ = total rms current or voltage

## Harmonic Sources

Nonlinear loads connected to the supply system produce most harmonics. The most common nonlinear loads in the power system are static power converters, arc furnaces, saturated magnetic devices, static var compensators and thyristor-controlled series compensators. These harmonic sources are presented in this section.

**Static Power Converters.** Static power converters form nowadays the largest nonlinear loads. These converters are widely used in industry and household appliances for a verity of purposes such as adjustable speed motor drives, uninterruptible power supplies (*UPS*s), static var compensators, and *HVDC* systems.

*Power Rectifiers.* The problems caused by power rectifiers are well known:

- Low power factor in the network feeding thyristor bridges, particularly at low load
- Nonsinusoidal currents with a high harmonic content (≤2 kHz)
- Switching pulses

In the following, these problems will be discussed in the case of three-phase and single-phase rectifiers.

*Three-Phase Rectifiers.* Three-phase ac/dc converters are extensively used in the case of industrial applications up to hundreds of kW level. Figure 1 shows the structure of a full-converter circuit with a high inductive dc load. The thyristors are fired at intervals of $\pi/3$ and $T_1$ is fired at $\pi/6 + \alpha$. The six-pulse bridge configuration shown in this figure can be assumed the most common source for harmonics and harmonic problems in power systems. The input current waveform and the output dc voltage of the converter bridge are shown in Fig. 2.

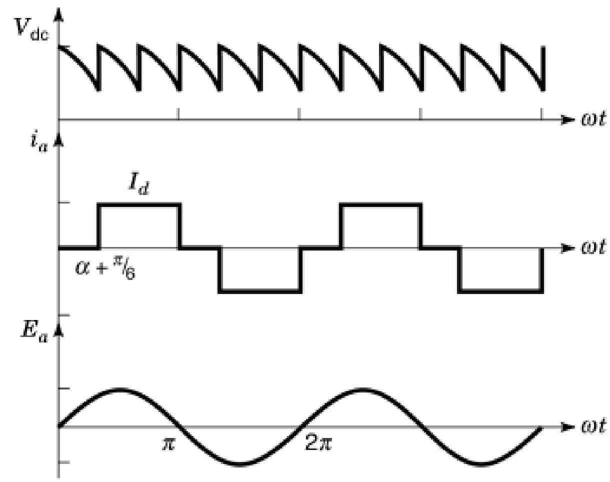


**Fig. 2.** Voltage and current waveforms of a 3-$\phi$ rectifier with a high inductive dc load.

The current harmonics may be calculated as (8)

$$i(t) = \sum_{n=1}^{\infty} \frac{4I_d}{n\pi} \sin\left(\frac{n\pi}{3}\right) \sin(n\omega t - n\alpha) \qquad (12)$$

where

$I_d$ = output dc current
$n$ = 1, 3, 5, ...
$\alpha$ = delay angle

Using Eq. (12), we can find the characteristic harmonics of the bridge. These harmonics are produced by semiconductor converter equipment in the course of normal operation. Note that two rules can be derived, regarding these harmonics: First is that the bridge can produce current harmonic orders, $n = kq \pm 1$, where $n$ is the order of harmonic and $q$ is the number of converter pulses (in this case $q = 6$) and $k = 1, 2, 3, 4 \ldots$. Thus, this six-pulse rectifier exhibits harmonics 5, 7, 11, 13, .... The second rule concerns the harmonic amplitudes, $I_n = I_1/n$, where $I_1$ is the current fundamental component.

The ac system impedance should be taken into consideration, especially in the case where it is significant, either in the form of a low short-circuit level compared to the bridge rating or through a transformer with a significant leakage reactance. This can cause a delay in the commutation of current from one phase to another. This delay (also called overlap) can alter the waveforms of input current and voltage of the rectifier, which are shown in (9) as Fig. 3. As can be seen, the ac current is slightly less blockshaped, which results in lower harmonic contents of the current wave. The other effect of overlap is producing notches in the input voltage wave. The depth of these notches is a function of relative size of the two reactances; ac system reactance and the converter transformer reactance. The width of these notches is determined by the overlap angle. The type of application in which overlap affects the lower-order harmonics considerably is restricted to very large converters, for example, in HVDC. For most drive applications the overlap is usually a few degrees and plays only a second-order role in harmonic levels.

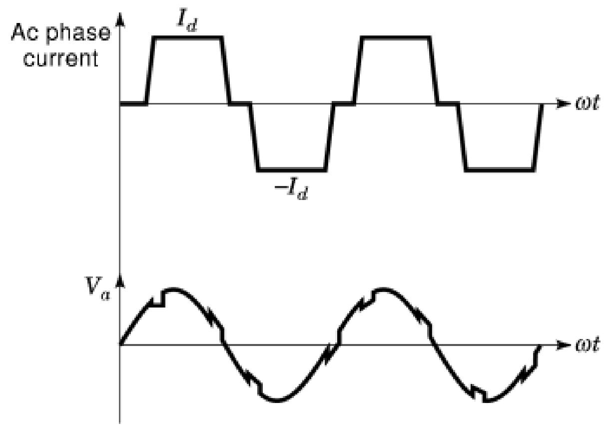


**Fig. 3.** Effects of overlap in input current and voltage of a 3-$\phi$ rectifier. The ac current is slightly less block-shaped compared to Fig. 2. There are also notches in the input voltage waveform.

The input power factor of three phase converters in continuous conduction mode is given as:

$$\text{Power factor} = \frac{q}{\pi}\sin\left(\frac{\pi}{q}\right)\cos\alpha \qquad (13)$$

where

$q$ = pulse number
$\alpha$ = delay angle

The power factor of phase-controlled converters depends on delay angle $\alpha$, and it is generally low, especially at low output voltage range. One way to improve this situation is using forced commutation techniques. These techniques take advantage of modern switching devices like GTOs. These methods are listed in (8) as:

- Excitation Angle Control In this method, thyristors in the bridge are replaced by full control switches like GTO, which can be turned on and turned off at any angle. The input current is shown in Fig. 4(a) for a two-pulse converter.
- Symmetrical Angle Control In this control strategy the conduction angle ($\beta$) of the switches are controlled. The turn on and turn off angles follow a symmetrical order. This is shown in the input current waveform in Fig. 4(b) for a two-pulse converter. Current harmonic components and power factor are as follows.

$$i(t) = \sum_{n=1}^{\infty}\frac{4I_d}{n\pi}\sin\frac{n\beta}{2}\sin n\omega t \qquad (14)$$

$$\text{PF} = \left(\frac{I_1}{I_s}\right)\cdot\text{DF} = \frac{2\sqrt{2}}{\sqrt{\beta\pi}}\sin\frac{\beta}{2} \qquad (15)$$

where DF and PF are displacement and power factors, respectively.

- Pulse-Width Modulation (*PWM*) The converter switches are turned on and off several times during an input voltage half-cycle. Voltage on the dc side and input current of the converter are controlled by width

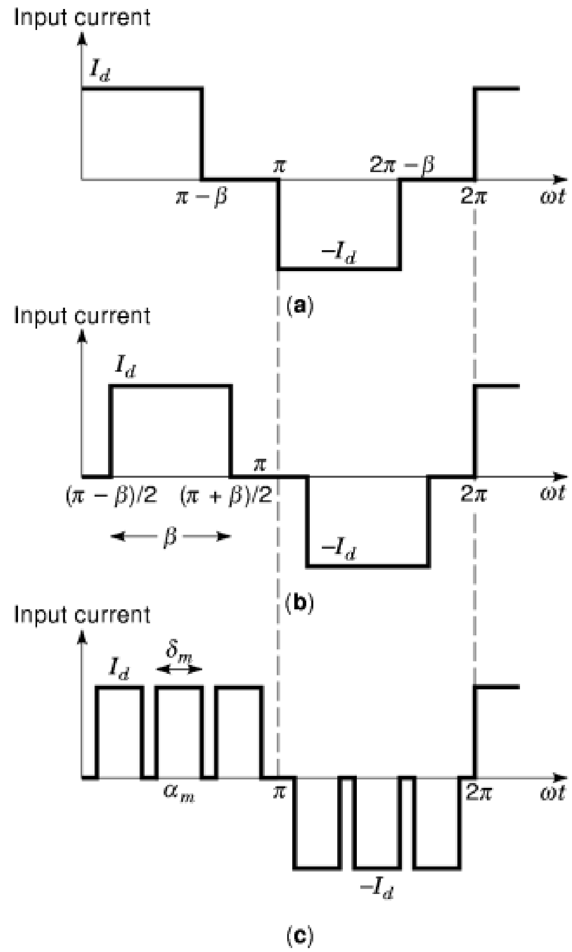


**Fig. 4.** Input current of three-phase rectifier using (a) excitation angle control, (b) symmetrical angle control, (c) PWM control. These methods are used for harmonic mitigation of the converter input current.

of the pulses. In Fig. 4(c) the input current waveform and turn-on and turn-off angles $\alpha_1, \alpha_2, \ldots, \alpha_p$ are shown. In this case the rms values of input current harmonics are calculated as:

$$I_n = \frac{\sqrt{2}I_d}{n\pi} \sum_{m=1}^{p} (-1)^m \cos \alpha_m \qquad (16)$$

As seen in Eq. (15), the harmonic amplitudes of different orders can be changed, depending on the angles $\alpha_1, \alpha_2, \ldots, \alpha_p$. So we can select these angles to eliminate specific harmonics from the input current waveform. This is usually done for lower-order harmonics, since these harmonics are the most difficult to filter. This method is used to shift harmonics to higher orders, which can be filtered much easier. Another method is to select the angles in a manner to minimize the total harmonic distortion of the input current wave.

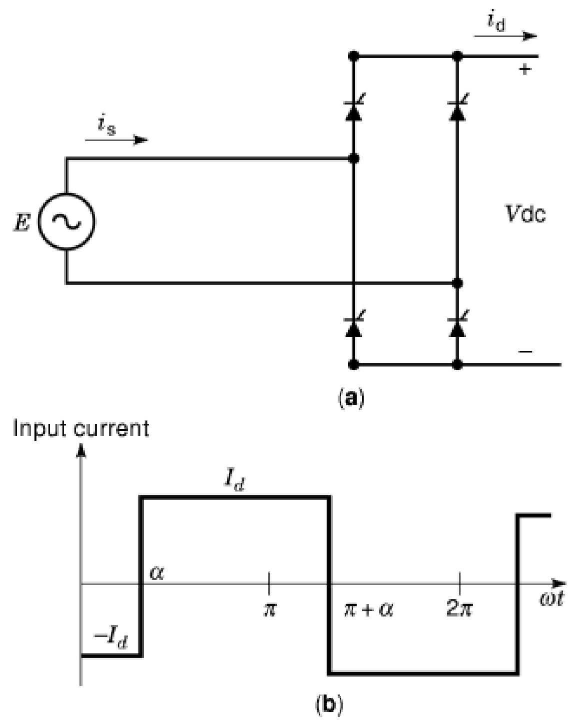


**Fig. 5.** (a) Single-phase full converter with a high inductive load. (b) Input current of the converter. $\alpha$ represents the firing angle of the converter. It also defines the phase shift between the input voltage and current.

Another method to eliminate lower-order input current harmonics is to use current mode control. In this method, after sensing and comparing the input current with a sinusoidal reference current, the error signal is passed through a PWM modulator to shape the desired sinusoidal input current waveform. This method will be further discussed later in the article.

*Single-Phase Rectifiers.* These rectifiers are used in applications such as low-power dc motor drives. Figure 5 shows an ideal single-phase bridge and its current waveform, assuming a high inductive load.

Fourier analysis of this waveshape yields the series:

$$i(t) = \sum_{n=1}^{\infty} \frac{4I_d}{n\pi} \sin(n\omega t - n\alpha) \qquad (17)$$

where $n$ is 1, 3, 5 .... It can be seen that the generated harmonics include all odds order ($2k \pm 1$) harmonics. This was predictable because this rectifier has two pulses per cycle ($q = 2$). Like the three-phase case, the overlap period decreases the harmonic amplitudes. Unlike three-phase rectifiers, single-phase rectifiers can generate triple-order current harmonics in network connections. They can also cause unbalance in three-phase systems. Single-phase rectifiers are also used in applications including power supplies for copiers, computers, TV sets, ballasts for fluorescent lighting, office equipment, and household appliances. In these applications single-phase rectifiers usually use a dc filter capacitor and draw impulsive current from the ac power supply. Therefore, their harmonic content is worse than harmonic values given by Eq. (17). Thus, they are significant sources of harmonics in an urban environment.

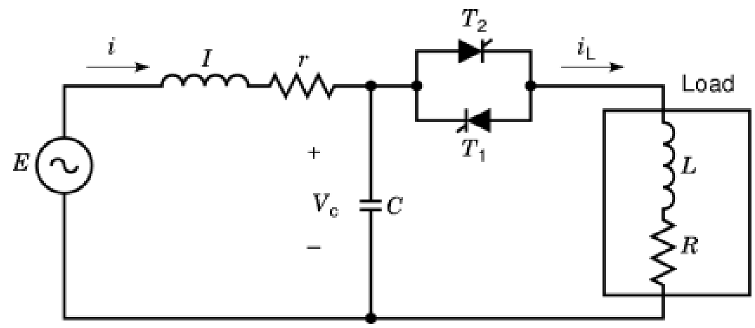


**Fig. 6.** An ac voltage controller. The input current, $i$, contains harmonics, which are multiples of the main frequency, or subharmonics causing flickers.

*ac Voltage Controllers.* A basic circuit of such a converter in a single-phase regime is shown in Fig. 6. The thyristors $T_1$ and $T_2$ are switched to control the rms value of the load side voltage. This control may be implemented as:

- Integral cycle control
- Phase angle control

In the first method the thyristors are turned on for integral cycles, while in the second type they are turned on for a portion of the switching period time defined as duty cycle. The latter produces characteristic harmonics, which are multiples of line frequency, while the former injects noncharacteristic harmonics, lower than line frequency. These noncharacteristic harmonics can result in voltage flickers.

*Cycloconverters.* A cycloconverter is an ac/ac converter, which directly converts ac power at one frequency to ac power at another frequency without an intermediate dc link. The output voltage of the cycloconverter is made up of segments of input voltage and the average value of a segment depends on the delay angle for that segment. These converters produce harmonics, which can be expressed as (3)

$$f_h = f_1(kq \pm 1) \pm 6nf_0 \qquad (18)$$

where

$f_1$ = ac system frequency
$f_h$ = harmonic frequency imposed on the ac system
$f_0$ = output frequency of the cycloconverter
$q$ = converter pulse number
$k, n$ = 1, 2, 3, ....

The first term in Eq. (18) represents $q$-pulse converter components and the second term denotes the converter's sideband characteristic frequencies. The input power factor of this converter is also low. For compensation of poor power factor and harmonic elimination, the delay angles of voltage segments are varied in such a way that the average values of the segments correspond as closely as possible to the variations of desired sinusoidal output voltage. Further details are given in (8).

*Adjustable Speed Drives.* The development of advanced power electronic switching devices has enabled high-frequency switching operation and has improved the performance PWM inverters for driving ac motors. Switching frequencies of 2 kHz to 20 kHz are common with insulated gate bipolar transistors (*IGBT*) technology for power levels up to 200 kW. In many industrial applications the PWM inverter and motor must be at separate locations, thus requiring long motor leads. While the high-frequency switchings significantly improve the performance of PWM inverters, the high rate of voltage rise (*dv*/*dt*) has adverse effects on the motor turn insulations and contributes to bearing currents (common-mode currents) (10). Traveling waves caused by long cables connecting the inverter to the motor can also increase the transient overvoltage across motor windings (11). Filtering techniques to reduce the adverse effects of long motor leads can be used for high-frequency PWM inverter-fed ac motor drives (12).

**Arc Furnaces.** The harmonics produced by electric arc furnaces are of a random nature due to variations of arc in multiple cycles. These include both integer and noninteger order harmonics. It has been noticed that integer lower order harmonics are the most significant and that the amplitude decreases with order.

**Saturated Magnetic Devices.** Power transformers generate small levels of harmonic currents in steady state condition. This is due to the hysteresis characteristic and to the small degree of saturation, which is present in all transformers. Balanced third-order harmonic current will normally be absorbed by the delta windings of most transmission and distribution transformers. Higher-order line current harmonics such as fifth and seventh will have a very low value, probably less than 0.1% of the transformer rated current. Transformers can produce very large harmonic levels when they are initially energized. The inrush currents of transformers include all harmonics including the dc component for few seconds after being energized. These transient-nature harmonics may be up to 60% of the rated current and can cause damage if they excite parallel resonance with capacitors used as power factor correction and harmonic filters (9). Another source of harmonics is the ballast inductor in fluorescent lamps, which can cause significant levels of harmonics (especially of third order), for example, in large buildings.

**Static Var Compensators (*SVC*s).** SVCs have been frequently used in power systems. They have replaced the old mechanically switched capacitor banks used for reactive power compensation. The advantages of SVC installations in power systems include:

- Reactive power compensation of loads
- Power factor correction
- Asymmetry compensation
- Voltage regulation
- Line sectioning
- Dynamic and transient stability improvement

Two types of SVC can be used for reactive power compensation: conventional SVC and advanced SVC.

*Conventional SVC.* The conventional type SVC uses one of the following three structures, to implement the variable reactive power generation:

- Thyristor controlled reactor (*TCR*)
- Thyristor switched capacitors (*TSC*)
- Saturable reactors

These structures all have a nonlinear nature and thus produce harmonics. The configuration of a TCR, which is the most commonly used structure, is shown in Fig. 7.

This structure can produce harmonic currents which, their rms can be written as (13)

$$I_n = \frac{4}{\pi}\frac{V}{X_L}\left[\frac{\sin(n+1)\alpha}{2(n+1)} + \frac{\sin(n-1)\alpha}{2(n-1)} - \cos\alpha\,\frac{\sin n\alpha}{n}\right] \quad (19)$$

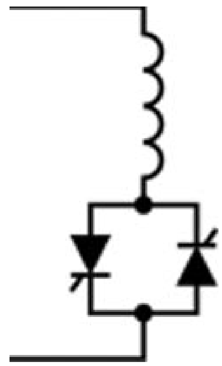

**Fig. 7.** Thyristor-controlled reactor (*TCR*) used for reactive power compensation. TCR generates characteristic harmonics in a power system.

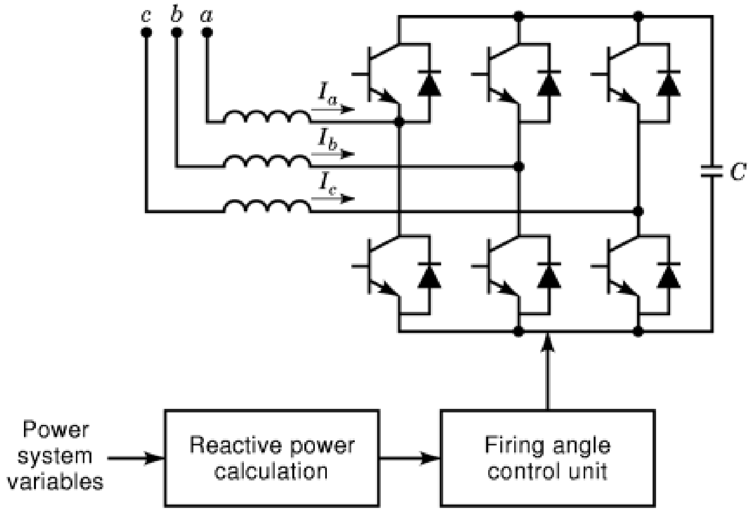


**Fig. 8.** The structure and control of a voltage-source inverter (*VSI*) advanced SVC. ASVC generates high-order harmonic currents which can be easily eliminated by a filter inductance.

where

$n$ = harmonic order (3, 5, 7, ...)
$V$ = line-to-line fundamental voltage
$X_L$ = reactance in each phase
$\alpha$ = firing angle of *TCR*

*Advanced SVC (ASVC).* This type of SVC, also called synchronous SVC, along with its appropriate control is shown in Fig. 8. The converter in this figure is a voltage-source inverter (*VSI*). An alternative is to use current-source inverters (*CSI*).

This implementation has advantages over conventional SVCs as:

- Large energy storage inductors or capacitors are not required to meet the var demand. Only a small capacitor or inductor with minimum energy storage is sufficient to cover the full reactive power range. The dc side voltage is controlled by the switching pattern of the inverter, which guarantees sufficient real power

transfer from the ac system to compensate for losses and to maintain the desired dc voltage, determined by reactive power demand.
- Instantaneous var control is achieved as the ac side voltage and current can be quickly controlled in magnitude as well as in phase compared to the network voltage (leading or lagging).

The advanced SVC can be controlled in many ways, among which PWM has the advantage of harmonic control in the ac side voltage. The output phase voltage harmonics produced by PWM controlled inverter, are calculated in Eqs. (20) and (21):

$$V_{\text{ph}} = \sum_{n=1}^{\infty} b_n \sin n\omega t \quad (20)$$

$$b_n = \frac{2V_{\text{dc}}}{n\pi}\left[2\left(\sum_{k=1}^{n}(-1)^{k+1}\cos\alpha_k\right) - 1\right] \quad (21)$$

where
$V_{\text{ph}}$ = output phase voltage of inverter
$V_{\text{dc}}$ = dc side voltage
$\alpha_k$ = PWM switching angles

By selecting the angles $\alpha_k$, harmonic content of the PWM wave can be minimized.

**Thyristor-Controlled Series Compensation (TCSC).** Series compensation of transmission lines can be implemented by using thyristor-controlled series capacitors. This controlled reactance placed in series with the line, have the following advantages:

- Increasing transmission line capacity
- Mitigation of subsynchronous resonance (*SSR*) phenomena, often caused by fixed series capacitors
- Transient and dynamic stability improvement
- Adaptation to network changes

TCSC structure consists of a TCR in parallel with a fixed capacitor. This type of compensator produces voltage harmonics in series with the line.

## Harmonic Calculations and Measurements

The measurements regarding harmonics consist of three main issues: the choice of transducer to connect the measurement system to the ac network, the type of measurement system used to store the data, and the analytical techniques used to process the data.

The transducers used are usually voltage and current transformers, which give reasonable accuracy in the range up to 2 kHz. This range covers the frequency range required for many harmonic measurement studies. The measurement instruments that can be used cover a wide range of applications and costs. These instruments usually consist of digital signal storage units with computer-based processing that sample the input voltages and currents and calculate fast Fourier transform (*FFT*) of these signals. A verity of such systems is mentioned in Refs. 3 and 14.

Analysis and calculations of harmonics and effects of nonlinear loads on system parameters can be carried out in two domains; frequency domain and time domain. In the frequency domain calculations, the harmonic spectrum of load is established; then load is treated as a current source, which injects harmonic currents into the network. In most of the time domain algorithms, computer packages are used to simulate the differential equations of the system and to solve these equations. In this way it will become possible to build up a system model for harmonic calculations which will avoid many of the approximations which are present in the frequency domain.

Another approach to model the system is to use state-space technique. In this method the differential equations that relate the voltages and currents to system parameters ($R$, $L$, and $C$) are found through basic circuit analysis. These equations are then presented in the form of state equations as

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{22}$$

where $A$ is the state matrix of the system, $x$ is the state vector, $u$ is the input or control matrix, and $y$ is the output vector. These equations are sufficient to determine the behavior of the system when one knows:

- initial values of state variables
- input signals

The matrices $A$, $B$, $C$, and $D$ are found from differential equations governing the system, as is extensively discussed in Ref. 15. In this approach one can determine:

- Values of poles and zeros of the network and the potentially dangerous resonance frequencies
- Ways to eliminate or shift these resonance frequencies
- Capacitor switching strategies in case of SVC or switched capacitor usage

## Harmonics Effects on Electrical Networks

The degree to which harmonics can be tolerated is determined by the susceptibility of electric devices. The least susceptible type of equipment is that in which the main function is heating, as in an oven or furnace. In heating devices, the harmonic energy is generally utilized and hence is quite tolerable. The most susceptible type of equipment is that whose design or constitution assumes a nearly perfect sinusoidal input. This equipment is frequently in the categories of communication or data processing equipment. A type of load that normally falls between these two extremes of susceptibility is the motor load, which is relatively tolerant of harmonics. However, generating oscillating torque in rotating machinery can cause audible noise and mechanical vibrations, which can be harmful to the machine and its load. Even in the case of the least susceptible equipment, harmonics can be harmful. In an oven, for example, they can cause dielectric thermal or voltage stress, which causes premature aging of electrical insulation. Electromagnetic interference (*EMI*) is a major problem caused by high-frequency harmonics. High-frequency switching converters are the main sources of EMI. Harmonics effects on electric networks are briefly discussed in the following sections.

**Effects of Network Impedance.** All network components—conductors, transformers, loads, and capacitors—are in series or parallel with the network, which represents complex impedance at harmonic frequencies. Figure 9 is the equivalent circuit of such a network.

The feeding network is represented by its short-circuit inductance $X_L$. The disturbance-generating load is represented by a source of harmonic currents $I_H$ connected across the network equivalent impedance $Z_H$. This

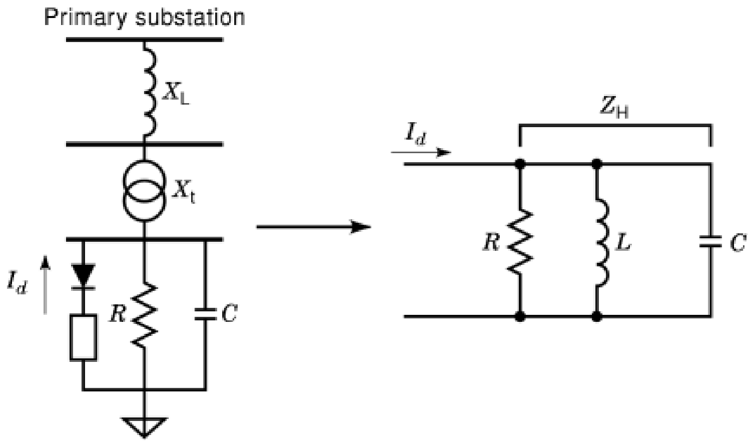


**Fig. 9.** Diagram of a primary substation feeding loads, including a rectifier, and the equivalent harmonic diagram.

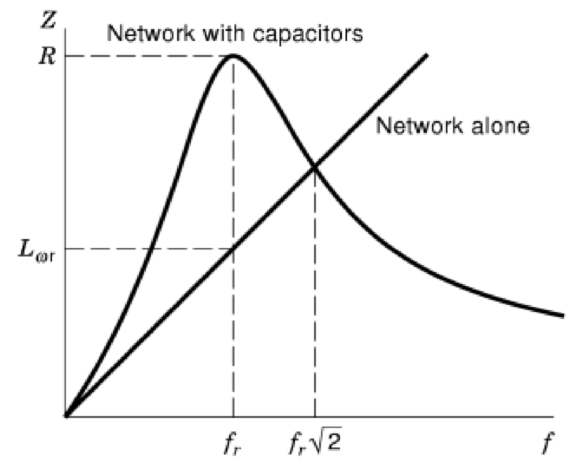


**Fig. 10.** Network impedance as a function of frequency with and without capacitors. One can see that with capacitors the impedance has a peak at resonance frequency $f_r$. The existence of a harmonic current at this frequency results in an overvoltage.

impedance includes resonant points, basically due to the presence of capacitor banks or the capacitance of the power supply cables. Connecting capacitors in parallel with the network equivalent inductance considerably increases the network impedance at resonant frequency. This can result in the flow of harmonic currents through the resonant circuit and thus generation of high harmonic voltages complying with Ohm's law: $V_H = Z_H \cdot I_H$. The resonant frequency is $f_R = f(S_{SC}/Q_C)^{1/2}$, where $f$ is line frequency, $S_{SC}$ is the network short-circuit power, and $Q_C$ is the capacitor reactive power. Currents flowing through the resonant circuit are amplified by a factor $F = (S_{SC} \cdot Q_C)^{1/2}/P$, where $P$ is the network active power (16). Figure 10 shows the network impedance with and without capacitors.

**Harmonic Effects.** Major effects of harmonics on electric equipment can be listed as (3):

- Lowered efficiency because of increased heating due to iron and copper losses at the harmonic frequencies in electromagnetic equipment. The current harmonics cause increase in copper losses, and voltage harmonics result in an increase in iron losses.

- Oscillating torque generated in rotating machinery, either synchronous or induction: Harmonics such as the fifth and seventh have the potential for creating mechanical oscillations in a turbine-generator combination or in a motor-load system. These oscillations are caused by the interaction between the harmonic currents and the fundamental frequency magnetic field.
- Audible noise generated in motors and transformers. One of the sources of noise in motors is the application of PWM motor drives. This problem can be overcome by application of the random PWM inverters to spread the concentrated noise energy of the PWM over a wide frequency range (17).
- Derated power cables. The increase in the resistance of cable is caused because of two phenomena: skin effect and proximity effect. This can result in increased loss, which may cause insulation failure in cables.
- Increased heat and dielectric stress in capacitors. Capacitors provide a low-impedance path for harmonic currents; thus all harmonic currents tend to pass through them, which causes heat loss and dielectric stress.
- Shifted zero voltage crossing. This phenomenon causes malfunction in the power electronic equipment and its control circuit whose operation depends on the zero voltage crossing of the voltage wave.
- Meter errors due to phase shifting resulted from higher-order harmonics. Induction disk devices, such as watthour meters, normally see only fundamental current; however, phase imbalance caused by harmonic distortion can cause erroneous operation of these devices.
- Harmonic currents can increase heating and losses in switchgear, thereby reducing steady-state current carrying capability and shortening the life of some insulating components. Fuses suffer a derating because of the heat generated by harmonics during normal operation. The operation of relays can also be affected in the presence of harmonics.
- Harmonic currents and voltages in circuitry associated by power conversion apparatus can produce magnetic and electric fields that will impair the satisfactory performance of communication systems.

***EMI* Problems.** Power electronic equipment usually generates disturbances in two ranges: low frequency and high frequency. The low-frequency range disturbances (below 1250 Hz) are harmonic currents and the voltages generated by non-linear loads discussed so far. These harmonics cause voltage distortion. By compensation techniques, they can be shifted to higher frequencies, for example, by applying passive or active filtering or active wave shaping. Using these techniques to eliminate low-frequency harmonics and to improve power factor can cause high-frequency disturbances. These disturbances are mostly generated by switching action of semiconductor devices (*BJT*s, *MOSFET*s, *IGBT*s, etc.). Disturbances in high-frequency range may also be generated by mechanical switches. These switches (relays, circuit breakers, etc.) cause wideband emission in the form of damped oscillation in the 10 kHz to 1 GHz range.

Disturbances generated by switching devices are due to:

- High-frequency switching harmonics
- Very short rise times and fall times caused by commutation action of switches. These rise times and fall times which are about 0.5 $\mu$s cause significant energy levels at radio frequency range.

These high-frequency disturbances are referred to, as electromagnetic interference (*EMI*). EMI can be transmitted in two ways: radiated and conducted. The radiated form is propagated in free space as electromagnetic waves, while the conducted form is transmitted through power lines, specially at distribution levels. Conducted EMI is usually orders of magnitude higher than the radiated noise. There are two types of propagation for conducted EMI: differential mode (or symmetrical) and common mode (or asymmetrical). Differential mode propagation takes place between two conductors that form a conventional return circuit, and common mode propagation takes place between a group of conductors and ground or another group of conductors (Fig. 11).

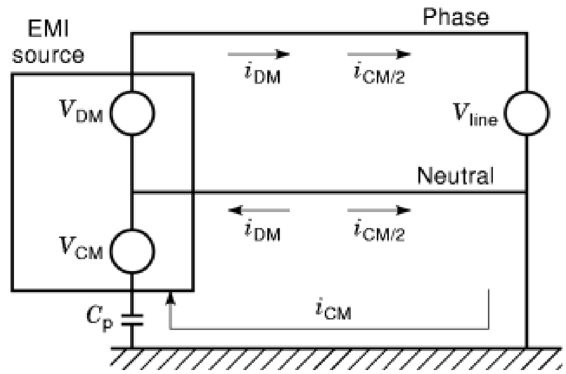


**Fig. 11.** Differential mode and common mode conducted EMI (18). $i_{DM}$ and $i_{CM}$ represent differential mode and common mode currents, respectively. $C_p$ is a parasitic capacitance between the device and the common ground.

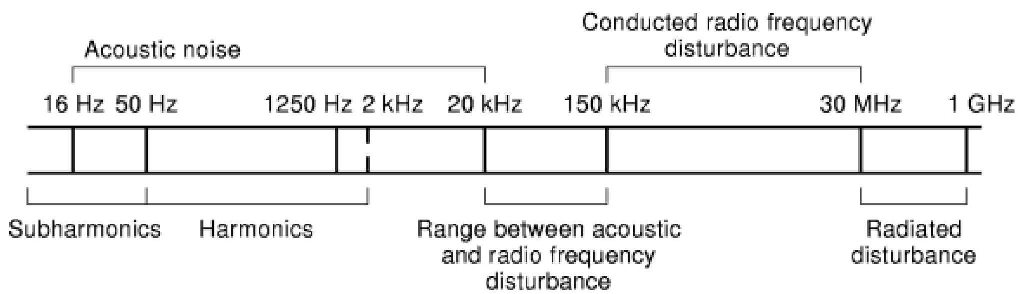


**Fig. 12.** Classification of electromagnetic disturbances by frequency (19).

The assorted high-frequency disturbances are illustrated in Fig. 12. The noise at frequencies around a few kilohertz can interfere with audiovisual equipment and electronic clocks, and depending on the particular customer, noise can cause audible effects. The ways to prevent such interferences from propagation is to apply:

- Shielding for radiated EMI
- Proper filtering for conducted EMI

There are various CISPR, IEC, VDE, FCC, and military standards that specify the maximum limit on the conducted EMI. These limits may vary for equipment used in commercial, industrial, and office or residential environments. To compare against these limits, the conducted noise is measured by means of a specified impedance network called *LISN* (line impedance stabilization network). Standards for the radiated EMI are also specified by various agencies. EMI problems and practical solutions and standardization status are fully illustrated in Refs. 18,19,20,21.

## Power Factor Control

In recent years the increasing use of nonlinear loads, specifically power electronic converters, has led to problems such as harmonic pollution and low-power factor. Electric energy providers penalize the low power factor of any type of load. The flow of reactive power due to low-power factor loads causes extra charge and occupies extra line capacity for power transmission. Therefore many economical reasons have forced the manufacturers of electrical equipment to include power factor correction devices into their products.

**Advantages of Power Factor Correction.** A high-power factor is desirable in many points of view. These advantages can be mentioned as:

- Utility Bill Reduction A number of utilities use kVA billing for their customers. Thus, by adding capacitors on the load side of the billing meter, the apparent power and therefore billing charges are reduced. In other words, reactive component of current is compensated by improving power factor. Thus the current rating of the equipment used to deliver the electric energy to the load is reduced. This results in cheaper equipment and reduced billing charges.
- Increasing Capacity for Existing Systems Power factor improvement reduces the line power rating; thus it releases system capacity. Adding capacitors to an existing system is often the most economical means of improving power factor to obtain more system capacity to serve additional loads. The necessary power factor for a certain per-unit release of system kVA is given by

$$\mathrm{PF_{new}} = \frac{\mathrm{PF_{old}}}{1 - \mathrm{kVA_{required}}} \tag{23}$$

  where
  $\mathrm{PF_{new}}$ = corrected power factor
  $\mathrm{PF_{old}}$ = uncorrected power factor
  kVA = required kVA production (in p.u. of existing kVA)

- Loss Reduction Losses are proportional to current squared, so a reduction of current flow results in a much greater reduction of power losses. The loss reduction is given by

$$\text{Loss reduction} = 1 - \left[\frac{\mathrm{PF_{original}}}{\mathrm{PF_{new}}}\right]^2 \tag{24}$$

  With most industrial power distribution systems, the joule losses vary from 2.5% to 7.5% of the load kilowatt hours, depending on hours of full-load and no-load plant operation, conductor size, and length of the main and branch feeder circuit (5).
- Voltage Improvement The following equation may be used to calculate the voltage drop in a line

$$E = IR\cos\varphi + IX\sin\varphi \tag{25}$$

  where
  $E$ = voltage drop across the line
  $I$ = current passing through the line
  $R$ = equivalent line resistance
  $X$ = equivalent line inductance

  Equation (25) for voltage drop may be written:

$$E = (I_{\mathrm{kW}}R) + (I_{\mathrm{kvar}}X) \tag{26}$$

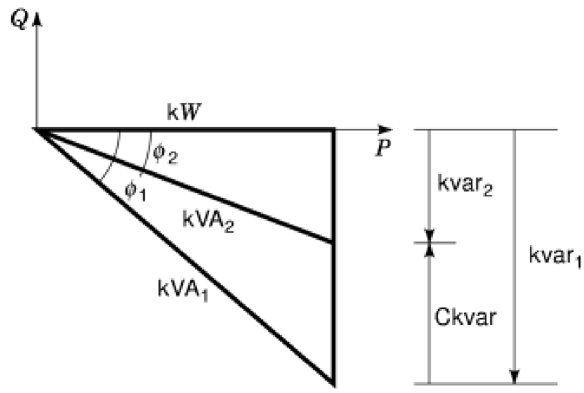


**Fig. 13.** Effect of adding shunt capacitors on improving power factor. Apparent power ($S$) is defined as $S = VI* = P + jQ$, where $P$ and $Q$ are active and reactive power, respectively. Decreasing the reactive power from $\text{kvar}_1$ to $\text{kvar}_2$ results in a smaller displacement angle $\phi$.

where
$I_{\text{kW}}$ = active component of the line current
$I_{\text{kvar}}$ = reactive component of line current

From this expression it can be seen that kvar current operates principally on reactance, and since capacitors reduce kvar current, they reduce the voltage drop by an amount equal to the capacitor current times the reactance.

**Power Factor Correction Methods.** Methods for improving power factor can be classified into two categories: (1) power factor correction for utility power systems, and (2) power factor correction for power electronic converters. As seen in Eq. (10), power factor can be improved by either decreasing the harmonic contents of the current wave or improving displacement factor. The methods for decreasing harmonic contents of current wave are discussed later in this article, while the methods for improving displacement factor for utility power systems are discussed in the following section.

*Power Factor Correction for Utility Power Systems.* Conventional shunt capacitors and static var compensators are the common methods for improving displacement factor and thus power factor in utility power systems. Parallel and series resonance caused by using shunt capacitors are also discussed in this section.

*Shunt Capacitors.* The most conventional and economical way of power factor correction through improving displacement factor is installation of shunt capacitor banks. These capacitors are often used to compensate the lagging power factor of power system loads and delivery apparatus (e.g., lines and transformers) which appear to be inductive in nature. Figure 13 illustrates the compensating role of shunt power capacitors in increasing power factor by providing reactive power for inductive loads. This figure shows reduction of reactive power after compensation ($\text{kvar}_2$) compared to the one before compensation ($\text{kvar}_1$). This is achieved by installing shunt capacitors that supply the system with reactive power equal to Ckvar. As seen in this figure, by using such a method the displacement angle is shifted from $\phi_1$ to $\phi_2$.

The problem in using shunt capacitors for power factor correction is that they can resonate with network reactances at a harmonic frequency. Two types of resonance can occur: parallel resonance which is a high impedance to the flow of harmonic current, and series resonance which is a low impedance to the flow of harmonic current.

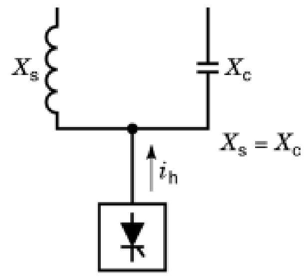


**Fig. 14.** Parallel resonance condition. Presence of harmonic current $i_h$ at resonance frequency causes overvoltage.

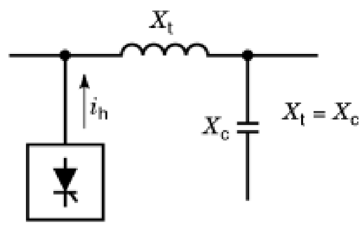


**Fig. 15.** Capacitor banks resulting in series resonance. A low impedance path for the harmonic current $i_h$ at resonance frequency results in high-voltage distortion levels.

*Parallel Resonance.* This kind of resonance occurs when the system inductive and capacitive reactances are equal at same frequency in presence of a harmonic source as shown in Fig. 14. If the combination of capacitor banks and the system inductance result in the parallel resonance, an amplified current is generated that oscillates between the energy storage in the capacitance and the inductance. This current can cause voltage distortion and telephone interference.

*Series Resonance.* This situation is the result of series combination of capacitor banks and line or transformer reactances. Series resonance provides a “trap” or low-impedance path for harmonic currents, which can cause high-voltage distortion levels. An example is shown in Ref. 3 as a transformer with a capacitor connected to its secondary (Fig. 15).

It must be mentioned that besides shunt capacitors, other types of capacitors can cause resonance problems as well. For instance, the capacitive impedance of cables and long overhead lines cause resonance in the range of 5 kHz to 15 kHz. Another example is the series compensation of power lines using series capacitors.

If resonance phenomena are discovered through analysis and experiment, possible solutions (22) include the following:

(1) Ungrounding grounded-wye capacitors, which can limit the level of third-order harmonics in system
(2) Changing capacitor bank sizes and/or locations, which can avoid resonance situations by changing the values of poles and zeros of the system
(3) Adding a reactor to tune the shunt capacitor bank to a harmonic frequency in order to trap a specific current harmonic (as further illustrated later in the article)
(4) Adding a small reactor to an existing capacitor bank, which is used to detune the filter. This method is used to avoid resonance in the tuned frequency by shifting the frequency at which resonance occurs. A disadvantage of such a filter is that it does not provide the zero-impedance path for desired frequency currents. Thus it can only damp such harmonics instead of eliminating them
(5) Controlling the capacitor-switching scheme to avoid resonance, which can be implemented using a conventional SVC or a thyristor or mechanically switched capacitor (TSC) or (MSC)

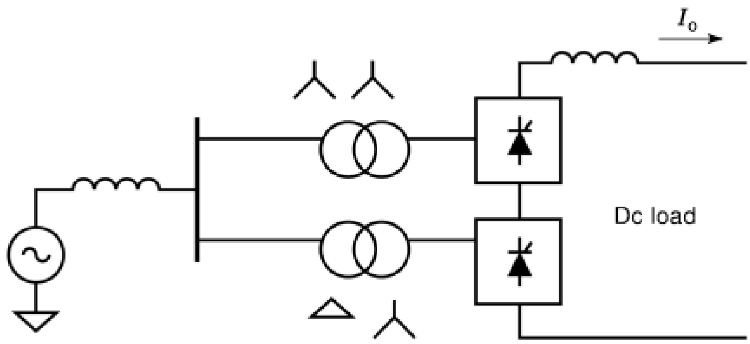


**Fig. 16.** Twelve-pulse converter using a delta–wye transformer for eliminating fifth and seventh harmonics.

*Static var Compensators (SVC).* As mentioned earlier, *SVC*s can be used for load compensation, which include power factor correction. SVC can improve power factor by generating the reactive current that load consumes. In this way the reactive current of the combination of SVC and load is minimized, which leads to near unity power factor. The difference of SVC and a fixed shunt capacitor lies in SVC control circuit, which allows momentary adaptation to load characteristics.

*Power Factor Correction of Power Electronic Converters.* Power electronics converters usually demonstrate low power factor as well as generating harmonics. Active filtering is a method in which harmonics generated by the power electronic converter are instantaneously compensated applying a harmonic generating converter. This method will be discussed later in the section concerning active filters. Active wave shaping is another method to improve displacement factor for ac/dc converters. In this method the phases of voltage and current are instantaneously matched to minimize reactive power demand of nonlinear loads. This will be discussed later in the section concerning active shaping of line current.

## Harmonic Control

Nonlinear loads draw current in a nonuniform manner, and the voltage drop caused by these currents across source impedances results in a distorted voltage waveform. In order to maintain harmonic disturbances at reasonable levels, to comply with existing standards, we can go through various solutions applicable to supply systems and to harmonics sources.

**Using Higher-Order Pulse Converters.** As derived in the section concerning static power converters, harmonic orders generated by power rectifiers are given by $n = kq \pm 1$. This equation clearly shows that an efficient way to reduce number of harmonics produced by such systems is using converters with higher-pulse numbers. The most widely used example is that of the 12-pulse bridge configuration. The layout of such bridge is shown in Fig. 16. In this bridge two 6-pulse converters are used, which produce fifth and seventh-order harmonics each. A delta–wye transformer shifts the phase of one six-pulse converter by $30^\circ$. This causes the fifth and seventh harmonic currents to cancel. Complex-wound transformers may be used to cancel out more harmonics in expense of higher transformer cost (23).

**Applying PWM Techniques.** This control scheme is used to cancel low-order harmonics. This technique was discussed earlier.

**Passive Filters.** Shunt power capacitors that improve the power factor can also be used to attenuate harmonic currents. However, as discussed earlier, shunt capacitors can cause resonance with power system reactances. To avoid resonant conditions and limit harmonic currents, two passive solutions are (a) increasing the source impedance by adding a line reactor and (b) providing a low-impedance path or sink for specific injected harmonic currents.

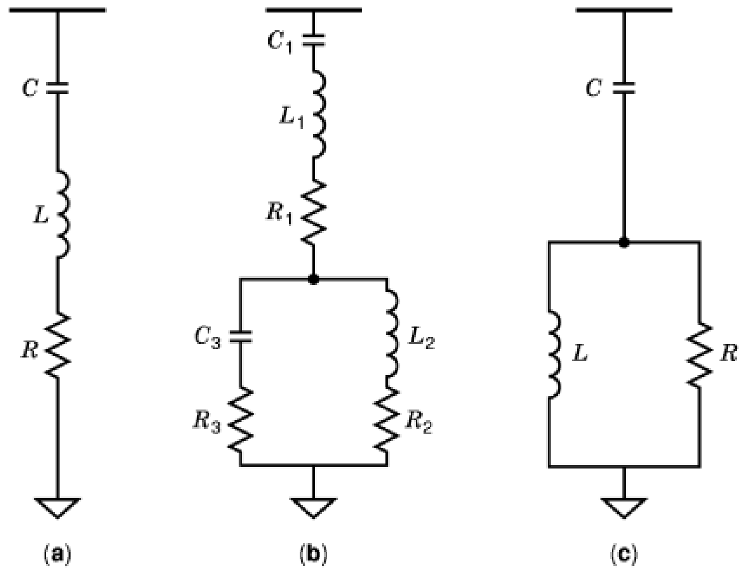


**Fig. 17.** Shunt filters: (a) Single-tuned filter; (b) double-tuned filter; (c) high-pass filter. These filters are used to attenuate harmonics and to improve power factor.

The first solution means applying a series L filter, so it is rarely used, since the full-load current passing through reactor causes great loss. The second can be implemented by dividing shunt capacitors into several banks and then tuning each bank to a different harmonic frequency by adding a series reactor to each bank. Therefore, by providing a low-impedance path for each injected harmonic current, the resulting harmonics in system is minimized.

*Tuned Filters.* The "tuned" filter is a highly selective shunt filter that offers low impedance at given frequencies. The most common tuned filters are single-tuned, double-tuned, and high-pass filters. The filter type usage depends on the nature of the harmonic problem. The general layout of shunt filters is shown in Fig. 17.

The equivalent circuit of a system using single-tuned filters to eliminate fifth-, seventh-, eleventh-, and thirteenth-order harmonics is shown in Fig. 18. In this figure the source of harmonic current is modeled as a constant current source. The transformer and the utility source inductance are modeled as $L_{\mathrm{t}}$, and $L_{\mathrm{u}}$, respectively. The resulting impedance $Z_{\mathrm{h}}$, as seen by the harmonic current source looks like the plot in Fig. 19.

As expected, the impedance has a minimum value at the tuned frequencies. But for each tuned filter there is also a parallel resonance or maximum impedance below the filter frequency but above the next lowest-tuned filter frequency. This is caused by the interaction between the tuned filter and the power system, which can be described as follows: Above the tuned frequency, the filter appears inductive, and hence there is no resonance. But below the tuned frequency, the filter appears capacitive and will resonate with the power system at some frequency. This shows why it is not reasonable to apply filters tuned to higher-order harmonics without using the lower-order ones.

*Damped Filters.* Damped filters generally consist of combinations of capacitors, inductors, and resistors that have been selected in such a way as to present low impedance over a broad range of frequencies. This kind of filter usually has a relatively low-quality factor and dissipates power, considering losses. The main advantage of these filters is that they can prevent resonance.

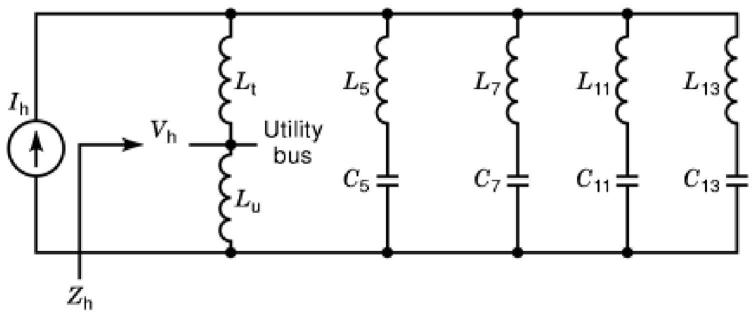


**Fig. 18.** Typical usage of passive filters. This filter contains four branches and attenuates fifth-, seventh-, eleventh-, and thirteenth-order harmonics.

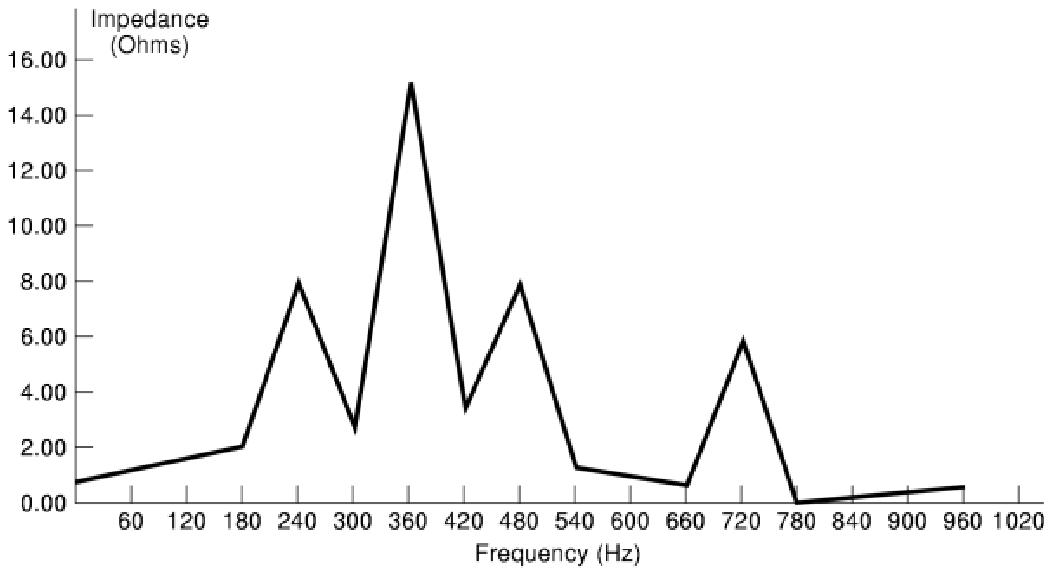


**Fig. 19.** Impedance $Z_h$ versus frequency for a four-filter system (24). The impedance has a minimum value at the tuned frequencies, but for each tuned filter there is maximum impedance caused by the interaction between the filter and power system.

**Active Methods.** Passive filters often provide a simple and efficient way to mitigate harmonics, specially if the harmonics are located inside a narrow-frequency range. The conventional systems used to limit harmonics and compensate for poor-power factors are reactive power compensation capacitor banks and "tuned" and "damped" passive filters, formerly explained. These systems can be installed when the industrial process is designed or added later. However, in certain cases the main drawback is still their rigidity, namely an inability to adapt to network changes and filter component variations (aging, temperature, burning of capacitor elements, etc.). A passive filter is efficient if its impedance at a given frequency is very low compared to that of the source. However, in certain cases compensation becomes difficult if the source impedance is low or if the filter frequency characteristics are not accurately tuned to the harmonics generated by the load.

Another problem with tuned filters is that although some kinds of loads generate second- and third-order harmonics, these filters are not feasible for these harmonics. Also the dc component which always accompanies the second-order harmonic causes reactor saturation. This will result in excessive harmonics and fundamental

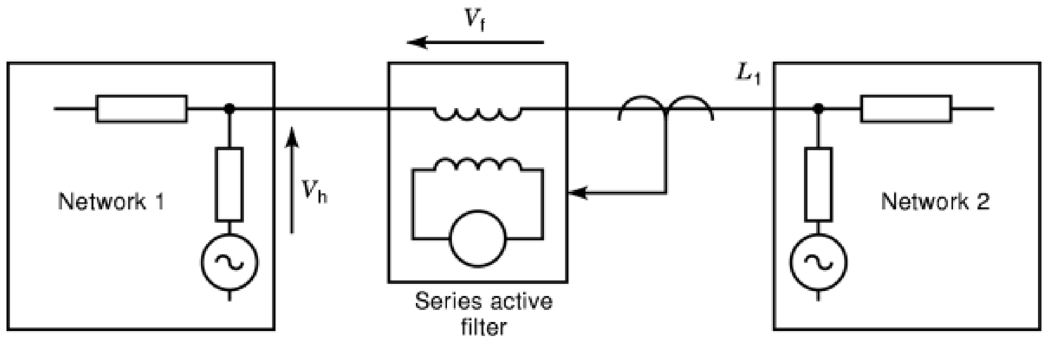


**Fig. 20.** Principles of series active filter. The filter prevents harmonics generated in network 1 from flowing into line $L_1$ to network 2.

current components, which lead to rapid thermal failure (25). The basic disadvantages of passive filters are discussed in detail in Refs. 16, 24, and we briefly mention them as:

- The source impedance strongly affects filtering characteristics.
- As both the harmonic and the fundamental component flow into the filter, the capacity of the filter must be rated by taking into account both currents.
- When the harmonic current components increase, the filter can be overloaded.
- Parallel resonance between the power system and the passive filter causes amplification of harmonic currents on the source side at a specific frequency.
- The passive filter may fall into series resonance with the power system so that voltage distortion produces excessive harmonic currents flowing into the passive filter.
- Insufficient ability for covering wide frequency range with high effectiveness leads to the installation of several filters to mitigate harmonics of various orders.
- The filters have limited flexibility for adapting to variations in the network.
- Where shunt capacitors are not needed to improve the power factor, the passive filter's size and cost can become a considerable issue because of the capacitor banks used in filter structures. So complexity and price of the passive filter must be taken into consideration.

Consequently both for the utility and/or the user, other compensation methods are required to decrease harmonic levels and improve power factor and thus make optimum use of the energy drawn from the network. New solutions offering better performance are under study, and some have already reached the industrial stage. Two existing methods consist of active filtering and active wave shaping.

*Active Filters.* Active filters are controllable voltage or current sources connected between two networks. These voltages or currents present waveforms, which counteract harmonics. According to the way they are connected to the network, active filters are classified as series or parallel ones (26).

A series active filter is shown in Fig. 20. In this case the filter's task is to prevent harmonics generated in the network 1 from flowing into line $L_1$ to the network 2. This is achieved if the active filter injects a voltage in series with the line to cancel out the harmonic component of the voltage $V_h$. A shunt active filter can be modeled as in Fig. 21. In this case the filter is controlled such that the harmonic component of the current of network 1 passes through active filter rather than line $L_1$. The combination of series and parallel topologies is also possible (27).

Active filters can be implemented using powerful microprocessors and *DSP*-based controllers that can handle sophisticated algorithms. These controls may employ time domain or frequency domain processing.

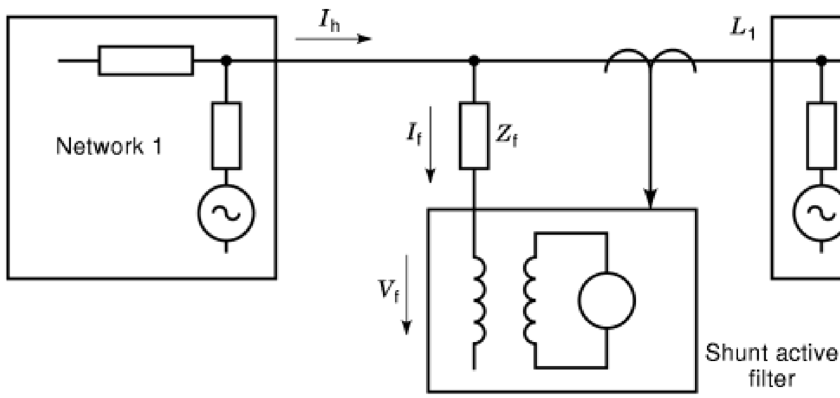


**Fig. 21.** Principle of shunt active filter. The harmonic current $I_h$ passes through the shunt filter rather than line $L_1$.

These filters, in general, can eliminate or attenuate harmonics in a considerable frequency range. They can also tolerate changes in the network characteristics, which permits efficient adaptation to variations in the network. These adaptations can be easily achieved through software modifications. These filters can also be used to avoid resonance situations caused by capacitors in the network and provide unity power factor if desired.

On the other hand, active filters have some drawbacks, which can be listed as:

- They are difficult to construct, specially as large-rated current source with rapid current response.
- Initial costs and running costs are high.

These drawbacks may be overcome by combining active and passive solutions, which can reduce the size and cost of active filters along with advantages of active filtering (28,29).

*Parallel Active Filters.* Three converter topologies can be used as parallel filters: (1) a single parallel converter, (2) a series connection of a converter and passive filters, and (3) a connection of a coupling filter and a converter.

Single Converter. As illustrated in Fig. 21 the active filter behaves as a harmonic current generator. One frequent structure consists of a three-phase voltage-source (Fig. 22) or current-source (Fig. 23) inverter and an output filter to attenuate the inverter switching effects (Fig. 24). The inverter control system is designed to ensure that the inverter outputs a harmonic current equivalent, but of the opposite phase, to that generated by the load. The source-side current is therefore sinusoidal, but the voltage at the connection point will only be sinusoidal if the network voltage source does not generate any harmonics. Because the inverter switching frequency is inevitably limited by the active filter capacity, it is better to compensate high-order harmonics by a small high-pass passive filter.

Series Connection of an Active Filter and Passive Filters. Another topology is to connect the active filter in series with the passive filter, both being parallel with the load as in Fig. 25. With suitable control of the active filter, it is possible to avoid resonance phenomena, improve filter performance and simultaneously reduce the size of the active filter converter. The active filter can be either voltage or current controlled. In current mode control, the inverter is a voltage source to compensate for the current harmonics in order to prevent them from entering the source side. The advantage of this method is that the converter is far smaller [approx. 5% of the

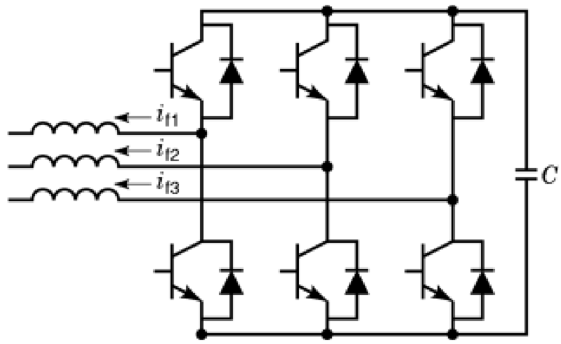


**Fig. 22.** Voltage-source inverter active filter. The inverter control system ensures that the inverter output current cancels the load harmonic currents.

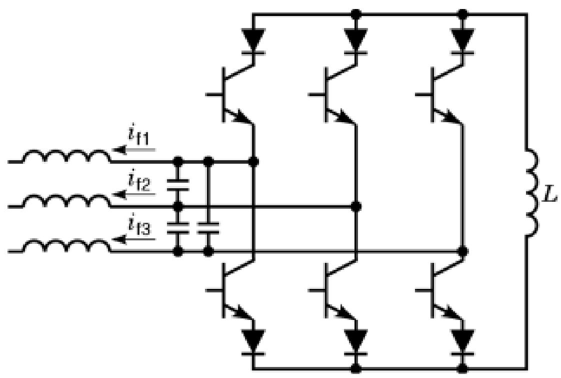


**Fig. 23.** Current-source inverter active filter. The resultant output currents $i_{f1}$, $i_{f2}$, and $i_{f3}$ compensate for load harmonics.

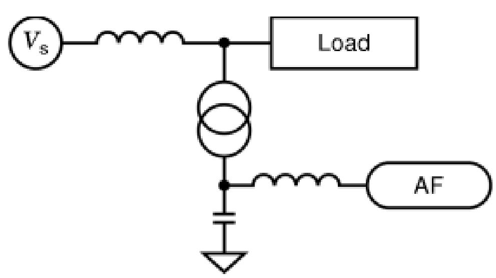


**Fig. 24.** Parallel active filter (AF) with an output filter to attenuate the inverter switching effects.

load power (29)]. Moreover any short-circuit on the load side cause no problems. In voltage mode control, the converter is a voltage-source inverter controlled to compensate for the voltage harmonics at the connection point to the network (16).

Connection of a Coupling Filter and Converter. It is possible to connect active filter to a higher-voltage network by using a coupling filter. This filter consists of two passive dipoles $Z_1$ and $Z_2$ as shown in Fig. 26.

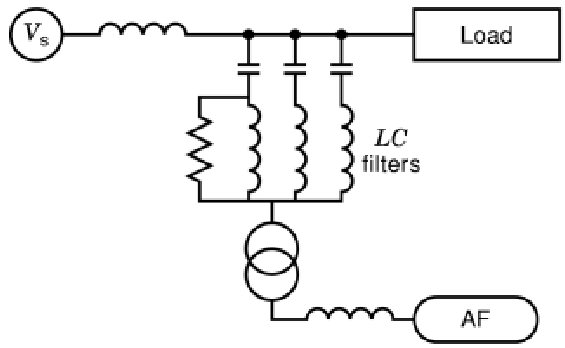


**Fig. 25.** Active filter (AF) along with parallel *LC* filter. This conjunction reduces the size and cost of the active filter as well as avoiding resonance phenomena and providing an improved filter performance.

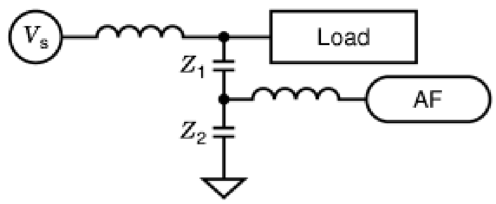


**Fig. 26.** Parallel active filter (AF) with coupling filter consisting of two impedances $Z_1$ and $Z_2$ as a voltage divider to reduce the voltage across the active filter.

Dipoles $Z_1$ and $Z_2$ act as a voltage divider, considerably reducing the voltage across the terminals of the active filter.

*Series Filters.* The only series configuration of any interest involves connecting passive filters in parallel with an active series filter (Fig. 27). In this case the passive filters absorb the current harmonics generated by the load, while the series active filter helps isolate the passive filters from the source. It is therefore reasonable to assume that the disadvantages of passive filters can be overcome. Thus the series filter must have:

- Zero impedance at the fundamental frequency
- Very high impedance to all harmonic currents on the load side
- A high impedance compared to the source impedance to avoid interaction between the source and the passive filter (antiresonance phenomenon)

This configuration compensates both for current harmonics on the load side and voltage harmonics originating from the source.

*Active Filter Control.* Various control strategies may be applied for controlling active filters. All these strategies share the same control principle shown in Fig. 28. In this control scheme a desired waveshape is calculated for the network voltage or current; then the converter switches are controlled in a manner to maintain the converter voltage or current close to the desired reference values.

Several methods can be applied to calculate the reference signal for proper harmonic elimination, power factor correction and asymmetric compensation. These methods are fully illustrated in Refs. 30,31,32,33,34. They either perform the calculations on input voltage/current signals or calculate the active and reactive components of the input signals in order to obtain the desired waveform. The former is the signal method. The

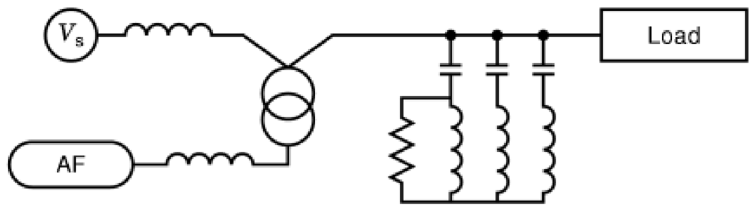


**Fig. 27.** Series filter and passive *LC* filter. The *LC* filters absorb the current harmonics and the active filter (AF) isolates the passive filter from the source side.

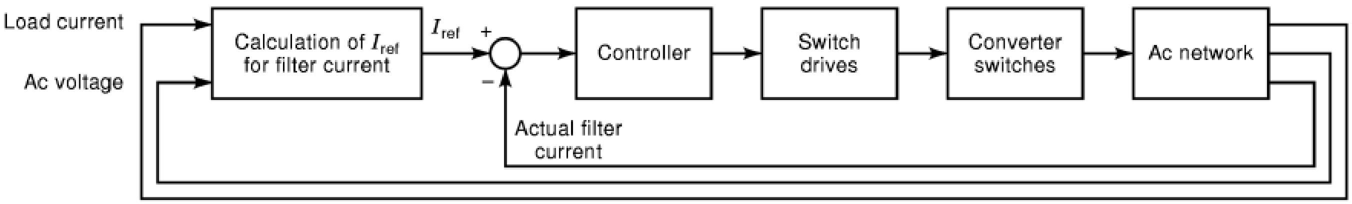


**Fig. 28.** General control block diagram of active filters. After comparing the calculated current reference with the actual current, the converter switches are controlled in a manner to reduce the error signal.

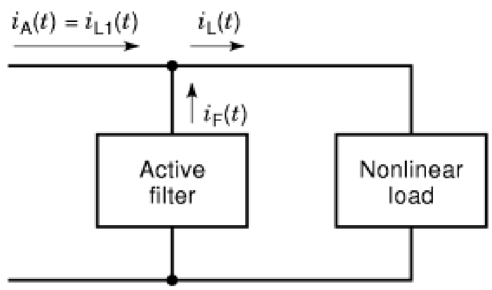


**Fig. 29.** The principal scheme of active power filter. The filter current $i_F(t)$ compensates for harmonic contents of load current $i_L(t)$.

later is based on power theory, which can be used in two ways: instantaneous reactive power compensation and current-voltage matching.

Signal Method. The basic principles of the first control method can be explained using Fig. 29. In order to eliminate harmonics from the source current $i_A(t)$, the current $i_L(t)$ is sampled. These samples are passed through passive filters, which take out the fundamental component of the load current $i_{L1}(t)$. Then the desired $I_F(t) = i_L(t) - i_{L1}(t)$, which guarantees that $i_A(t)$ is free of harmonics (34).

Instantaneous Reactive Power Compensation. The instantaneous power method calculates the desired current such that the instantaneous active power and reactive power in a three-phase system are kept constant. In other words, the active filter compensates for the variations in instantaneous power. The theory of this method is developed by Akagi and is now widely applied in active filters and reactive power compensators (29,30). This theory can be shortly explained as follows: By applying a linear transformation the phase voltages $e_u$, $e_v$, $e_w$ and the load currents $i_{Lu}$, $i_{Lv}$, $i_{Lw}$ of a three-phase system are transformed into the $\alpha$–$\beta$ coordinate (two-phase system) frame by the expressions

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_u \\ e_v \\ e_w \end{bmatrix} \tag{27}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \tag{28}$$

Two new definitions—instantaneous real power $p$ and instantaneous imaginary power $q$ on the load side—can be defined as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{29}$$

In Eq. (29) $q$ does not have the dimension watt, volt-ampere, or var because $e_\alpha . i_\beta$ and $e_\beta . i_\alpha$ are defined by the product of the instantaneous voltage in one phase and the instantaneous current in the other phase. This equation can be rewritten as

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \tag{30}$$

This implies that the determinant with respect to $e_\alpha$ and $e_\beta$ in Eq. (30) is not zero. Now let $p_{dc}(q_{dc})$ and $p_{ac}(q_{ac})$ be the dc and ac components of $p(q)$, respectively. The following equations exist:

$$p = p_{dc} + p_{ac} \tag{31}$$

$$q = q_{dc} + q_{ac} \tag{32}$$

where

$p_{dc}$ = dc component of instantaneous real power due to fundamental frequency
$p_{ac}$ = ac component of instantaneous real power due to harmonic frequencies
$q_{dc}$ = dc component of instantaneous imaginary power due to fundamental frequency
$q_{ac}$ = ac component of instantaneous imaginary power due to harmonic frequencies

From the Eq. (30) the $\alpha$ and $\beta$ phase load currents $i_\alpha$, $i_\beta$ can be written as

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ q \end{bmatrix} = \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \tag{33}$$

where

- $\alpha$-axis instantaneous active current:

$$i_{\alpha p} = \frac{e_\alpha}{e_\alpha^2 + e_\beta^2}\, p \tag{34}$$

- $\alpha$-axis instantaneous reactive current:

$$i_{\alpha q} = \frac{-e_\beta}{e_\alpha^2 + e_\beta^2}\, q \tag{35}$$

- $\beta$-axis instantaneous active current:

$$i_{\beta p} = \frac{e_\beta}{e_\alpha^2 + e_\beta^2}\, p \tag{36}$$

- $\beta$-axis instantaneous reactive current:

$$i_{\beta q} = \frac{e_\alpha}{e_\alpha^2 + e_\beta^2}\, q \tag{37}$$

The physical meaning and reason for the naming of the instantaneous active and reactive currents are fully illustrated in Ref. 35.

In the active filter control circuit, first the values of $p$ and $q$ are computed using Eqs. (27)–(29). Then the reference current signals are calculated using the equation

$$\begin{bmatrix} i_u^* \\ i_v^* \\ i_w^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} -1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p^* + p_{av} \\ q^* \end{bmatrix} \tag{38}$$

Where $p_{\rm av}$ is the instantaneous real power corresponding to the loss of the active filter, and the reference power components $p*$ and $q*$ are given by the equations for proper harmonic filtering:

$$p^* = -p_{ac} \tag{39}$$

$$q^* = -q_{ac} \tag{40}$$

This is due to the fact that the $p_{\rm ac}$ and $q_{\rm ac}$ are generated by higher-order harmonics other than the fundamental components of voltages or currents. By canceling these power components, the corresponding harmonics will be eliminated. This can be realized by application of a high-pass filter to calculate the ac components of $p$ and $q$. In the case where reactive power compensation is also desired, the reference $q*$ must be calculated as:

$$q^* = -q_{\mathrm{dc}} - q_{\mathrm{ac}} \tag{41}$$

Current-Voltage Matching. The basic principle of this method is that the current is forced to match the fundamental component of voltage (31). In other words the desired current is calculated by multiplying the sinusoidal voltage by a coefficient $K$, which is determined by load power. So both harmonic elimination and power factor correction can be achieved. We can assume that the load current $i_{\mathrm{Load}}(t)$ is composed of two components:

$$i_{\mathrm{Load}}(t) = Kv(t) + i_q(t) \tag{42}$$

where

$Kv(t) =$ active component of load current
$i_q(t) =$ nonactive component of the load current
$v(t) =$ fundamental component of source voltage

$K$ is a coefficient that is calculated in the control system. The nonactive component must be compensated to have the maximum power factor and efficient harmonic rejection. So the desired instantaneous reference current for the active filter is written as

$$i_q(t) = i_{\mathrm{Load}}(t) - Kv(t) \tag{43}$$

*Active Shaping of Line Current.* By using power electronic converters with appropriate control systems, the input current of these converters can be forced to follow a sinusoidal waveform in phase with voltage. This implies that the input displacement factor of the converter is equal to 1, and the power factor is thus maximized. Various solutions based on the use of reactive components have been proposed, but they are impractical in 50 Hz to 60 Hz single-phase lines due to size, weight, and cost problems.

An attractive solution is to use a diode bridge in conjunction with a single-switch chopper. In this method the dc/dc converter is placed between the bridge rectifier and the dc load. A sample diagram of such a system, employing a boost dc/dc converter, is shown in Fig. 30. This is an extremely simplified circuit, since it only has one single fully controlled switch. Using this configuration allows one to:

- Change the dc output voltage or regulate it as input voltage changes
- Compensate for the poor power factor and high harmonic contents of the input current wave

In this method, low-frequency harmonics generated by nonlinear loads are shifted to higher frequencies by switching frequency modulation.

It should be noted that these converters require passive filters on the ac side to attenuate the ripple caused by switching. Smaller filters are possible if the switching frequency is increased. Nonetheless, depending on the capacity of the power supply, the frequency is inevitably limited by switching losses. Based on these considerations, various converter topologies can be used for active wave shaping, among which a diode bridge along with a step-up (boost) dc/dc converter is the most common. A unity-power factor converter, which uses boost pre-regulator, is shown in Fig. 30.

*Control Strategies.* As mentioned previously, all control strategies of the dc/dc converter must guarantee that:

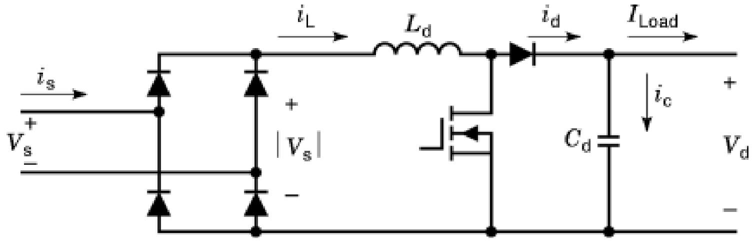


**Fig. 30.** Sinusoidal input current rectifier using boost preregulator. The current mode operation of the boost converter ensures that the rectifier draws a sinusoidal current in phase with the voltage from the ac source.

- The output voltage has the desired value.
- The input current has the same waveform and phase as the input voltage.

There are two ways to accomplish the above requirements, which are presented below.

*Multiplier Control Approach.* This method uses an input-current feedback loop which commands the dc/dc converter to work as a current sink, programmed from the input voltage. This control is called the multiplier control, based on the fact that an analog multiplier is used in the feedback loop. This feedback control of the step-up converter is given as the block diagram in Fig. 31. In this figure the $i^*_L$ represents the desired value of the input current, which must have the same waveform as $|v_s|$. Its amplitude must be such that the output voltage $v_d$ is maintained on a level determined by $v^*_d$ despite input voltage and load variations. The switching pattern for the step-up converter is determined by comparing the desired input current and the actual current. This comparison may be done in several ways (21):

- Constant frequency control
- Constant tolerance-band control
- Variable tolerance-band control
- Discontinuous current control

In the first method, the switching frequency $f_s$ is kept constant. When $i_L$ reaches $i^*_L$, the switch in the step-up converter is turned off. The switch is turned on by a clock at a fixed frequency $f_s$. In the second way, the current is controlled such that the peak-to-peak ripple $I_{rip}$ in $i_L$ remains constant. That means that using a preselected value of $I_{rip}$, $i_L$ is forced to be within the tolerance band (hysteresis band), determined by ($i^*_L + I_{rip}/2$) and ($i^*_L - I_{rip}/2$) by controlling the switching status. The current-mode control block diagram and waveforms of $i^*_L$ and $i_L$ are shown in Fig. 32.

In the variable tolerance-band control, the peak-to-peak ripple current $i_L$ is increased in proportion to instantaneous value of $|v_s|$. In the last method, the switch is turned off when $i_L$ reaches $2i^*_L$. The switch is kept off until $i_L$ reaches zero, at which instant the switch is turned on.

During a switching-frequency time period, the following equations can be derived during the on and off intervals of the switch in continuous mode conduction:

$$t_{on} = \frac{L_d I_{rip}}{|V_s|} \tag{44}$$

$$t_{off} = \frac{L_d I_{rip}}{V_d - |v_s|} \tag{45}$$

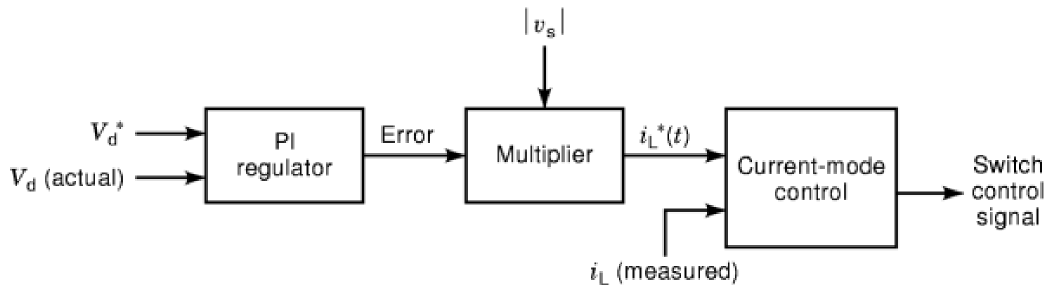


**Fig. 31.** Feedback control of unity-power factor converter (21). The sinusoidal reference of preregulator converter in conjunction with the current-mode controller guarantees the unity power factor operation of the converter.

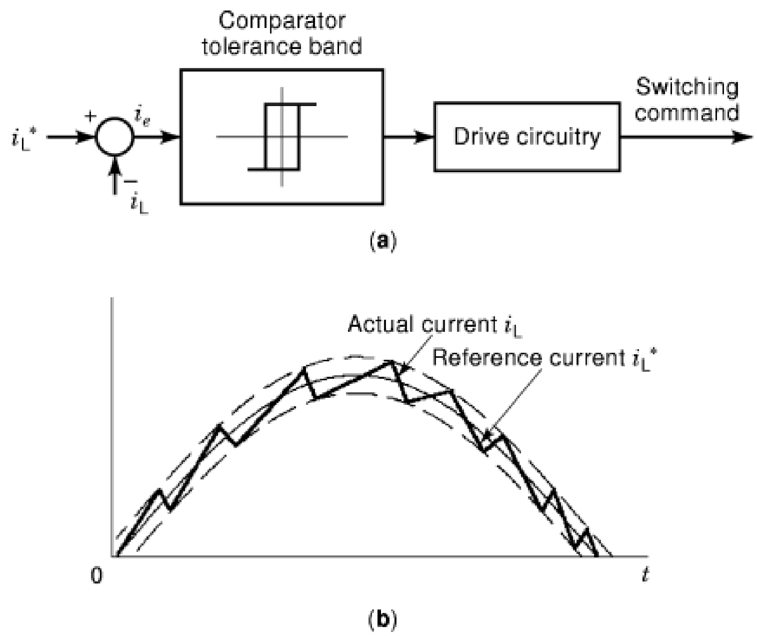


**Fig. 32.** (a) Tolerance-band current-mode control block diagram; (b) $i^*_L$ and $i_L$ waveforms. Converter switching action is performed such that the actual current resides in a band around a sinusoidal reference current.

And the switching frequency $f_s$ is given as

$$f_s = \frac{1}{t_{on} + t_{off}} = \frac{(V_d - |v_s|)|v_s|}{L_d I_{rip} V_d} \tag{46}$$

From Eq. (44), the maximum ripple current in a constant frequency control scheme is given as:

$$I_{rip,max} = \frac{V_d}{4 f_s L_d} \quad \text{when} \quad |v_s| = \frac{V_d}{2} \tag{47}$$

where

$V_d$ = constant output voltage of the step-up converter
$I_{rip}$ = peak-to-peak ripple current during one time period of the switching frequency
$|v_s|$ = absolute value of input ac voltage

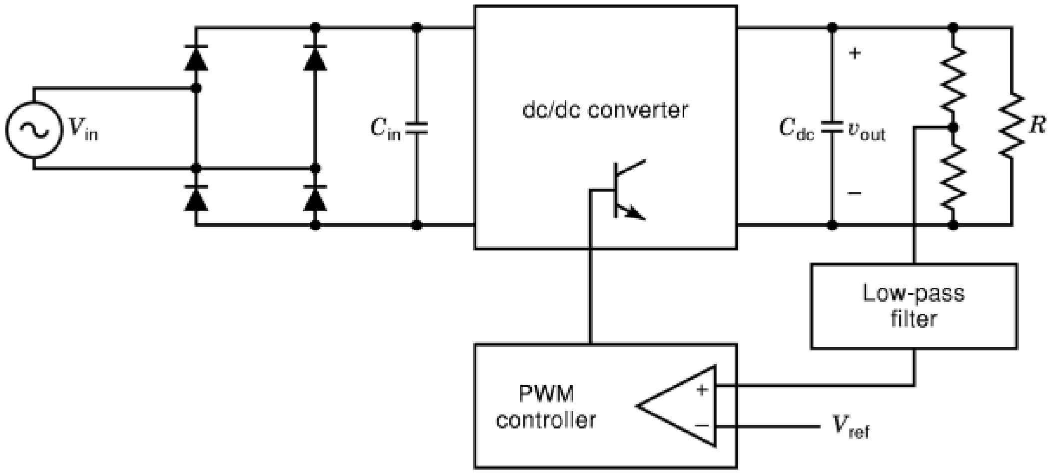


**Fig. 33.** Voltage follower approach. In discontinuous conduction mode operation, the converter can be controlled in such a way that no current feedback is needed.

*Voltage Follower Approach.* Some dc/dc converters like Buck-boost, Sepic, Cuk, and flyback have the property that when they are working in discontinuous conduction mode, the average value of their input current is proportional to the input voltage when the duty cycle and the switching frequency are kept constant. Thus no input current control loop must be used to obtain unity power factor behavior. This control scheme is shown as Fig. 33 (36).

In the figure the low-pass filter is included in the voltage feedback loop in order to keep the output of the error amplifier constant each half-cycle. This type of control can be easily explained referring to the Buck-boost converter in discontinuous conduction mode or a boost converter at the boundary between continuous and discontinuous conduction modes, which are shown in Fig. 34.

In both cases the value of the input current in each switching cycle can be expressed by:

$$i_{\mathrm{gmax}} = \frac{v_{\mathrm{s}} d T}{L} \tag{48}$$

The average value of the input current in switching period will be

$$i_{\mathrm{g,av}} = \frac{v_{\mathrm{s}} d^2 T}{2L} \quad \text{(Buck-boost)} \tag{49}$$

$$i_{\mathrm{g,av}} = \frac{v_{\mathrm{s}} d T}{2L} \quad \text{(Boost)} \tag{50}$$

Where $d$ is the duty cycle and $T$ is the switching period.

Thus the average current is proportional to input voltage if $d^2T$ or $dT$ are kept constant. As seen in Fig. 33, the input current loop is not necessary because the average input current follows the input current naturally. The other advantage of this control is that it is applicable when the line frequency is higher than usual cases (e.g., 400 Hz), and the disadvantages include:

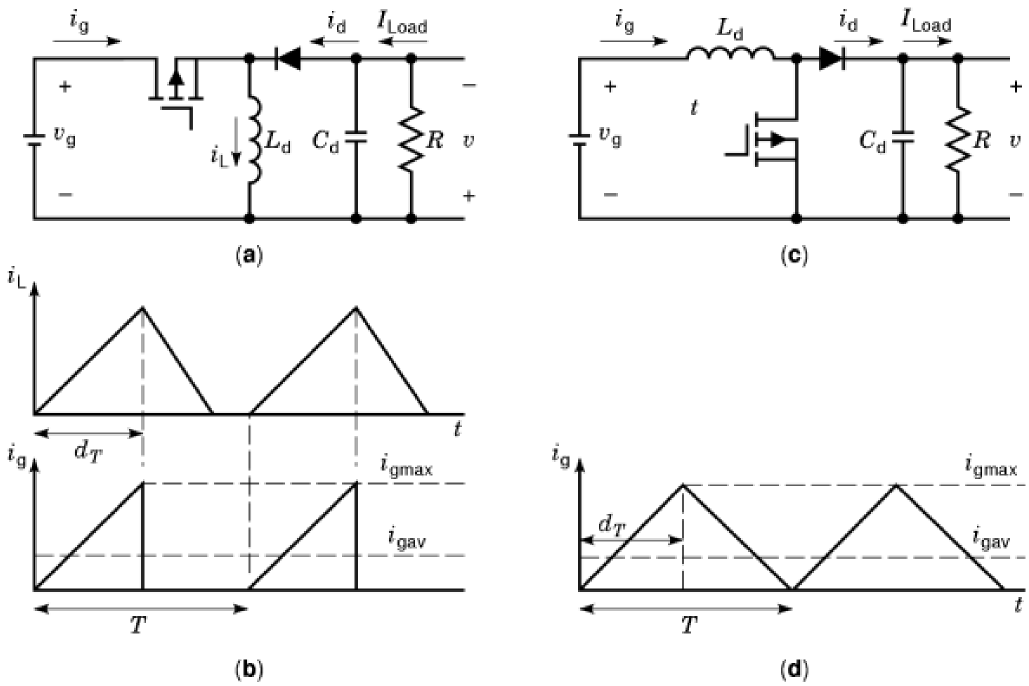


**Fig. 34.** (a) Buck-boost dc/dc converter in discontinuous conduction mode. (b) Main waveforms. (c) Boost dc/dc converter at the boundary between continuous and discontinuous conduction modes. (d) Main waveforms.

- Higher semiconductor stresses when working in discontinuous mode
- High-frequency ripples in the input current

It is important to note that beside conventional dc/dc converter topologies, several-switch topologies can be used for the same purpose. A full discussion of these topologies is found in Refs. 21, 36.

*Common Problems to All Classical Topologies.* Two main limitations exist regarding these converters:

- The switching frequency is limited to 100 kHz to 200 kHz by the switching losses.
- The regulation of the output bus is poor because of the low-pass filter shown in Fig. 33, which is absolutely necessary to obtain a true sinusoidal input current and thus used in all topologies.

In order to overcome these problems, other techniques are used including soft-switching topologies among which zero-voltage transition (*ZVT*) converters can be mentioned. The main disadvantage of resonant converters is additional hardware used for auxiliary switches (37,38).

*Comparison between Different Structures in Active Current Shaping.* In Buck and Buck-boost topologies due to the series connection of the switch, the input current is chopped. This causes high levels of conducted and radiated electromagnetic interference (*EMI*), hence an increase in the size and cost of the input filter. These converters can control the starting input current. So they can provide a short-circuit protection for the load. The Buck-boost converter also has the advantage of full control range of output voltage, and if its parallel inductance is replaced by a transformer, galvanic isolation between input and output stages of converter is possible (flyback converter).

Regarding boost converter, which is fully discussed in the beginning of this paragraph, the following characteristics can be mentioned (21,39):

- The input current is continuous due to series connection of reactor.
- One terminal of the switch is grounded. Therefore the isolating transformer is not required, which simplifies the switch driver.
- The output voltage across the capacitor $C_d$ contains a ripple at twice the line frequency. The feedback control circuit, used to control the output voltage, cannot compensate this voltage ripple without distorting the input line current.
- Output voltage must be kept higher than input ac voltage, which may cause problems for output stages connected to this type of converter.
- The step-up converter topology is well suited for the input current shaping because, when the switch is off, the input current directly feeds the output stage. In a constant-frequency current mode control the switch duty ratio, $d$, depends on the input voltage $|v_s|$ and the output voltage as

$$d = 1 - \frac{|v_s|}{V_d} \tag{51}$$

  It can be seen that $d$ is smallest at the peak of inductor current. Thus large values of $i_L$ flow through the switch only during a small fraction of the switching time period.
- There are no abrupt variations in the inductor current. Therefore a small input EMI filter is sufficient to prevent the inductor current ripple from entering the utility system.
- The dc output voltage can be stabilized to a nearly constant value for large variations in the line voltage.
- No galvanic isolation is provided between ac and dc stages.
- No short-circuit protection is supported.

## Conclusions

In this article harmonics and power factor issues were discussed. Important definitions and existing standards regarding these issues were presented. Nonlinear loads, especially power electronics equipment, substantially contribute to the deterioration of power quality. After presenting the harmonic sources, their effects on the power system were discussed. These effects include resonance phenomena, malfunction of delicate electronic devices, power factor degrading, and overheating. Two types of solutions can be used to mitigate harmonic problems: passive and active. Passive methods consist in using tuned and damped filters, and they have widely been used in power systems. Because of some inconveniences and problems, passive solutions are being replaced by the active methods. In these methods power electronic converters with appropriate control systems are used to compensate for harmonics and to improve power factor. Mathematical formulations regarding the active methods were given. Modulation techniques which are the base of active solutions do shift harmonics to higher frequencies, and this can result in electromagnetic interference. *EMI* problems have also been shortly discussed. Unity-power factor converters implemented by applying active wave-shaping technique is one of the active methods used to improve the power factor against the conventional shunt capacitor banks. Various implementations of this technique and a comparison between them was presented last.

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