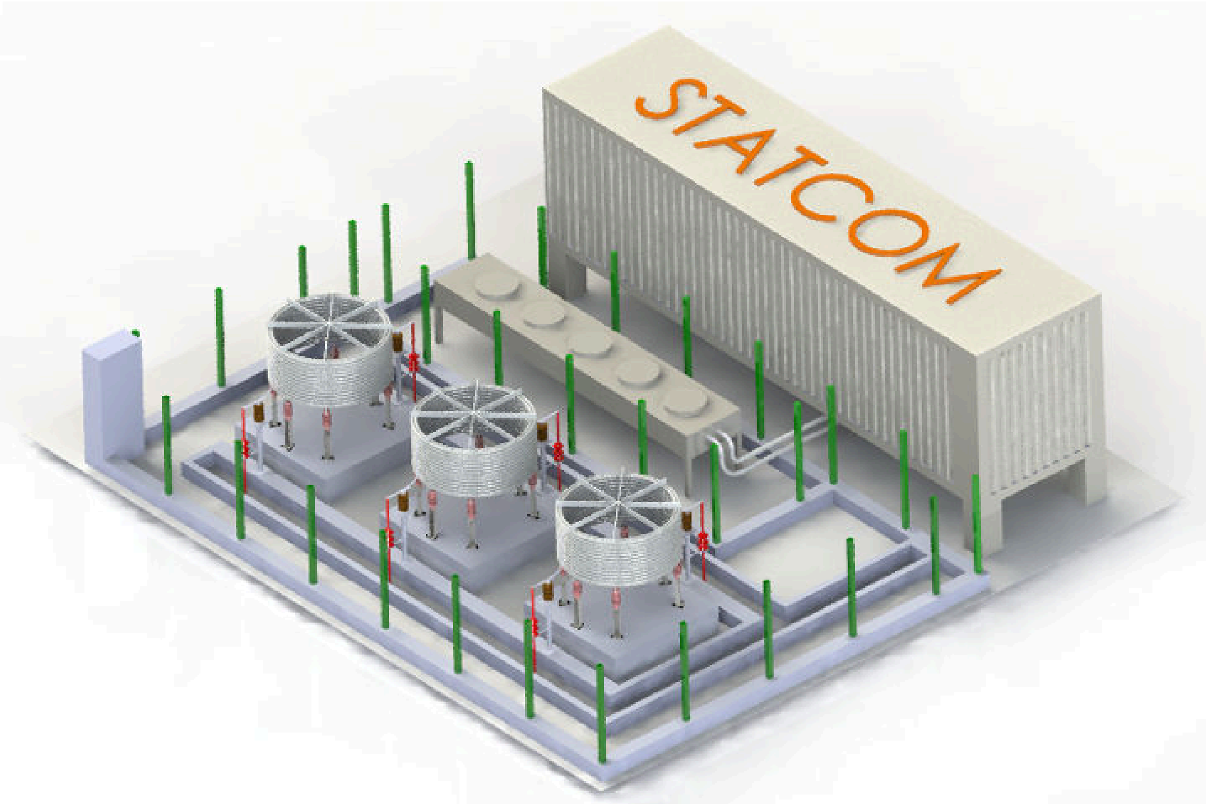
EPRLAB



EPRLAB

Electric Power Research Laboratory, EPRLAB is a high-tech power electronics company that has been specialized on design, manufacturing and implementation of industrial electronic and power systems including Static VAr Compensation (SVC), STATCOM, harmonic filtering and custom design multidisciplinary solutions based on challenging power quality problems.

We utilize our high-tech designs based on continuous research, development and field tests that enables us to achieve highest product reliability while providing innovative solutions for the future leading edge designs.

Serving the power electronics and power quality industry with exceptional expertise and customer satisfaction, EPRLAB continues to be recognized for high-tech engineering, extensive experience, and commitment to excellence.

Keywords of EPRLAB: Power Quality, Renewable Energy, Voltage Regulation, Reactive Power Compensation (RPC), Power Factor Correction (PFC), Flicker Compensation, Harmonic Mitigation, Flexible Alternating Current Transmission System (FACTS).

Products of EPRLAB: Static VAr Compensation (SVC), Static Synchronous Compensator (STATCOM), Multi-level Converter, Voltage Source Converter (VSC), Passive Harmonic Filter (HF), Thyristor Switched Capacitor (TSC), Thyristor Switched Reactor (TSR), Thyristor Controlled Reactor (TCR), RC Snubber, DC Chopper, DC Injection Brake Module, Remote Monitoring and Control System Design.

Services of EPRLAB: Power Quality Analysis, Commissioning, Supervision, Training, Consulting, Engineering, Technical Support, Maintenance.

Please visit http://www.eprlab.com for detailed information on products and solutions.

Send e-mail to info@eprlab.com for any queries, technical questions, and sales information.

Knowledge is POWER

POWER QUALITY and HARMONIC FILTERING

1. POWER QUALITY

1.1. What is Power Quality?

Power quality is broadly defined as the current, voltage and frequency values staying in the limits defined in standards, for the points in electrical grid where loads are connected. In order for an electrical network to be regarded as having high quality power:

a) It should be uninterrupted
b) The voltage magnitude and the frequency should stay within allowed limits
c) The voltage waveform should be purely sinusoidal

Although the voltage magnitude and frequency of the power delivered to the end-user are usually controlled and maintained by the suppliers, the distortion in voltage waveform are due to the connected loads.

The linear loads directly connected to the grid, such as induction motors, lighting armatures, and resistive heaters, etc. draw sinusoidal current. However, in the present day, the widespread use of nonlinear loads such as variable frequency motor drives, uninterruptible power supplies, rectifiers, computers, office equipment, furnaces, etc., causes the current drawn from the grid to change form. It becomes a distorted sinusoidal waveform, eventually distorting the bus voltage due to voltage drops, and hence affects the grid's power quality adversely.

1.2. Power Quality Problems

Power quality problems may be listed as follows:

a. Harmonics
b. Flicker
c. Reactive power consumption
d. Overvoltages and undervoltages
e. Transients and events (sags and swells)
f. Brownouts and blackouts
g. Voltage unbalance

2. HARMONICS

2.1. What are Harmonics?

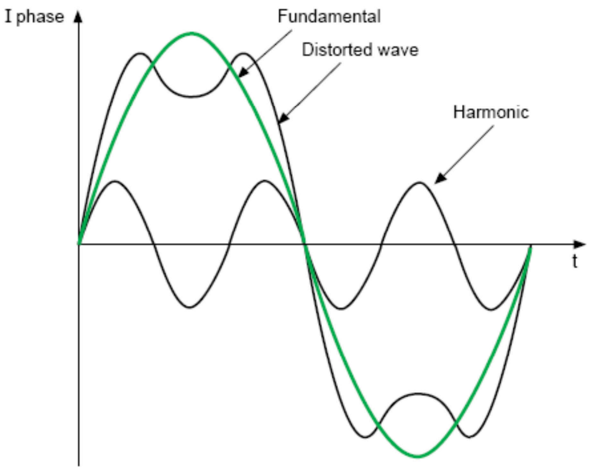
Harmonics are defined as positive integer multiples of the fundamental frequency (50 or 60Hz) components in both voltage and current waveforms. E.g. 5^{th} harmonic corresponds to a 250Hz component for a grid having 50Hz rated frequency.

The amount of harmonics in voltage and current are usually defined with total harmonic distortion (THD) and total demand distortion (TDD), respectively defined as follows:

$$THD\% = 100 * \frac{\sqrt{\sum_{n=2}^{\infty} V_n{}^2}}{V_1} = 100 \frac{\sqrt{V_{rms}{}^2 - V_n{}^2}}{V_n}$$

$$TDD\% = 100 * \frac{\sqrt{\sum_{i=2}^{\infty} I_n{}^2}}{I_{rms}} = 100 \frac{\sqrt{I_{rms}{}^2 - I_1{}^2}}{I_{rms}}$$

In the figure below, a current waveform consisting of fundamental component and 3rd harmonic is given. This waveform is close to the currents encountered in single phase rectifiers.



2.2. Sources of Harmonics

Nonlinear loads supplied from the grid are the sources of harmonics present in the current. The waveform of such loads' currents are not purely sinusoidal, and harmonic components that vary with respect to the type of load will be present in their current waveforms. Examples to nonlinear loads are:

- Switch mode power supplies (SMPS)
- Single or three phase rectifiers
- Ac and dc motor drives
- Cyclo-converters
- Office loads (PCs, photocopy machines, printers, etc.)
- Fluorescent lamp ballasts

- Arc, ladle melt, and induction furnaces

2.3. The Effects of Harmonics

The harmonic currents (and hence voltages) lead to the following negative effects in the grid:

- Overheating in cables, motors, transformers and other switchgear equipment
- False trips in protection equipment
- Blown fuses
- Losses on insulation materials of conductors due to quick aging
- Overloading and bursts in capacitors
- Series and parallel resonance problems in the grid
- Overheating in the neutral conductor

2.4. Harmonic Standards

The following regulations are due in Turkey:

- Bozucu Etki Yaratan Müşterilerin Uymak Zorunda Olduğu Koşullar, TEK, 1992
- Elektrik Sistemi Arz Güvenilirliği ve Kalitesi Yönetmeliği, EPDK, 2004

International standards are used to define, measure and put limits on harmonics:

- IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Std. 519-1992
- IEC 61000-2-x, 61000-3-x, and 61000-4-x

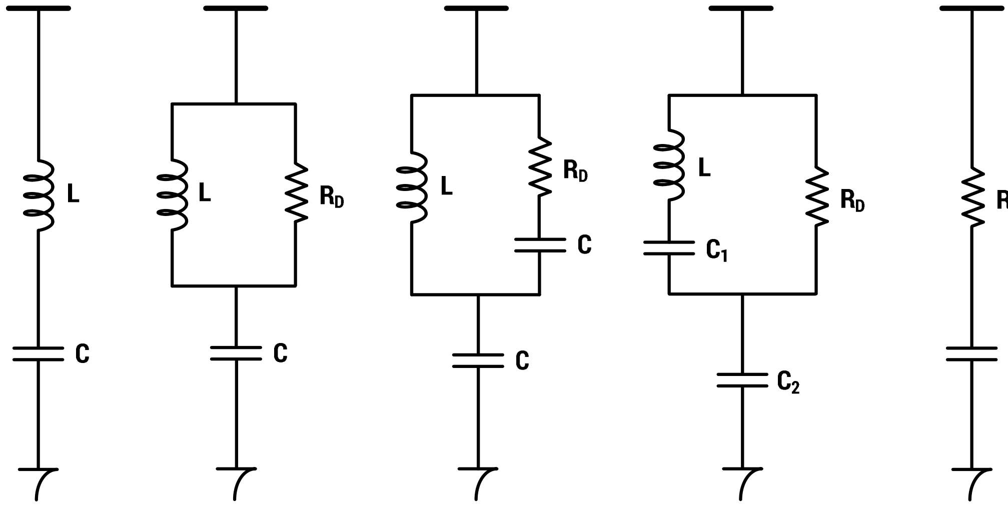
2.5. Harmonic Filtering

The harmonic currents which are formed by nonlinear loads and become a problem for the grid are filtered with different methods to bring their values under the limits defined in standards. The methods include electrical filtering equipment either consisting of R, L, C only (passive filters), or also containing semiconductor switches such as IGBTs and MOSFETs (active filters), or a combination of both (hybrid filters). Therefore, the filter types may be listed as:

- Passive filters
    - Single-tuned
    - 2^{nd} order
    - 3^{rd} order
    - C-type
    - 1^{st} order high-pass
- Active power filters
- Hybrid filters

2.5.1. Passive filters

Passive filters are based on use of passive elements such as capacitor, inductor and resistor, and they are the most used type of harmonic filters. In low voltage (LV) and medium voltage (MV) levels in industry and distribution systems, it is possible to see different topologies of these filters. Some of these topologies may be seen in the figure below.

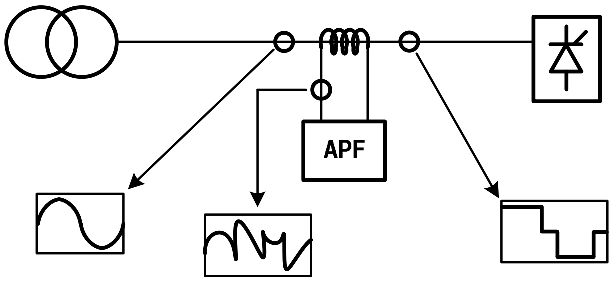


In the industry, at LV level, the passive filters shown above were not very common in the near past. This was partly because, although the legislations dictate the limits for harmonic current magnitudes to its customers, the sanctions are not applied by the distribution companies for LV. However, with the use of nonlinear loads becoming more widespread, it will be inevitable for the distribution companies to apply sanctions to its LV customers. Otherwise, the power quality will become too poor that the customers themselves will complain about it. On the other hand, the capacitor banks used for reactive power compensation (RPC) purposes at LV level started to be designed usually in single-tuned filter type. These are mostly used in "detuned" frequency setting. Detuned filter means that the series resonance frequency (the frequency where the series combination of the impedances of the inductor and capacitor becomes minimum, and hence almost all of the current, if present at that frequency, goes through the filter, but not to the grid) of the filter is not arranged to filter out a specific harmonic. It is tuned in a way that the series resonance frequency stays away from any harmonic. A tuned filter, on the other hand, is tuned very close to a frequency of a harmonic current injected by the load. Another important thing in the selection of the tuning frequency is the parallel resonance, which will be described later on below.

The use of passive filters is economical, but care should be taken about parallel resonance problem and the change in the values of filter components due to ageing, since the latter would take the tuning of the filter to an undesired frequency.

2.5.2. Active power filters

The main idea in an active power filter (APF) is to form one or more harmonic current components, with 180° phase difference with the load's harmonics. By this way, the harmonic currents coming from the load would be cancelled with the harmonic currents formed by APF. Therefore, the grid would not be affected by those harmonics. APFs are composed of inductive, capacitive and resistive elements as well as semiconductor devices (mostly IGBTs and MOSFETs). Working as a controlled voltage or current source, they can filter the desired currents with changing magnitudes at specific frequency intervals. The basic working principle of an APF may be seen in the figure below.



The advantages of APFs can be listed as follows:

- They can filter out almost all of a specific harmonic
- Their filtering performance does not degrade due to ageing.
- They can filter out more than one harmonic, i.e. they can filter out all components in a specified frequency interval; these include interharmonics also.
- They can make RPC also, even in both capacitive and inductive regions

The main disadvantages of APF are having complex control and circuitry, and being expensive.

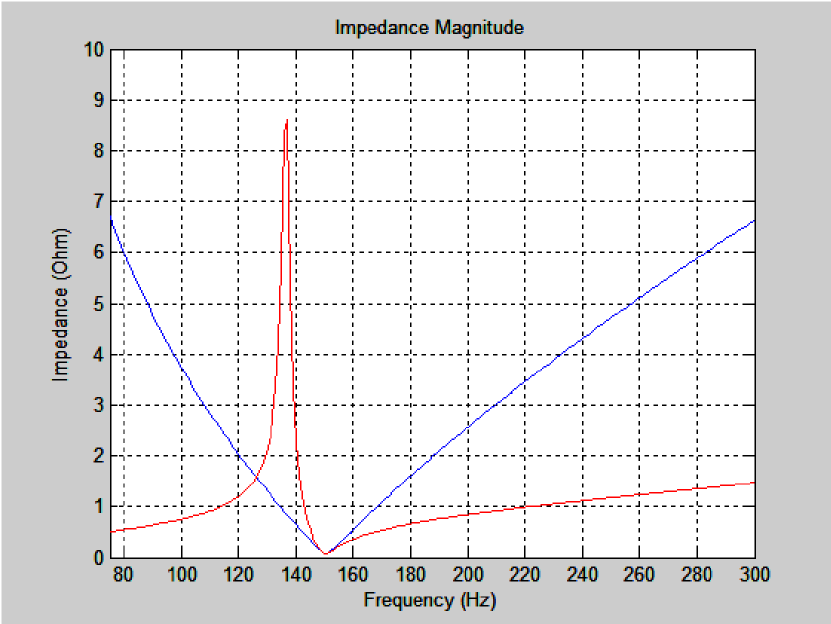
2.5.3. Hybrid filters

Hybrid filter is a combination of an APF, and one or several passive filters. This combination may have some advantages, mainly economical, because the sizing of an APF can be optimized. Some of the frequencies may be filtered by passive filters, whereas a critical frequency band which cannot be filtered out satisfactorily by passive filters may be covered by the APF.

2.6. Parallel Resonance Problem

The passive harmonic filters connected to the grid go into parallel resonance with the impedance of the grid itself at a specified frequency. This means that the parallel impedance of the passive filter and the grid becomes a very high value at the parallel resonance frequency. If there is a harmonic current source near this frequency, very high voltages and currents at this frequency occur which causes damage to equipment. This phenomenon is defined as the parallel resonance problem.

In the figure below, the impedance magnitude versus frequency plot of a single tuned filter tuned to 150Hz is given in blue color, whereas the equivalent parallel impedance magnitude of this filter and the grid together versus frequency is given in red color. As it can be seen, the series and parallel resonance frequencies are approximately, 150 and 135Hz, respectively. The difference between these two depend on several factors such as the power rating of the filter and the grid's short circuit current capacity.



In some cases of wrong design or due to ageing of filter equipment, the latter especially causing a capacitance drop, the parallel resonance frequency changes in such a way that it may coincide with a current harmonic frequency injected by the load. This will cause overvoltages and overcurrents in the system equipment, leading to failure; and in some cases together with catastrophic damage.

A very important fact about the passive filters is that although the parallel resonance frequency of a filter does not coincide with or come close to a harmonic (positive integer multiple of the fundamental frequency) existing in the grid, the problem may still develop. This case is mainly observed with some special types of loads which inject interharmonic currents, such as furnaces. This is why these types of loads cannot be handled by passive harmonic filters, and the use of an APF is inevitable.

2.7. Interharmonics

Interharmonics are defined as positive non-integer multiples of the fundamental frequency (50 or 60Hz) of both current and voltage waveforms. E.g., it is possible to define an 89Hz interharmonic which corresponds to 1.78th interharmonic for a grid having 50Hz as the fundamental frequency.

Interharmonic currents are produced by some special loads. These include arc, ladle melt, and induction furnaces, frequency converters, and rectifiers operating asymmetrically.
The failure to conduct detailed analysis and field measurement for such loads, and identifying harmonics and interharmonics with their magnitude and phase characteristics, may cause damage to both filtering equipment and to other loads supplied from the same grid. The detuned or tuned filters present or will eventually present a threat for grids with such type of loads, because the parallel resonance frequency of these filters would or will coincide with an interharmonic injected by the load. Usually the problem starts to show itself as an increased THD, while the contrary would be expected from a harmonic filtering installation. Moreover, the techniques and equipment used in both the field measurement and analysis are important in order not to overlook any interharmonics and harmonics, and not to treat interharmonics as they were harmonics.

3. FLICKER

Flicker is basically defined as the pulsation in the lighting magnitude with a defined frequency which causes discomfort to human eye. This happens because the changes in voltage magnitude affects the intensity of light directly. The disturbing frequency of flicker is in the 5 to 15Hz interval, and the most disturbing frequency is found to be 8.8Hz.

The places where flicker is encountered most are the areas where industrial, large, and rapidly changing loads exist. The best example for such loads is iron and steel factories. The rapidly changing and stochastic loads that exist in these factories cause flicker, which disturb people who are close to these areas, or are connected to the same transmission and distribution lines, where these areas are fed from.

The effects of flicker observed on people range from headache to vertigo, temper and even to epilepsy. Therefore, it is claimed in the standards that the level of flicker should be confined within some limits for every voltage level. IEC 61000-4-15 is the commonly accepted standard on these limits. According to this standard, two parameters are defined as long term flicker, P_{lt} (2 hour), and short term flicker P_{st} (10minutes). The electricity transmission and distribution authorities may apply sanctions according these two values.

Flicker and interharmonics are actually related issues. The interharmonics being in 8.8Hz vicinity of both the fundamental component and the harmonics also cause flicker. Similarly, the flicker may be treated as the source of such interharmonics.

The most common ways used as solutions to flicker are Thyristor Controlled Reactor (TCR) based Static VAr Compensator (SVC) systems, and the Static Synchronous Compensator (STATCOM).
For detailed information on these systems, please refer to *RPC and FACTS.pdf.*

4. REACTIVE POWER CONSUMPTION

The energy which does not turn into work, but is stored in electric and/or magnetic field is called reactive energy. The amount of this energy in unit time is called reactive power and it is represented in Volt-Amper reactive (VAr). Most of the industrial loads draw reactive power from the grid, which decreases the active power transfer capacity of the lines, transformers, switchgear, and etc. There are also other problems related to the inevitable consumption of reactive power. As described in *RPC and FACTS.pdf*, the reactive power need not be transferred all the way from the production to the consumer. It may supplied just at the point where it is needed. Basically, this is called Reactive Power Compensation (RPC). Today, different kinds of systems and control algorithms are used for achieving RPC.

5. OVERVOLTAGES AND UNDERVOLTAGES

Overvoltages and undervoltages can be defined as prolonged durations for the grid voltage being above and below the rated voltage level, with a specific percentage, say 10%. The durations may vary from seconds to days. These are two situations which show that the power quality of the grid is poor. Both overvoltages and undervoltages are generally related with the strength (short circuit MVA) of the grid. A strong grid's voltage does not change significantly under light loading, capacitive loading, resistive loading, and inductive loading cases. Such a grid's voltage regulation value is low. However in practice, the use of long lines, limited short circuit capacity, highly reactive loads, and daily, monthly or seasonally characteristic changes in the loads make it nearly impossible to avoid overvoltages and undervoltages without the help of some compensation devices. Please see *RPC and FACTS.pdf* for details.

6. TRANSIENTS AND EVENTS

The events are voltage swells and sags, which are basically sudden increases and decreases in grid voltage, respectively. The difference between overvoltages-undervoltages and swells-sags is the duration. Swells and sags last on the order of milliseconds, and are defined in the standard as the sudden voltage rises and drops with the magnitude of change higher than 10%. It should be noted that not all of the transients cause events. Both swells and sags are caused by transients in the grid which may be listed as:

- Connection and disconnection of a large load
- Connection and disconnection of a large power plant
- Power faults (short circuits) in a close area
- Inrush currents of large motors and transformers
- Switching and lightning surges

7. BROWNOUTS AND BLACKOUTS

Brownouts and blackouts are loss of electricity, in a regional and complete base, respectively in a power grid. These are also known as interruptions. These two may be thought as a case where the undervoltage gets worse, going to complete loss of voltage.

There are different reasons for brownouts and blackouts. Brownouts may sometimes occur intentionally due to load shedding, to prevent complete outage, which is blackout. This is because the operator knows that the grid cannot hold all the loads any more with the production in hand, so he (or a control system) decides to sacrifice some of the loads, which may be defined as less critical. This is also known as load shedding. Apart from an intentional outage, some of the reasons why brownouts and blackouts may occur are:

- Power faults (short circuits)
- Lightning
- Instability problems
- Wrong, late or missing load allocation and/or protection measures

A brownout may be handled with some sophisticated FACTS devices as described in *RPC and FACTS.pdf*.

8. VOLTAGE UNBALANCE

Under normal circumstances, the electricity generated in the plants are of balanced form. This means that all three phase voltages are of the same magnitude and they are separated with exactly 120^0 phase angles. Also, the currents are expected to be almost balanced for the plants, in a well-planned transmission and distribution scheme.

However, as the electricity travels away from the plants to the customers through transmission and distribution, the voltage becomes unbalanced, i.e., both the magnitudes and phase differences differ from each other. This is mainly due to unbalanced loading of the customers. The unbalance mainly comes from single phase loads distributed from the three phase transformers. Due to chaotic and irregular current drawing nature of single-phase customers, the three-phase balance in current is lost. This results in different voltage drops in the phases, and hence in unbalanced voltage. Another reason for having unbalanced voltages is the different impedances of transmission and distribution lines. This may be due to failure of line transposition. On the other hand, short term unbalances may be due to asymmetrical faults.

No matter the duration of unbalance, it can be corrected up to a point by FACTS devices such as SVCs and STATCOMs as described in *RPC and FACTS.pdf*.

All the power quality related problems described in this document are mostly handled by RPC systems and FACTS devices. Please see *RPC and FACTS.pdf* for details.