Power Quality Application Guide

LEONARDO POWER QUALITY INITIATIVE

Voltage Disturbances

Flicker

5.1.4

Voltage Disturbances

Copper Development Association
Institution of Engineering and Technology Endorsed Training Provider

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Voltage Disturbances

Flicker

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Flicker

Introduction

Flicker is the impression of unsteadiness of visual sensation induced by a light stimulus, the luminance or spectral distribution of which fluctuates with time. Usually, it applies to cyclic variation of light intensity of lamps caused by fluctuation of the supply voltage.

Flicker is a symptom of voltage fluctuation which can be caused by disturbances introduced during power generation, transmission or distribution, but are typically caused by the use of large fluctuating loads, i.e. loads that have rapidly fluctuating active and reactive power demand.

The following sections examine the nature of voltage fluctuations, their causes, effects, methods of measurement, mitigation and applicable standards.

Causes of voltage fluctuations

The classification of rms voltage variations is shown in Figure 1 as a plot of voltage against duration of disturbance. The hatched areas correspond to the voltage changes considered in this paper.

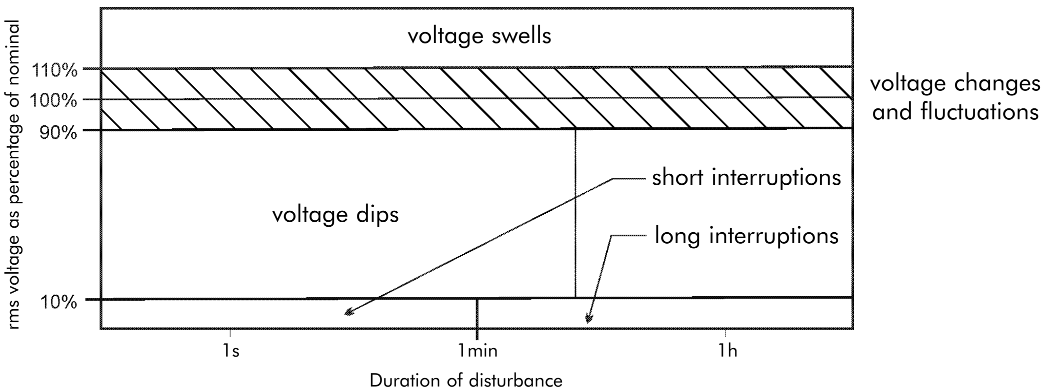


Figure 1 - Classification of voltage variations

For any supply line, the voltage at the load end is different from that at the source. This can be demonstrated from the per-phase equivalent circuit in Figure 2a. The relationship (1, below) illustrates how the value of the voltage difference ΔU, defined in Figure 2b, can be derived from the phasor diagram and simple geometrical rules.

$$\frac{E-U_0}{U_0} \approx \frac{\Delta U}{U_0} = R_S \frac{P}{U_0^2} + X_S \frac{Q}{U_0^2} \cong R_S \frac{P}{U_0^2} + \frac{Q}{S_{zw}} \qquad (1)$$

where

E	= the source voltage
U_0	= the voltage at the load terminals
I_0	= current
Z_S, X_S, R_S	= equivalent impedance, reactance and resistance of the line respectively
P, Q	= active and reactive power of the load
S_{ZW}	= short-circuit power at the point of load connection (S_{SC}).

Assuming that the equivalent resistance of the line is negligibly small compared with its reactance ($X_S > 10R_S$), which holds true for practical MV and HV supply systems, the following relationship defines the relative value of voltage change at the load-end of the line:

$$\frac{\Delta U}{U_0} \cong \frac{Q}{S_{ZW}} \quad (1a)$$

Depending on its cause, voltage change ΔU can take the form of a voltage drop having a constant value over a long time interval, a slow or rapid voltage change, or a voltage fluctuation. Voltage fluctuation is defined as a series of rms voltage changes or a cyclic variation of the voltage waveform envelope (see Figure 3).

The defining characteristics of voltage fluctuations are:

- the amplitude of voltage change (difference of maximum and minimum rms or peak voltage value, occurring during the disturbance),
- the number of voltage changes over a specified unit of time, and
- the consequential effects (such as flicker) of voltage changes associated with the disturbances.

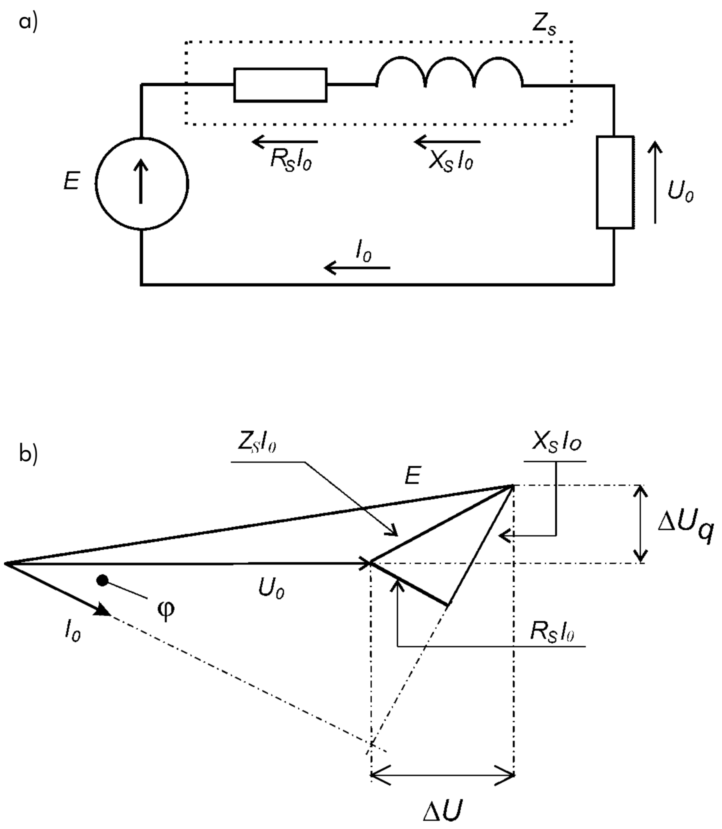


Figure 2 - Per-phase equivalent circuit of supply network (a) and phasor diagram for a resistive-inductive load $E \geq U_0$ (b)

Sources of voltage fluctuations

From the relationship in (1a), above, it can be seen that the primary cause of voltage changes is the time-variability of the reactive power component of fluctuating loads. Such loads include, for example, arc furnaces (Figure 4), rolling mill drives, main winders, etc. – in general, loads with a high rate of change of power with respect to the short-circuit capacity at the point of connection to the supply.

It is very important to note that small power loads such as starting of induction motors, welders (Figure 5), boilers, power regulators, electric saws and hammers, pumps and compressors, cranes, elevators etc. can also be the sources of flicker.

Other causes are capacitor switching and on-load transformer tap changers, which can change the inductive component of the source impedance.

Variations in generation capacity of, for example, wind turbines can also have an effect. In some cases, voltage fluctuations can be caused by low frequency voltage inter-harmonics.

Effects of voltage fluctuations

Voltage fluctuations in power systems cause a number of harmful technical effects resulting in disruption to production processes with substantial costs. However, the physiological effect of flicker is the most important because it affects the ergonomics of the production environment, causing operator fatigue and reduced concentration levels.

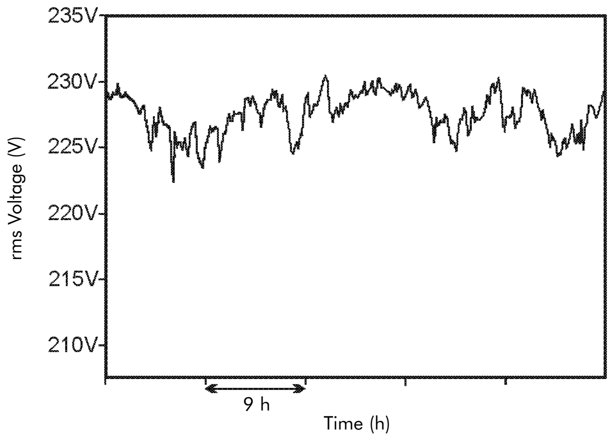


Figure 3 - Example of rms voltage fluctuation

In addition, irregular operation of contactors and relays can cause severe disruption to production processes. Illustrative examples of the adverse effects of voltage fluctuation are presented below.

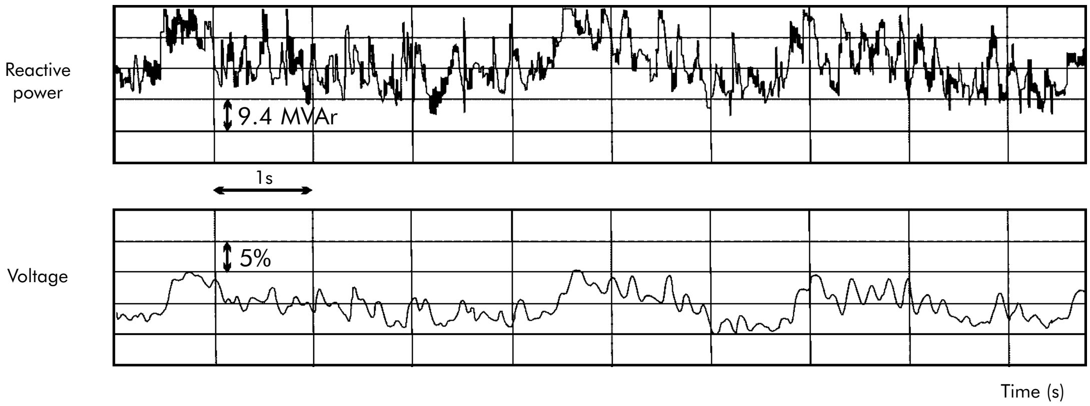


Figure 4 - Changes in the reactive power and the resulting voltage fluctuations at the point of connection of an arc furnace

Electric machines

Voltage fluctuations at the terminals of an induction motor cause changes in torque and slip, and consequently affect the production process. In the worst case they may lead to excessive vibration, reducing mechanical strength and shortening the motor service life.

Voltage fluctuations at the terminals of synchronous motors and generators give rise to hunting and premature wear of rotors; they also cause changes in torque and power and an increase in losses.

Static rectifiers

The usual effect of voltage fluctuation in phase-controlled rectifiers with dc-side parameter control is a reduction of power factor and the generation of non-characteristic harmonics and inter-harmonics. In the case of drive braking in an inverter mode, it can result in commutation failure, and consequent damage to system components.

Electrolysers

Both the useful life and the operational efficiency of electrolyser equipment can be reduced in the presence of voltage fluctuations. Also, elements of the high-current supply line can become significantly degraded, thereby increasing maintenance and/or repair costs.

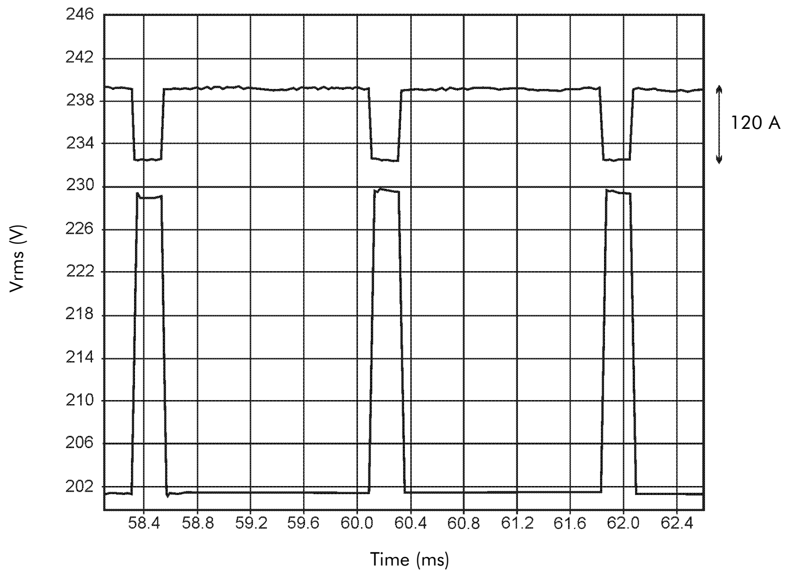


Figure 5 - Power system voltage fluctuation during welding work

Electro-heat equipment

Operational efficiency of all heating equipment is reduced in the presence of significant levels of voltage fluctuation e.g. an arc furnace would require a longer melt time.

Light sources

Any change in supply voltage magnitude results in a change in the luminous flux of a light source. This is known as flicker, which is a subjective visual impression of unsteadiness of a light's flux, when its luminance or spectral distribution fluctuates with time.

Incandescent light sources are particularly sensitive to changes in supply voltage as the luminous flux, Φ, is proportional to the applied voltage according to the relationship $\Phi \sim U^y$, where the exponent y typically varies between 3.1 and 3.7. (For fluorescent lamps, the exponent is typically lower [circa 1.8].)

Figure 6 illustrates the change in luminous flux, caused by supply voltage fluctuation, of a 60 W, 230 V incandescent lamp. The flicker that is generated significantly impairs vision and causes general discomfort and fatigue. The physiology of this phenomenon is complex. In general terms, it can be assumed that flicker affects the vision process and human brain reaction. Flickering light sources can produce discomfort and deterioration in work quality - in some situations causing accidents in the workplace.

Flicker Measurement

Voltage fluctuation measurements are required to determine actual load emission levels for comparison with limit values given in the electromagnetic compatibility (EMC) standards.

Flicker measurements are carried out for two purposes. The first is to assess the quality of a supply, i.e. to compare the existing flicker level at the measurement point to the recommendations formulated by the standards. The second is to assess the emission levels of a design of equipment before it is introduced to the market, i.e. a type test for certification purposes.

Voltage fluctuation factors

Until quite recently, voltage fluctuations in power systems, or at the load terminals, were characterised using factors associated with the peak-to-peak rms voltage change in the power system. The energy of voltage fluctuations and their power spectrum, also called the energy spectrum of voltage fluctuations, and their duration were taken into account when assessing voltage fluctuations. Currently, the basic parameters that determine voltage fluctuations are the short-term flicker severity P_{ST} and long-term flicker severity P_{LT} index. These parameters refer to voltage fluctuation effects on lighting, and their influence on humans.

Research on the process of visual perception has a history going back over forty years. Initially, it consisted mainly of tests carried out on selected, representative, groups of individuals using diverse light sources and various waveforms of voltage changes. On that basis, the perceptibility and flicker severity curves were determined. These curves present values of sinusoidal or rectangular voltage fluctuations (vertical/y axis), and frequency (horizontal/x axis). The area above the curve defines voltage fluctuations that produce noticeable, unacceptable flicker, whereas the area below the curve defines acceptable flicker levels.

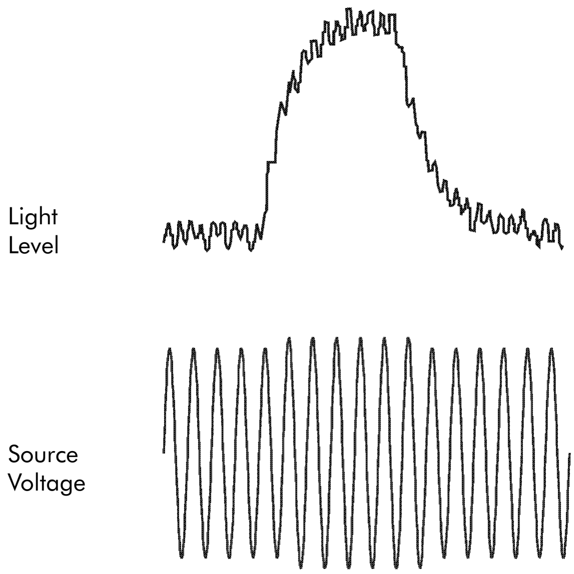


Figure 6 - The effect of a voltage change on the luminous flux of an incandescent lamp [1]

The participation of physiologists and psychologists in these experiments allowed the development of improved mathematical models for the neuro-physiological processes. De Lange's experiments offered the first opportunity to advance the thesis of similarity between the sensitivity of the human eye to light stimuli and the frequency characteristic of an electrical analogue signal. Further extensive studies carried out by Kelly took into account, not only the amplitude of changes, but also different levels of eye adaptation to the average luminance. An important contribution to developments in this field of knowledge was made by Rashbass, Koenderink and Van Doom [1, 2]. Their research work resulted in the development of the UIE flickermeter, which employs voltage fluctuation as an input signal, rather than the luminous flux changes themselves. This required the physiological process of visual perception to be modelled, according to the work of Rashbass and Koenderink, within the instrument.

Their work demonstrated that the response of the human eye has the characteristic of a band-pass filter between 0.5 Hz and 35 Hz, with maximum sensitivity to the luminous flux at a frequency around 8-9 Hz. For incandescent light sources, voltage fluctuations of circa 0.3% of the average value are detected at this frequency. Physiological effects depend on the amplitude of luminous flux changes, the frequency spectrum and the disturbance duration. The brain response to the light stimulus has an inertial characteristic with a time constant of circa 300 ms, meaning that slow changes of luminous flux are followed and fast changes are 'smoothed'. For instance, two short changes in the luminous flux, occurring within 300 ms, are perceived as a single change. Short changes of luminous flux, followed by a longer pause, are more annoying. The phenomenon of flicker is more dominant in the periphery of the visual field than in those areas on which the observer's attention is focused. The voltage fluctuation necessary to produce perceptible flicker is independent of the type of supply voltage (ac or dc) used for the lamp.

The concept of assessment of the influence of voltage fluctuation on user comfort

The phenomenon of flickering in light sources has been an issue from the very beginning of the use of power distribution systems. However, with the increase in number of customers and the installed power, it started to grow rapidly. To understand the phenomenon of flicker and its effects in the countries where it was a serious problem, investigations were carried out to measure it and then to address it. Initial steps employed a simple observation of luminous flux variations. Subsequently, a model of human reaction (fatigue) to luminous flux variations was developed, and this led to the design of the first instruments for measuring light source flicker severity. These instruments comprised a normal incandescent lamp (60W, 230V), a luminous flux sensor and an analogue model (using operational amplifiers) to simulate human reaction. The end of the 1980s brought more systematic and organised work on the assessment of the flicker severity, mostly co-ordinated by the International Union for Electrotechnology (UIE).

The standardised model of an instrument measuring the flicker severity in terms of P_{ST} for the short time of observation and P_{LT} for long time periods was adopted. This is an entirely electronic instrument, which models both the behaviour of the tungsten light source and human response to that behaviour. The design principles are discussed in another section of this Guide.

Mitigation of voltage fluctuations in power systems

The effects of voltage fluctuations depend first of all on their amplitude, influenced by the characteristics of the power system, and rate of their occurrence, determined by the technological process, i.e. type of load and character of its operation. Usually, mitigation measures are targeted at actions focused on limiting the amplitude of the voltage fluctuations; the technological process is seldom influenced. Example of these methods are:

- arc furnace - incorporating a series reactor (or variable saturation), proper functioning of the electrode control system, segregation and preliminary heating of charge, etc.; these methods are familiar to metallurgical process engineers.
- welding plant - supplying the plant from a dedicated transformer, connecting single-phase welders to the three-phase network for balanced load distribution between phases, connecting single-phase welding machines to different phases from those powering lighting equipment, etc.
- adjustable speed drives – use of softstart devices.

As follows from relationship 1a, above, the amplitude of voltage fluctuations can be limited in two ways:

- **increasing the short circuit power** (with respect to the load power) at the point of coupling to which a fluctuating load is connected. In practical terms, this means:
    - connecting the load at a higher nominal voltage level
    - supplying this category of loads from dedicated lines
    - separating supplies to fluctuating loads from steady loads by using separate windings of a three-winding transformer
    - increasing the rated power of the transformer supplying the fluctuating load
    - installing series capacitors.
- **reducing the changes of reactive power** in the supply system by installing dynamic compensators/stabilisers.

Dynamic voltage stabilisers

Dynamic voltage stabilisers are a technically viable solution for elimination or mitigation of voltage changes. Their effectiveness depends mainly on their rated power and speed of reaction. By drawing reactive power at the fundamental frequency they produce voltage drops on the supply network impedances. Depending on whether the reactive power is inductive or capacitive, the rms voltage value at the point of common connection (PCC) can be increased or reduced. Figure 7 shows the classification of various solutions for dynamic voltage stabilisers. They are mainly three-phase systems, of high rated power, designed for voltage stabilisation at the main point of a distribution system or of a specific load or group of loads at a PCC. As these systems are often used as dynamic compensators of reactive power at the fundamental, the terms 'stabiliser' and 'compensator' will be used interchangeably.

Synchronous machines

Synchronous machines are a traditional source of fundamental harmonic reactive power, lagging or leading, supplied in a continuous manner. They can also be the source of mechanical energy when operated as a compensator and a motor.

The use of a synchronous machine with no excitation current control is pointless because, in order to reach the standard limit level of voltage changes, the machine would need a power rating several times greater than the power of the load requiring stabilisation. This fact, as well as the required dynamic parameters of the stabilisation process, requires the synchronous machine to be operated in a closed-loop voltage control system with fast excitation current control (Figure 8). Such a solution enables a fast rise time of the machine's reactive current.

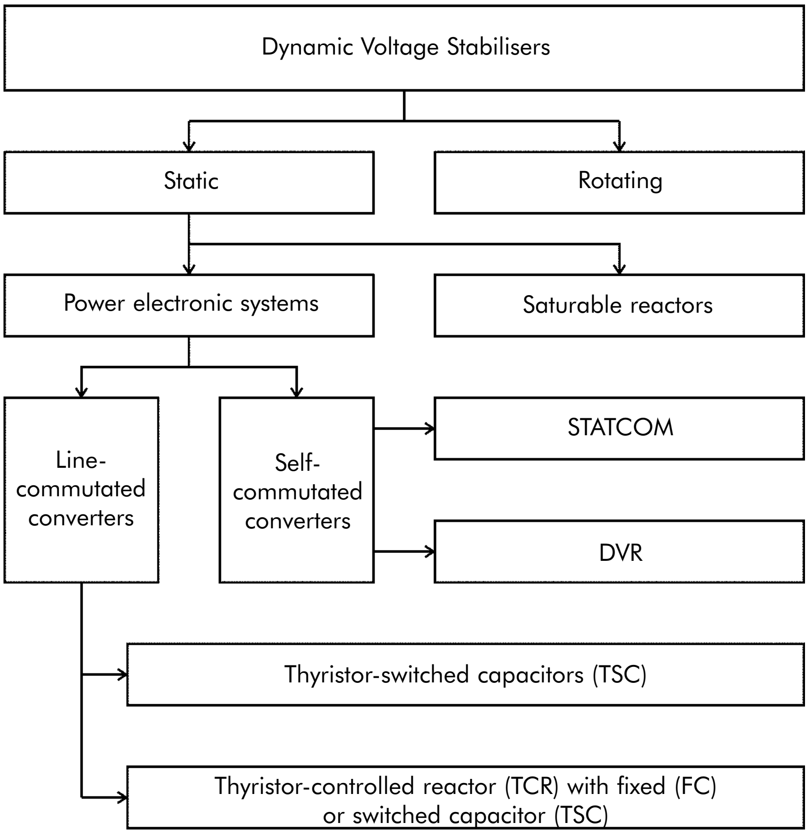


Figure 7 - Classification of dynamic voltage stabilisers

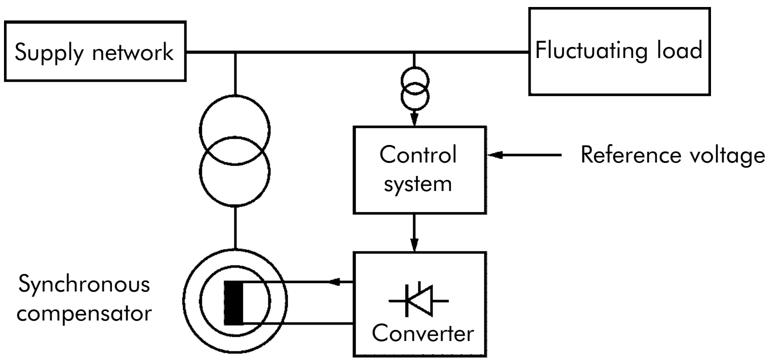


Figure 8 - Voltage stabilisation control system using a synchronous compensator

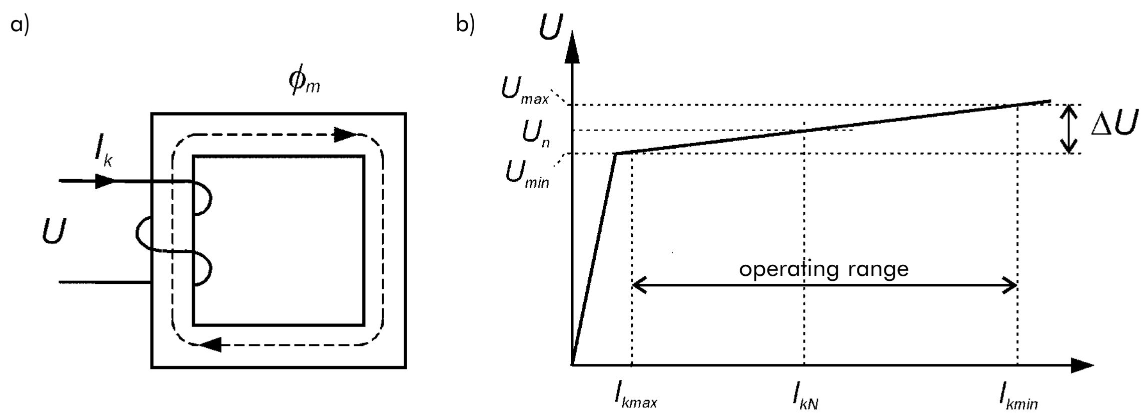


Figure 9 - Principle of operation of the self-saturable reactor: schematic diagram (a), magnetic characteristic of the core (b)

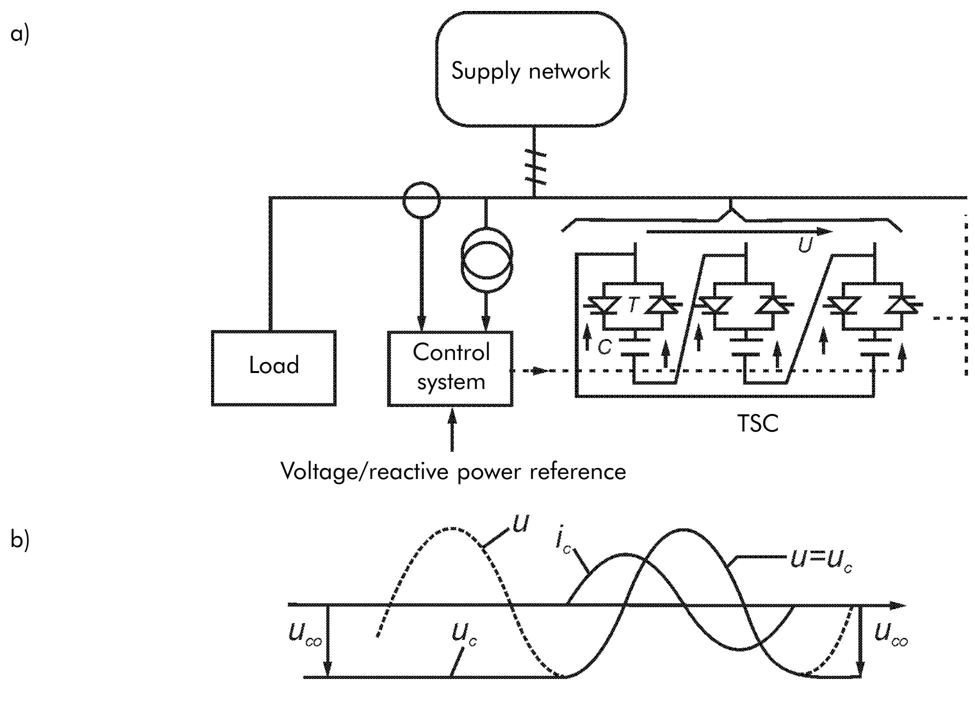


Figure 10 - Schematic diagram of a TSC compensator (a), current and voltage waveforms during capacitor switching (b)

Static compensators

Static compensators (other than STATCOM) employ capacitive and/or inductive passive components that are switched, phase controlled or combined with controlled core saturation. They supply the required stabilising reactive current either in discrete steps or, more often, in a continuously variable fashion. Static compensators are considered to be the most advantageous solution for improving the power supply quality, in both technical and economic terms.

Compensators with saturable reactors

There are many devices that employ magnetic circuit saturation for voltage stabilisation. Two of these solutions have found a wide practical application: self-saturable reactor (SR) and a reactor with dc control circuit.

Self-saturable reactor (SR)

This was one of the first static compensators applied on an industrial scale to mitigate the effects of voltage fluctuations. The reactor is designed such that the magnetising characteristic has a defined ‘knee’ with a small linear positive slope over a wide current range above the saturation point (Figure 9). The reactor is designed so that, at the minimum of the voltage range, the core is just below saturation and a magnetising current flows, similar to that of an unloaded transformer. In this state it has practically no influence on the voltage magnitude. At nominal voltage the reactor is saturated, so a small change in the supply voltage effects a considerable change in the current. The compensator is usually connected to the supply network without a step-down transformer.

Reactor with a dc control circuit

The stabiliser is most often operated with a parallel capacitor bank, which forms a filter for high order harmonics. It essentially works as a transductor, in which the primary current magnitude is controlled by adjusting the dc magnetising current. The control dc winding is usually supplied from a fully controlled thyristor converter, the power of which does not normally exceed 1% of the stabiliser rated power. This solution enables the forcing of transient current, thus faster operation of the system.

By adjusting the magnetising current, the reactor’s primary current changes from practically zero (unsaturated core) to the maximum value (saturated core) over the entire range of the primary current changes. A considerable disadvantage of this solution is the generation of the high order current harmonics. In the three-phase version a larger number of slots and appropriate linking of numerous windings allow the high order current harmonics to be practically eliminated, but at the cost of slower system response. The use of three, single-phase, stabilisers allows for correction of unbalance.

Thyristor switched capacitors (TSC)

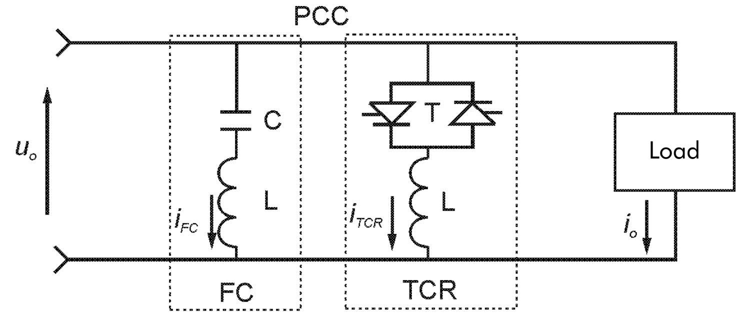
In this solution, the sectioned capacitor banks are connected phase-to-phase with each section switched (on or off) by means of ac thyristor switches (Figure 10). Therefore, the values of the compensator equivalent susceptances change in a discrete manner, depending on the number of active sections. By providing a suitably large number of small sections, the required resolution of change of susceptance for a single step can be obtained. Synchronisation of switching and initial pre-charging of the capacitors avoids the overcurrents and overvoltages normally associated with capacitor switching. Time of reaction for symmetrical operation does not exceed 20 ms.

FC/TCR compensator

This solution is an example of indirect compensation. Depending on the required function - voltage stabiliser or reactive power compensator - the value of the sum of two components of the current is controlled (Figure 11):

- fundamental harmonic of the capacitor current; the capacitor is operated as a filter or as switched capacitor steps (TCR/TSC),
- fundamental harmonic of the reactor current, controlled by means of a thyristor ac switch.

a)



b)

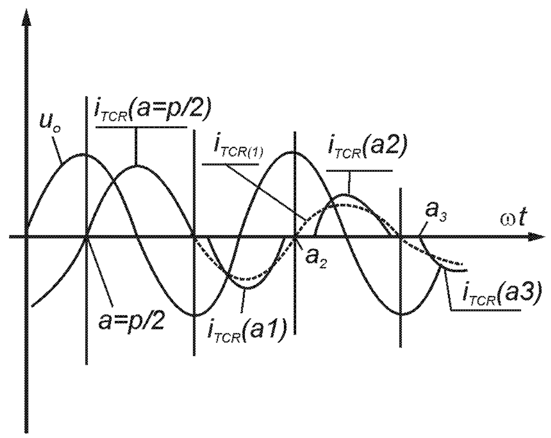


Figure 11 - Conceptual diagram of a single-phase FC/TCR compensator (a), TCR current waveforms (b)

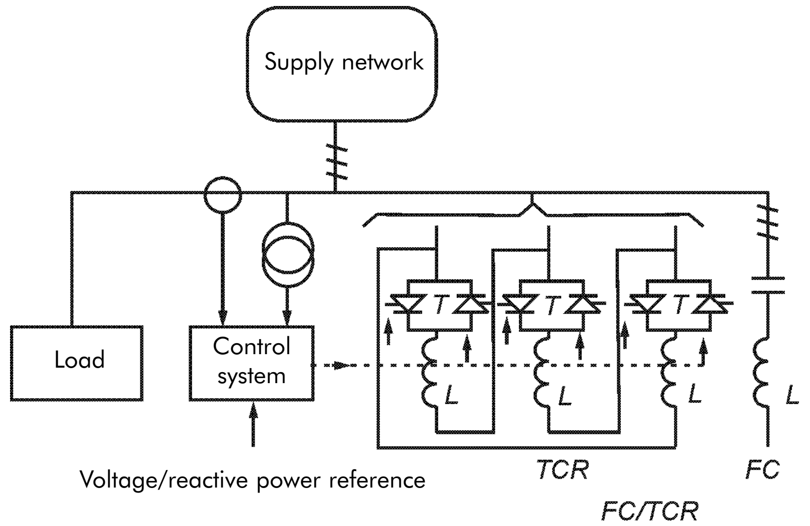


Figure 12 - Three phase FC/TCR compensator

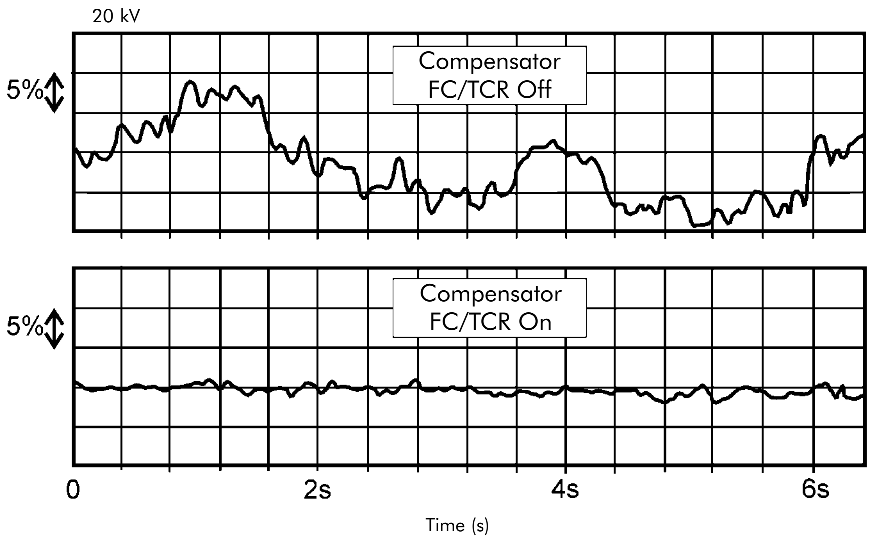


Figure 13 - An example effect of compensator FC/TCR performance

In the classical, three-phase configuration (Figure 12), the reactor branches are delta connected with shunt filters and are seen from the supply network as phase-to-phase connected equivalent susceptances. By changing the control angles, the values of susceptances are changed steplessly and independently from each other. The function of the reactor can be performed by the equivalent reactances of a transformer with a large short-circuit voltage.

Example effects of compensator performance are shown in Figure 13.

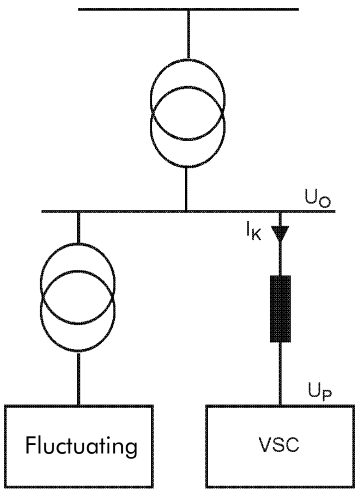


Figure 14 - Schematic diagram of a compensator (VSC) connected to the supply network

Self-commutated converter voltage sources and reactive current/power sources

The compensator comprises a voltage source converter (VSC). The switching states of semiconductor devices (pulse width modulation) determine the value and character of reactive power (inductive or capacitive) – Figure 14.

A number of various practical solutions for these compensators are described in literature. Capabilities of such a compensator are analogous to those of the synchronous machine, yet with much faster operation. The most commonly used compensator is STATCOM.

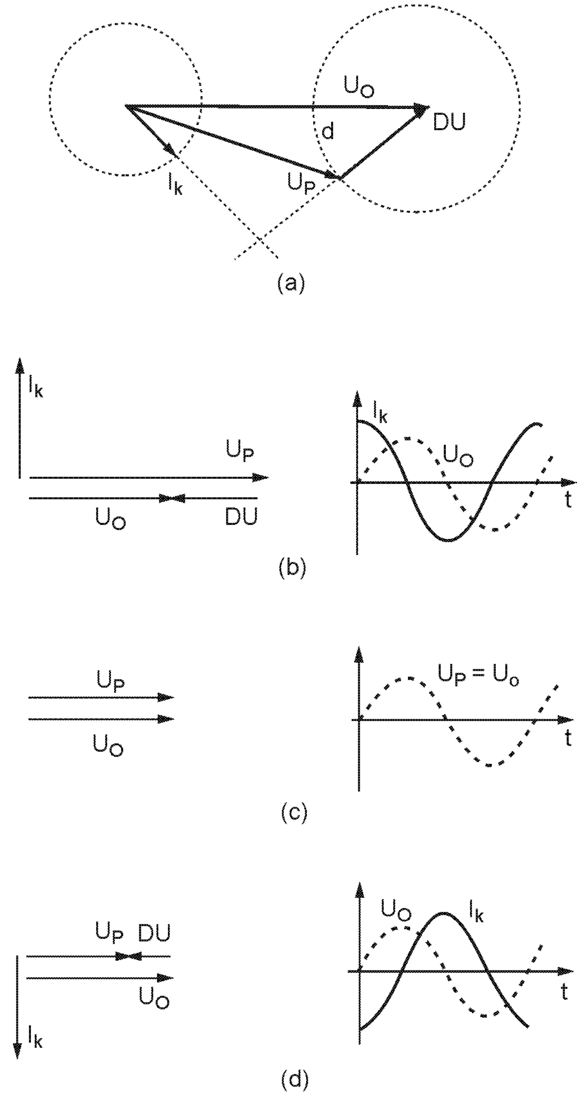


Figure 15 - STATCOM voltage and current waveforms and phasor diagrams for different phase relationships between U_0 and U_P

STATCOM is a new generation of static compensators, which employs semiconductor devices with forced commutation. Its name - *Static Synchronous Compensator* – is derived from the principle of operation, analogous to the operation of the synchronous compensator. The basic part of the compensator is an ac/dc converter, connected to the network via an inductive reactance, usually the leakage inductance of transformer. When the converter voltage is lower than the supply network voltage, the compensator is an inductive load; conversely, when the converter voltage is greater than the supply voltage, the compensator supplies reactive power to the network, thus behaving as a capacitive load – Figure 15.

Conclusion

Flicker is a subjective phenomenon. Consequently, it is difficult to determine the direct cost of its effect. It affects the fundamental quality of utility service – that is, the ability to provide lighting that is steady and consistent. Certainly it can affect productivity in an office or factory but the cost of flicker is usually based on the cost of mitigating it when the complaints become significant. Developments in power electronics, in particular in semiconductor device manufacturing, has enabled the practical realisation of voltage dynamic stabilisation systems of larger and larger rated power, while at the same time investment and operational costs have been minimised. The availability of equipment with the ability to execute complex control algorithms allows the implementation of diverse functions, including dynamic voltage stabilisation.

References

[1] Guide to Quality of Electrical Supply for Industrial Installations, Part 5, Flicker and Voltage Fluctuations, 'Power Quality' Working Group WG2, 2000.

[2] UIE Guide to Quality of Electrical Supply for Industrial Installations. Part 1: General Introduction to Electromagnetic Compatibility (EMC), Types of Disturbances and Relevant Standards, 1994.

Appendix

Item	Standard Number	Title
1.	IEC 61000-2-2: 2002	Electromagnetic compatibility (EMC). Part 2. Environment. Section 2. Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems.
2.	IEC 1000-3-5: 1994	Electromagnetic compatibility (EMC). Part 3. Limits. Section 5. Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current greater than 16 A.
3.	IEC 1000-3-7: 1996	Electromagnetic compatibility (EMC). Part 3. Limits. Section 7. Assessment of emission limits for fluctuating loads in MV and HV power systems.
4.	IEC 61000-4-14: 2002	Electromagnetic compatibility (EMC). Part 4. Testing and measuring techniques. Section 14. Voltage fluctuation immunity tests.
5.	IEC 60868: 1986	Flickermeter - Functional and design specifications.
6.	IEC 61000-4-15: 2003	Electromagnetic compatibility (EMC) - Part 4. Testing and measurement techniques. Section 15. Flickermeter - Functional and design specifications.
7.	IEC 61000-4-30: 2003	Electromagnetic compatibility (EMC). Part 4. Testing and measuring techniques. Section 30. Measurements of power quality parameters.

Table A1 - IEC standards related to voltage fluctuation

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