

Influence of Voltage and Current Harmonics on Behavior of Electric Devices

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ABSTRACT

The influence of voltage and current harmonics on equipment connected to electrical supply systems can cause serious problems. This paper presents a synopsis of the problem. The equipment most sensitive to harmonics is considered, such as -- asynchronous motors, synchronous machines, transformers, capacitors, ripple control receivers, electricity meters, radio receivers, TV-sets, electronic control devices, power and distribution equipment and computers.

1. Introduction

It is the objective of the electric utility to supply its customers with a sinusoidal voltage of fairly constant magnitude. The generators that produce the electric power generate a very close approximation to a sinusoidal signal. However, there are loads and devices on the system which have nonlinear characteristics and result in harmonic distortion of both the voltage and current signals. As more nonlinear loads are introduced within a facility, these waveforms gets more distorted.

The advancement and wide application of adjustable speed drivers, electronic devices, microprocessors, etc. in many areas have significantly contributed to the voltage and current waveform distortion in power and distribution system [9, 14]. This has created the need for better understanding of the impact of harmonic distortion on protection, control and instrumentation in power systems, industrial equipment and even house hold appliances.

The objective of this paper is to consider the effect of voltage and current harmonics on many types of equipment, ranging from synchronous machines, to house hold appliances, such as TV sets. Several elements on this list have already been analyzed from the point of harmonic sensitivity.

Therefore, for these reasons, it is almost impossible to consider in detail all the above elements. We will examine mainly those that, in the course of the study, seem to be important to the definition of harmonic limits, or those for which the already existent limits must be taken into consideration. The physical phenomena produced by sources of harmonics will be briefly described and analyzed over a base of defined criteria.

2. Criteria of evaluation

The following question is to be answered: What are the criteria which permit on to judge the influence of harmonics upon the considered devices?

From the point of view of the harmonics of voltage and current, there exist 3 possibilities:

1. The device is sensitive to one or two adjacent harmonics, and these harmonics should not exceed an established level, for example 5% of a single harmonic or 4% of each on two adjacent harmonics.
2. The device is sensitive to the arithmetic sum of all the harmonics. This summation should not exceed an established value, for example 5 or 10%.
3. The device is sensitive to the present of total harmonic distortion (THD) according to the formula :

$$\% \text{ THD} = \frac{\sqrt{U_2^2 + U_3^2 + \dots}}{U_1} \cdot 100 = \frac{\sqrt{\sum_{v=2}^n U_v^2}}{U_1} \cdot 100$$

For the sake of example, a percent of total harmonic of 10% or 4 individual harmonics are excluded.

With respect to harmonics of current, it is the effective value of the resultant current that must be taken into consideration [3].

$$I_{eff} = \sqrt{I_1^2 + I_2^2 + I_3^2 + \dots} = \sqrt{\sum_{v=1}^n I_v^2}$$

3. Asynchronous Machines

The influence of voltage and current harmonics upon asynchronous machines is manifested in two different ways [2.4]:

1. The first phenomenon concerns the influence of the harmonics upon the torque:

Calculations (and also measurements) show the effect of a 10% to 20% harmonic distortion is practically negligible. This holds for the permanent torque as well as for the starting torque. On the other hand, it has been observed that harmonics distortion causes the development of oscillatory torque. This is due to the interaction between the harmonic currents and the magnetic field of fundamental frequency. These torques have relative amplitudes that are approximately proportional to the relative amplitudes of the corresponding harmonic currents. (In other words if the harmonic currents have, in relation to the fundamental current, an amplitude of 10%, the oscillatory torque will have, in relation to the fundamental torque, a similar amplitude). The average torques, in service or at starting, are not affected, but the oscillatory torque can eventually create mechanical oscillations and resultant bearing wear.

2. The harmonics of the supply voltage and current cause some supplementary losses in the machines. Some of these losses may be summarized as follows [12]:

- (a) Primary I^2R losses. The harmonic currents contribute to total R.M.S input current. Skin effect in the primary conductors maybe neglected in small wire-wound machines, but it should be taken into account when primary-conductor depth is appreciable.
- (b) Secondary I^2R losses. When calculating the additional secondary I^2R losses, skin effect must be taken into account for all sizes of motors since the secondary frequencies concerned are high.
- (c) Core losses due to harmonic main fluxes. These core losses occur at high frequencies, but the fluxes are highly damped by induced secondary currents.

- (d) Losses due to skew-leakage fluxes. These losses occur if there is relative skew between the primary and secondary conductors. At 50 or 60 Hz the loss is usually small, but it may be appreciable at harmonic frequencies. Since the time harmonic M.M.F.S. magnetically couple the stator and rotor windings, skew-leakage losses are produced in both windings.
- (e) Losses due to end-leakage fluxes. As in the case of skew-leakage losses, these losses occur in the end regions of both stator and rotor windings and are a function of harmonic frequency.
- (f) Space harmonic M.M.F. Losses exist by time-harmonic currents. These correspond to the losses which, in the case of the fundamental current component, are termed high-frequency stray load losses.

The supplementary losses in the iron are practically negligible (a few % of the normal losses in the iron, which in general are in the order of 30% of the total losses).

On the contrary, the supplementary losses in the copper due to the harmonic currents circulating in the windings in the rotor and stator must be taken into consideration.

4. Synchronous Machines

The manner by which the harmonics of voltage and current affect synchronous machines (generators and motors) is similar to the way they act upon the asynchronous machines. The additional losses in the iron and copper in the stator winding are of little importance.

The principal effect of the harmonics is upon the rotor, where some non-negligible additional currents are induced in the damper winding. In addition, an asymmetrical current due to a negative sequence component of the three-phase supply voltage can circulate in that winding.

5. Transformers and Other Distribution Equipment

At the present, harmonic currents and voltage are unlikely to cause power equipment overload or system overvoltage. In this section we will present a summary of some of the main harmonic effects on power system components [13,14]

5.1 Transformers and reactors

- (a) winding stray (eddy-current) losses due to nonsinusoidal load currents rise in proportion to the square of the load current and the square of the frequency;
- (b) Hysteresis losses increase;
- (c) Possible resonance may occur between the transformer inductance and the line capacitance.

5.2 Capacitors

- (a) Reactive power increases due to harmonic voltages;
- (b) Dielectric losses increase thus additional heating occurs;
- (c) Capacitor bank failure from dielectric breakdown or reactive power overload;
- (d) Life expectancy decreases;
- (e) Resonance may occur resulting in harmonic magnification;
- (f) Overvoltage can occur.

5.3 cable

- (a) Additional heating occurs due to nonsinusoidal current and because of skin and proximity effects which are a function of frequency;
- (b) Dielectric breakdown of insulated cables resulting from harmonic overvoltage on the system;
- (c) R_{ac} increases, therefore $I^2 \cdot R_{ac}$ Losses increase.

5.4 Switchgear

- (a) Medium-voltage, single-bar switchgear current carrying parts will behave similar to cables, with regard to skin and proximity effect;
- (b) Changes the rate of rise of the transient recovery voltage;
- (c) Affects the operation of the blow out coil.

5.5 Relaying

- (a) Affects the time delay characteristics;
- (b) Signal interference and relay malfunction, particularly in solid-state and microprocessor-control systems;
- (c) False tripping may occur (in general their sensitivity to currents of higher order discrete frequencies decreases).

5.6 Generators

- (a) Rotor heating (in cylindrical rotor synchronous generators);
- (b) Production of pulsating or oscillating torques which involve torsional oscillations of the rotor elements and flexing of turbine buckets.

5.7 Motor

- (a) Stator and rotor I^2R losses will increase due to the flow of harmonic currents;
- (b) Leakage fields set up by harmonic currents in the stator and rotor end windings produce extra losses (losses in the stator and rotor conductors are greater than those associated with the DC resistance because of eddy currents and skin effect);
- (c) In the case of induction motors with skewed rotors, the flux changes in both the stator and rotor and high frequency can produce substantial iron losses;
- (d) Core losses increase due to harmonic voltage;
- (e) Positive sequence harmonics develop shaft torques that aid shaft rotation; negative sequence harmonics have the opposite effect;
- (f) Excessive losses in -and heating of- induction and synchronous machines.

5.8 General

- (a) Errors in induction kilowatt meters;
- (b) Interference with ripple control and power line carrier systems, causing misoperation of systems which accomplish remote switching, load control, and metering;
- (c) Overvoltage and excessive currents on the system from resonance due to harmonic voltages or currents on the network;
- (d) Inductive interference with telecommunications systems;
- (e) Unstable operation of firing circuits based on zero voltage crossing detection or latching.

6. Electrical meters

A meter is designed and is adjusted, in practice, to operate in circuits of standard frequency and voltage in with little or no waveform distortion exists. These conditions are usually closely approximated in practical systems and the errors in energy measurement due to the approximations are negligible. However, the increasing industrial application of electronic and high frequency equipment causing harmonic distortion in the load current has caused concern regarding the performance of the meters used to measure the energy required.

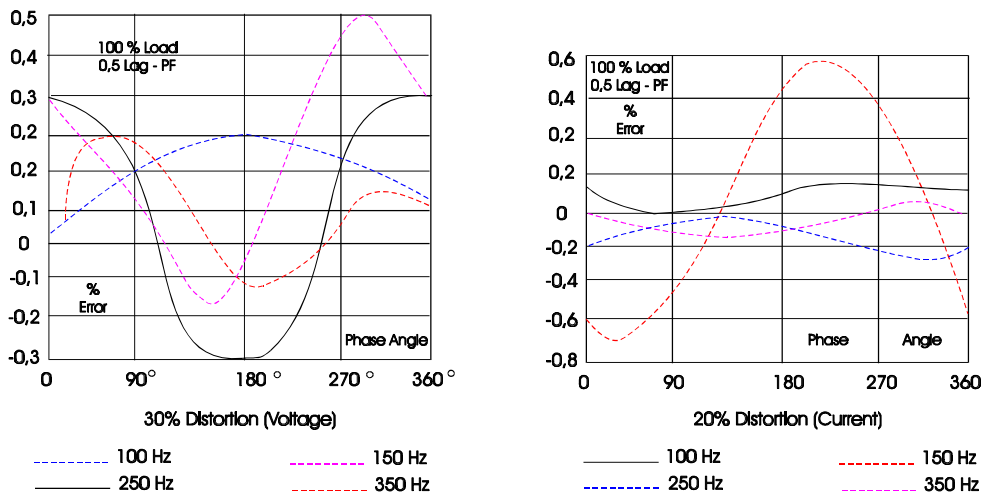


Figure 1

Voltage-and current-waveform distortion can result in inaccurate operation of induction-type meters. Tests have shown that a wide variation in performance exists between different makes and even between production samples from the same manufacturer [15]. Harmonic voltages or currents will degrade the capability of a meter. Fluxes produced by harmonics currents combine with spurious fluxes of the same frequency that maybe present due to the imperfection in the meter element and produce secondary torques. Typical responses for the degrading effect of harmonics of various phase angles and amplitudes in the voltage and current coils are shown in figure 1 above [11].

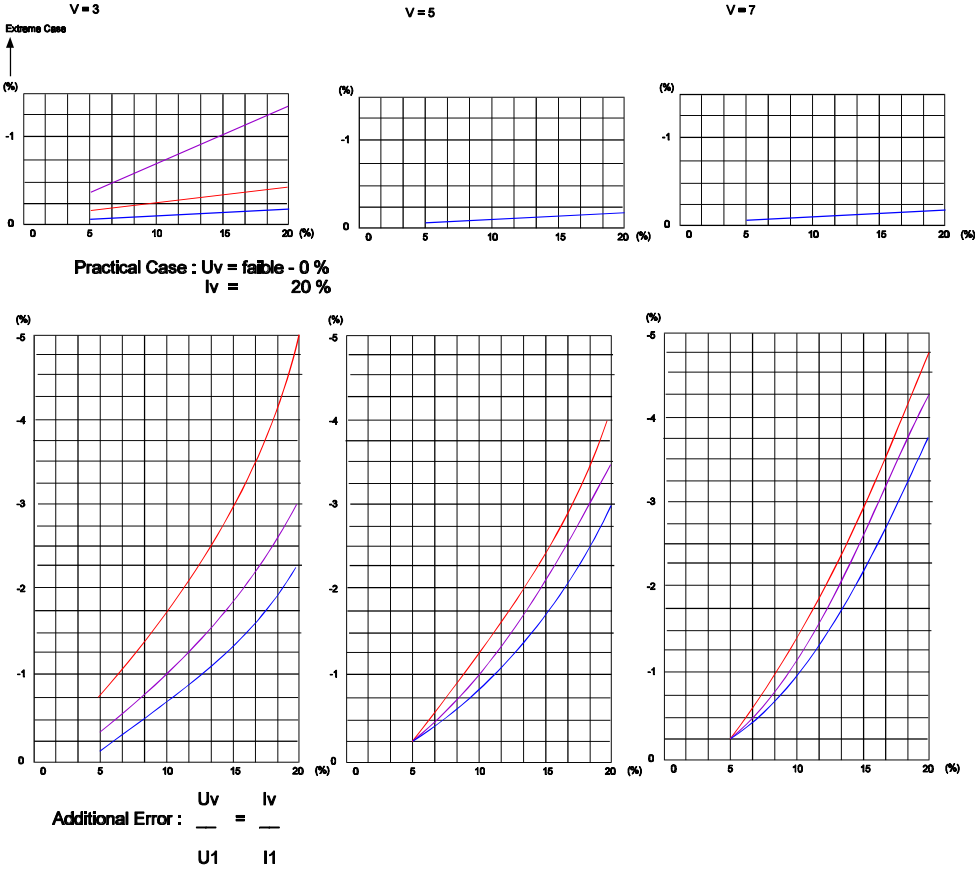


Figure 2 :

Influence of voltage and current harmonics on the accuracy of electrical meters.

The influence of harmonics upon the accuracy of meters is manifested in three ways(5):

- a. The meters are frequency sensitive, with negative error increasing with the frequency.

One can see from the fact that the inductance of the voltage coil is increased, that the magnetic field and the driving torque are decreased.

- b. The magnetic fields of the voltage coil of a meter are not linear and contain some harmonic components due to compensation devices. It is believed that some additional torque will develop anyway, even though there aren't harmonics of voltage and current in the distribution network. These errors are negative.
- c. The meters do not measure the component of energy due to the DC.

However, these negative errors are weak. Figure 2 [3] represents the result of measurements taken over different devices. It shows, for example, an additional error less than 1% for a purely sinusoidal voltage and a 3rd order harmonic current of 20%. A similar error is reached in the even less realistic case of a 10% harmonic of voltage simultaneously with a 10% harmonic of current.

7. Electronic Devices

Electronic devices such as rectifiers, inverters, and cycloconverters which are sensitive to the zero-crossing point of the voltage waveform can obviously be affected by harmonic distortion. The effect on converters is to displace the natural commutation point. In an article concerned with this problem it is written: “ *The harmonics of voltage act upon the supply transformers, the devices of command and control, the characteristics of the output voltage, the waveform of the output voltage, and the auxiliary devices* ” [6].

Figure 3 and 4 give some examples of phenomena produced.

- a. Figure 3 shows how the harmonics of the supply voltage displace the point of natural commutation of a converter. The control apparatus of the thyristors should provide for a supplementary safety margin to account for this gap:
 - In case thyristors are used as rectifiers, the firing angle should be longer than the angle that decreases the performance of the equipment.
 - In the case of service as an inverter, it is necessary to provide for a larger reserve in order to avoid the commutation errors which could carry an internal short-circuit. This limits the domain of the regulation.

- b. Figure 4 is related to the regulators, which very often consider the zero crossing of the voltage as a point of reference. The more important devices are equipped with harmonic filters, but the simpler devices are not. The latter are relatively sensitive to harmonics, especially if they are strong.

It is necessary to establish a convention with the total harmonic distortion of the voltage which should be considered as normally admissible otherwise it is necessary to define special conditions). Goldberg [3] uses the following recommendations as a guide for allowable harmonic levels or electronic equipment : the total harmonic distortion of voltage must not exceed 10%. Each individual voltage harmonic must not exceed 5% up to the 13th harmonic and then decrease to 1% at 5000 HZ (50HZ fundamental frequency)

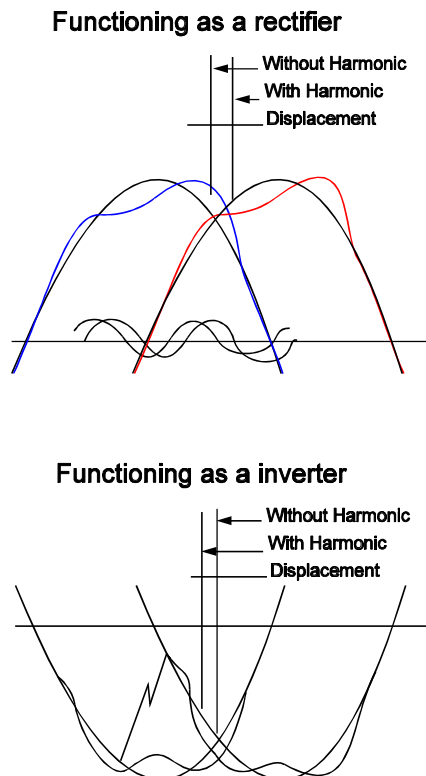


Figure 3: Influence of currents and voltages harmonics on the communication electronic converters.

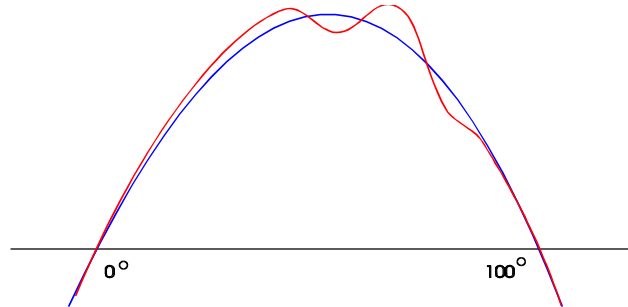


Figure 4: Influence of voltage harmonics on the electronic control devices.

8. Computers And Processors

The manufacturer adopt, with respect to harmonics of the supply voltage for these devices, the following conditions [7]:

1. The THD of the voltage measured at no load be less than a value of 3 (Honeywell, DEC) to 5% (IBM),
2. Or still the relationship peak/effective-value of the voltage should be equal to 1.41 ± 0.1 (CDC)

The reasons which impose these conditions are not explained in detail in the technical literature (and the manufacturers are quite reticent to give information this subject). It seems that it can, in any case consider the following to effects:

- a. The density of information recorded in the magnetic media (tapes or disks) is very high, it requires a very high precision and a high stability of the driving gears of the motors. These should have, on the other hand, very weak inertia to stop and start within the minimum possible time. One can imagine that oscillatory torques like those mentioned in the section devoted to asynchronous motors can disturb the operation of such equipment. The problem is more difficult when the movement of the peripheral elements is related to a network different from the central equipment.

- b. The computers require highly stabilized voltages (1%) for some circuits Ferro-resonance regulators are often used to obtain these voltages. These regulators are very sensitive to frequency variation.

The conditions imposed upon the manufacturers are quite severe:

- a. The first condition can be translated to practice by saying that the official rate of harmonic of 5% does not permit only that two simultaneous harmonics of voltage--for example, the 5th and the 7th --- with a level of 3.5% each.
- b. The second condition limits the arithmetic sum of all of the harmonics to 7%. This takes into account the phase of the harmonics.

It would appear from these restrictions that computers and processors seem to be the harmonic sensitive pieces of equipment

9. Radio And TV Receivers

For radio receivers, the “Meister’s Curve” (curve no 6, figure 5) [3], established in its time to define limits for the voltage of the remote controlled centrals in the network, is also valid for individual harmonics, indeed even for 2 or 3 harmonics.

Where:

- a. Computers and processors (limit for 2 simultaneous harmonics)
- b. Rotating Machines (limit of the summation of the harmonics)
- c. Centralized Telecommand (limit for 2 simultaneous harmonics)
- d. Rectifiers and Converters (limit for individual harmonics)
- e. Condensers (limit for 2-3 individual harmonics)
- f. Radio and TV Receptors (curve of Meister-individual harmonics)
- g. Recommendation from the UNIDEPE (limit for individual harmonics)

In black and white TV receivers, non-regulated full-wave rectifiers produce a DC voltage which is directly proportional to the peak value of the input voltage . So the DC voltages can vary if a harmonic is superimposed on the fundamental voltages. The resultant effect consists of a light variation in the picture and its luminosity. The variations seem to be proportional to the average of the relative variations of the voltages amplitude. In this case, it will be the arithmetic sum that will come into play. such variations are of no importance with harmonics of constant amplitude. However, the spectators can be bothered by these continued fluctuations. An acceptable level by the spectators is still to be determined. The color TV sets seem to be less sensitive because they are equipped with voltage stabilizers [8].

10. Result And Conclusions.

Before any conclusions, it is convenient to make the following two remarks:-

- The influence of the harmonics has been described for the most important devices. A number of devices is still left to be examined, but these do not seem to be important in the definition of the boundary limits.
- The conclusions reached are based upon the behavior of the devices and machines on the network. Nevertheless, the phenomena particular to the network (additional losses, neutral current, influence over fault to the ground, etc...) should be computed in the study of a general recommendation. This should be the object of an appropriate study.

The results of the analysis of the different devices considered in this study are summarized in figure 5, which shows acceptable values of harmonics of voltage for the most important devices, in order of their sensitivities :

- * Computers and Processors (which seem to be the most sensitive devices).
- * Rotating Machines.
- * Receivers of Centralized Remote Control.
- * Electronic Equipment of Power and Control.
Capacitors.

There are already for numerous devices and machines, either over a physical base of consideration, or according to rules or recommendations in current use, an upper limit for the acceptable level of harmonics of voltage. It can be observed that the existent rules and recommendations fall sensibly apart from each other, and are quite incoherent. The elaboration of rules or general recommendations for a limitation of the harmonics of voltage should be very useful to judge their effects; to sets a means of neutralization to take either from the side of the network or from the side of the equipment; or to set particular conventions.

Therefore, general rules are not simple to formulate because, while in some cases it is necessary to compute one isolated or two adjacent harmonics, in other cases the entire harmonic spectrum must be taken into consideration. It can be simultaneously indicated as, for the case of the already existent prescriptions, a value for each individual harmonics and a value for the spectrum altogether.

It is equally necessary to examine the direct currents which are defined by a maximum value of current and not of voltage.

With regard to the values for possible limits, one can reach the following conclusions from this study :

- * If the most severe conditions are considered, the admissible level for odd harmonics less than or equal to 350 Hz, should be between 3% to 4%; for harmonics higher than 350 Hz, the level should decrease as the frequency increase. For the even harmonics, the level to be considered should be in the range of 0.2% to 0.5%.
- * If average conditions are considered, in order to reduce the requirements on the network side a little, a level of 4 to 5% for odd harmonics up to 350 Hz can be tolerated (with a decreasing level beyond 350 Hz). For even harmonics up to 300 Hz, a value of 0.5% should represent an acceptable solution (for some higher frequencies, the value decreases proportionally).
- * The spectrum of harmonics recommended by the UNIDEPE corresponds to the first proposition and can serve as a basis to a general discussion with the objective of defining the limits for harmonics in a distribution network.

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