EFFECTS OF HARMONICS ON POWER SYSTEM PROTECTION AND PROTECTIVE RELAYS

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Abstract - Power system harmonics can be detrimental to system performance and components in a number of ways. Harmonic problems often manifest themselves as nuisance tripping of sensitive loads, telephone interference, or resonance in distribution feeders. The purpose of this paper is to give a brief overview on harmonics and, specifically, to describe their impact on system protective devices.

INTRODUCTION

Power system harmonics are produced when nonlinear devices chop, flatten or otherwise distort voltage and current waveforms in a predictable and periodic manner. This results in nonsinusoidal but periodic voltages and currents which can be described in the frequency domain by the following truncated Fourier series:

$$v(t) = \sum_{h=1}^{N} V_h \sin(h\omega_o t + \phi_h), \quad i(t) = \sum_{h=1}^{N} I_h \sin(h\omega_o t + \theta_h),$$

where the highest harmonic of interest N is usually 25 (1500 Hz) or lower.

Power system harmonics are not a recent development. Early harmonic sources were rotating machines and transformers, which were studied in detail by Steinmetz in the early 1900's [1]. Many of the early problems were resolved by using improved machine winding distributions and wye-delta transformer connections to block third harmonics. Later, arc furnaces became a large source of voltage flicker and current harmonics. Arc furnaces remain a major problem, but since they do not produce steady state waveforms, their harmonic content is not constant and it is difficult to predict.

Harmonics are of increasing interest today due to the proliferation of solid state controlled loads which chop current or voltage. Examples include diodes, SCRs, and thyristors. Applications range from small single phase loads such as light dimmers, appliance motor speed controllers, and "light saver" button diodes to megawatt size three phase devices such as adjustable speed drives (ASDs), HVDC terminal stations, photovoltaic inverters, etc. A result of the increasing significance of these loads is increased background harmonic levels on feeders and an increasing number of incidents of harmonic voltage resonance. A working group of the IEEE-PES Transmission and Distribution Committee was established several years ago to study these problems and to recommend harmonic guidelines [2]. Also, the IEEE-PES Relaying Committee has produced a report concerning the impact of sine wave distortion on relaying and protection [3].

The effects of harmonics on all power system components are not known completely. However, some effects have been well quantified - for example, overheating in transformers and excessive capacitor currents. Nuisance trips of sensitive loads, such as computer controllers, are a common symptom of harmonics. The effects on power system protective devices vary widely and are, for the most part, largely unpredictable.

The purpose of this paper is to provide an introduction on the topic of power system harmonics and to describe their known impact on power system relays and protection.

HARMONIC PHASE SEQUENCES AND RELATED DEFINITIONS

Certain definitions are needed in order to characterize harmonics. For relays, harmonic phase sequences are of particular importance. In addition to the Fourier series' given previously, the following definitions are commonly used to describe power, RMS value, and distortion:

Active Power: $P = \sum_{h=1}^{N} V_h I_h \cos(\phi_h - \theta_h)$

Reactive Power: $Q = \sum_{h=1}^{N} V_h I_h \sin(\phi_h - \theta_h)$

Voltage RMS: $V_{RMS} = \sqrt{\sum_{h=1}^{N} V_h^2}$

Voltage Distortion: $THD_V = \dfrac{\sqrt{\sum_{h=2}^{N} V_h^2}}{V_{RMS}}$.

Similar definitions apply for RMS current and current distortion.

In a *balanced three phase system*, certain other assumptions can be made. In the balanced case, individual voltage and current harmonics exist in the particular phase sequences shown in Table 1. Note that when harmonics are present in a balanced system, negative and zero sequence signals exist. This is contrary to conventional fundamental frequency concepts. Furthermore, since triple harmonic currents (3, 6, 9, etc.) are entirely zero sequence, they cannot flow into a delta or ungrounded wye device. Also, line to line voltages cannot contain zero sequence components.

One additional assumption is made in most instances - if the voltage and current waveforms are *half wave symmetric*, where

$$f(t) = f(t \pm \frac{T}{2}), \; T = \text{Waveform Period},$$

they contain no even-ordered harmonics (2, 4, 6, etc.). Half wave symmetry implies that the positive and negative portions of the waveforms are mirror images of each other, which is usually the case unless half wave rectification is present.

For most power system harmonic studies, the harmonic phase sequences shown in Table 1 are assumed, and even-ordered harmonics are assumed to be nonexistent.

SOURCES OF HARMONICS IN POWER SYSTEMS

Harmonic sources are often classified as traditional (i.e. having existed for many years in significant numbers) and modern (i.e. new loads or old loads which are now significant). Traditional sources of harmonics include:

1. Tooth ripple in the voltage waveforms of rotating machines
2. Nonsinusoidal flux distribution and air gap reluctance in machines
3. Nonsinusoidal transformer magnetizing currents
4. Superposition of small distributed loads such as rectifiers and welders
5. Arc furnaces.

These items are generally modeled in steady state, except for arc furnaces and welders which are transient in nature and do not lend themselves to conventional harmonic analysis techniques.

Modern harmonic sources include:

1. Motor speed controllers and adjustable speed drives (ASDs)
2. Fluorescent lamps
3. HVDC and static VAr compensators
4. Solar and wind inverters, battery chargers

Table 1: Harmonic Phase Sequence in a Balanced Three Phase System

Harmonic	Phase Sequence
1	+
2	-
3	0
4	+
5	-
6	0
7	+
8	-
9	0

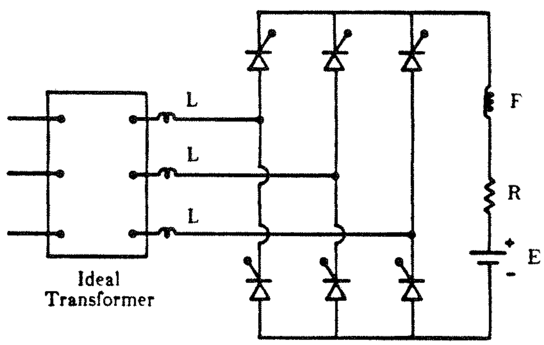
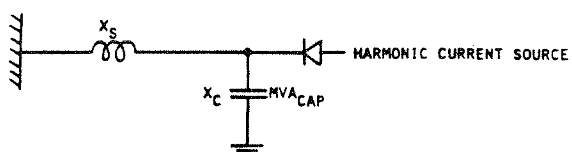


Figure 1: Six Pulse Line Commutated Converter



RESONANT FREQUENCY (PARALLEL CIRCUIT - HIGH VOLTAGE)

$$F = \frac{1}{2\pi\sqrt{LC}} = F_0\sqrt{\frac{X_C}{X_S}}\ \text{Hz},\ F_0 = 60,$$

$$MVA_{SC} = \frac{1}{X_S}\ \text{PU}$$

$$MVA_{CAP} = \frac{1}{X_C}\ \text{PU}$$

$$F = F_0\sqrt{\frac{MVA_{SC}}{MVA_{CAP}}}\quad (3\phi \text{ OR } 1\phi \text{ QUANTITIES})$$

Figure 2: Parallel Resonance on a Simple Distribution Feeder

5. All types of AC/DC converters.

The most common harmonics source on distribution systems is the standard six pulse line commutated converter, shown in Figure 1. This device is very efficient and can be used to control power flow in either direction. Furthermore, several of these can be configured for twelve or higher pulse operation. Since the six pulse converter is a delta connected device, no zero sequence currents (or triple harmonics) can flow into it.

As a first approximation, the AC waveform produced by this device resembles a symmetric square wave - on for 120° and off for 60°. The Fourier series for this type of wave has the following component magnitudes:

$$|I_h| = \frac{|I_1|}{h}, \; h = \text{harmonic order.}$$

The exact harmonic current magnitudes and phase angles can be calculated more accurately if needed [4]. In practice, the total current harmonic distortion is in the range of 20% - 30%. As a result, when megawatt-size converters are used on distribution feeders, serious voltage and current distortion can result.

PROPAGATION OF HARMONICS IN POWER SYSTEMS

The most simple example of harmonic propagation and resonance in a system is illustrated in Figure 2. The system shown is a simple one-load feeder with a single power factor correction capacitor. If the resonant frequency of the system is at or near one of the characteristic harmonics of the source, serious voltage distortion may result. In actual feeders, the resonant point is often between the 5th and 13th harmonics, which makes them very susceptible to resonances when large converter loads are connected.

Distributed capacitor banks result in complicated patterns of series and parallel resonance. In these cases, voltage distortion can be low at the harmonics source but very large at a remote customer many miles distant. This phenomenon is known as *harmonics amplification* and explains why the source of voltage distortion can be difficult to locate.

Modeling of actual systems requires a sophisticated computer program. Several are available, including the EPRI - HARMFLO program [4]. This program can be used to simulate systems of 100 busses or larger with several converter loads. Typical information needed includes "loadflow type" data plus additional data describing the converter loads.

Several comments are in order concerning harmonics analysis. First, proper models of system components must be used, including hyperbolic "long line" models for transmission lines, resistive skin effect for line and transformer resistances, and accurate harmonic load models for conventional loads. The HARMFLO program contains the proper models, thereby freeing the user from complicated calculations where possible. In all cases, the locations and sizes of shunt capacitors are extremely important.

References [4-6] are helpful in describing the various system analysis programs and techniques.

EFFECTS OF HARMONICS ON POWER SYSTEM RELAYS

Power system relays have long been subjected to wave distortions, but the frequency of occurrence and significance of distortions are increasing. At the present time, there are few limits or guidelines concerning harmonic injection from loads, and no guidelines regarding the performance of relays when harmonics are present. Thus, the material presented here is more qualitative than quantitative. However, it does represent the level of knowledge at this time, as reported by the IEEE Power System Relaying Committee [3].

Relays can be classified according to three basic types: electromechanical, static, and computer based. For the most part, low frequency audio-range harmonics (1 - 25th harmonic) pass through instrument transformers unchanged, providing that the transformers are not saturated. Therefore, the relays "see" all of the harmonics.

Some general comments are in order concerning relay performance with harmonics present. First, it is difficult to generalize relay response, since some types become more sensitive, and some less sensitive. Second, whenever phase shifting circuits are employed, as in the case of phase sequence or reactive power detection, the frequency response depends totally on the circuit parameters. These may be known only by the manufacturer.

Furthermore, relays which respond to peak values will probably be affected much more by harmonics than those which respond to RMS values. Known information for the types mentioned is given in the following section.

Electromechanical Relays

The performance is frequency sensitive. However, this cannot be generalized since some relays tend to be less sensitive when harmonics are present, and some tend to be more sensitive. The wide range of responses makes it impossible to generalize.

Instantaneous overcurrent relays using plungers are largely independent of frequency effects since their response is based on RMS current (which is not usually affected greatly by harmonics). **Voltage relays** respond only to the fundamental component of a distorted waveform, making them insensitive to harmonics. **Distance relays** cannot be generalized. **Sequence relays** are affected greatly since these employ frequency shifting networks for 60 Hz.

Static Relays

The design variations for static relays are significant. Their response can be based on: Peak Value; Average Value; or RMS Value. Most static relays use small input transformers which have significant equivalent air gap to suppress the dc component of asymmetrical current. This results in increased sensitivity to high frequency harmonics.

Computer Based Relays

These devices are not immune to harmonics, although they may be made more immune than electromechanical or static relays. Harmonics of higher frequency than the sampling rate can cause "aliasing" which results in erroneous conclusions. Other than this problem, once the input waveform is digitized, the relay response is based entirely on the controlling software.

OTHER PROTECTION CONSIDERATIONS IN THE PRESENCE OF HARMONICS

There are other considerations in power system protection when harmonics are present. These include:

Derating of Transformers
Effects of Harmonics on Large Motor Loads
Protection of Capacitors and Reactors.

Transformers must be derated when harmonic currents are present. The IEEE Transformers Committee is presently publishing a method to determine the amount of deration, which depends on the levels of harmonic currents [7]. Likewise, motors appear as low impedance ground paths to harmonic signals, making them susceptible to excessive winding losses. Capacitors are often the major sinks of harmonic currents, and their current distortion is usually noticeable on an oscilloscope. The rating of each of these devices must be reconsidered when significant harmonic levels are present.

CONCLUSIONS

The effect of harmonic current and voltages on some power system components, such as motors, transformers, and capacitors, can be quantified. The effect on protective relays, however, varies widely according to specific design and type. Protective devices which use 60 Hz phase shifting circuits are quite sensitive.

General comments regarding relays include [3,8]:

Tendency toward slower operation and/or higher pickup values
Superposition does not apply
Multi-input relays tend to be more unpredictable
Variation of relay response occurs among relay manufacturers
Harmonic tests are not generally included in relay testing
Harmonics should be a significant consideration in applying and setting relays for non-fault load

operation.

Other notable items include:

- Minimal effects on electromechanical voltage relays
- Peak sensing static relays may be adversely affected
- Aliasing may impact performance of computer based relays.

As a general rule, voltage or current distortion levels greater than 5% warrant extra consideration.

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