TECHNICAL CONSIDERATIONS IN HARMONIC MITIGATION TECHNIQUES APPLIED TO THE INDUSTRIAL ELECTRICAL POWER SYSTEMS

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ABSTRACT

Power system harmonics cause many problems like equipment failures, malfunctions and plant shutdowns. Accordingly, mitigation of these harmonics is considered an important target especially for the industrial applications where any short downtime period may lead to great economic losses. There are at least ten different mitigation techniques to choose from, each with specific technical advantages and disadvantages. Comparative studies for the harmonic mitigation techniques in industrial electrical systems are rarely found in the literature even though they are strongly needed. This paper, almost for the first time, provides comprehensive technical studies on the various practical harmonics mitigation techniques for the industrial electrical systems. This has been carried out with the aid of our research and experience in the industrial field. Hence, this paper is considered as a helpful guide for design engineers, consultants and customers of the industrial sector.

INTRODUCTION

Due to the dramatic increase in the applications and usage of nonlinear loads in the industrial applications (mainly, the variable frequency drives VFD's), the power system harmonics problems arise and represent a big obstacle against the wide application of the VFD's although they enhance system efficiency and provide great energy saving. The power system harmonics have many harmful effects such as over-heating of electrical equipment, failure of capacitor banks, nuisance tripping to protection relays and interference to communication systems [1].

An extensive literature review over the past thirty years ensures us that there are few articles that can compare and summarize the various available harmonic mitigation techniques especially for the industrial sector.

The goals of this paper can be summarized as follows:

a. To extract and highlight some design precautions that can lead to mitigation of power system harmonics
b. To investigate the various mitigation techniques with the merits and demerits of each technique
c. To provide comprehensive comparative studies between these various harmonic mitigation techniques to enable design engineers, consultants and plant owners of selecting the optimal harmonic mitigating technique for their plant

HARMONIC MITIGATION TECHNIQUES

First, harmonic mitigation design precautions, during the design stage of the project, are discussed followed by harmonic mitigation techniques after project completion or solutions for an existing facility.

1. Harmonic mitigation design precautions (during the design stage of the project):

1.1 Segregation of harmonic producing loads from sensitive loads

Harmonic producing loads may be separated from sensitive loads so that sensitive loads are not influenced by loads with high harmonics. All heavy nonlinear loads (in the order of several MVA) should have their own dedicated transformers, such as the practical case of the large drives or arc furnaces in a steel mill [2].

1.2 Using star/ delta transformers for trapping triplen (3rd, 9th…etc) harmonics

Transformer connections can be utilized to reduce harmonics in a three-phase system by using delta connected transformers to block the third order (triplen) harmonics. The delta transformer connection provides a zero sequence trap for the triplen harmonics. This is accomplished by the fact that the third and multiples of third harmonic currents have the same magnitude and direction in all three legs of the delta connected transformer, accordingly there is no resulting change in the zero sequence flux, $(d\Phi_o/dt)$, thus the current in the line side of the transformer contains no third harmonics.

1.3 Optimum usage of the VFD and soft starters

The variable frequency drive has great advantages such as speed control, energy saving and motor's starting current limitation. As a misapplication, some design engineers use the VFD as a soft starter only, thus giving the benefit of reducing the motor starting currents but at the same time injecting a large amount of unwanted harmonics into the electrical network.

1.4 Optimum selection of the generator pitch factor

The magnetic circuit of an AC generator produces voltage harmonics that can be minimized through the proper arrangement of the stator windings. Table 1 shows the effect of varying the generator pitch factor on the harmonic voltage content output from the generator [3].

Table 1 Effect of pitch factor variation on voltage harmonic magnitudes

Pitch factor	Fundamental	3rd	5th	7th	9th
2/3	0.87	0.00	0.86	0.87	0.87
4/6	0.95	0.58	0.00	0.59	0.95
5/6	0.96	0.71	0.26	0.26	0.97
6/7	0.97	0.78	0.44	0.00	0.78

From Table 1, it can be concluded that the optimum pitch factor is (5/6) because it results in reducing the 5th and 7th harmonics, in addition, as clearly described in section 1.2, using delta connected transformer would filter the 3rd and 9th harmonics, thus finally a relatively good reduction in harmonics arising from the generation units is achieved.

2. Harmonic mitigation techniques after project completion or solutions for an existing facility:

2.1 Harmonic mitigation by using AC line reactors

The AC line reactor is the simplest and cheapest mean of mitigating harmonics. It is connected in series with an individual nonlinear load such as a VFD. The impedance rating of the line reactor indicates the per unit impedance relative to its rated full load current [1].

2.2 Harmonic mitigation by using DC reactors

The DC reactor is simply a series inductance (reactor) installed on the DC link of the VFD. The harmonic mitigation achieved by using the DC choke effect is comparable to an equivalent AC line reactor, while the DC choke provides a greater harmonic reduction for the 5th and 7th harmonics.

2.3 K-factor transformers and drive isolation transformers

Underwriters' laboratories (UL) and many transformer manufacturers established a rating method called the K-factor, for dry-type transformers, to evaluate their suitability for operation in a harmonic polluted environment. This factor is specifically defined for transformers that feed variable frequency drives. The K-factor transformers by themselves are a method for "living with" harmonics but will not significantly reduce the harmonics over the less expensive reactor solution [4].

2.4 Multi pulse drive configurations (6 pulse, 12 pulse, 18 pulse and 24 pulse)

Transformer connections can be beneficial in harmonics cancellation by creation of specific phase shifts. These phase shift are the key in minimizing the generated harmonic currents in the 12, 18, 24 and higher pulse numbers VFDs [5, 6]. The relation between the harmonics present in the VFD and the number pulses is as follows:

$$h_P = P.n \pm 1 \tag{1}$$

Where,

h: Harmonic order present in the VFD

P: Number of pulses of a VFD

n: Integer = 1,2,3,….

The six pulse drive is the simplest and least expensive drive. The input supply current to a six pulse VFD is approximately a square wave. The 12 pulse VFD is formed by connecting two 6 pulse rectifiers in parallel to feed a common DC bus. The input to these rectifiers is provided with one three-winding transformer. This transformer has double secondaries that are in 30° phase shift. The benefit of this arrangement is that in the supply side, some harmonics are in opposite phase and thus cancel each other. Theoretically, this transformer arrangement yields to eliminating the 5th and 7th harmonics. The 18 pulse VFD uses three-phase three winding transformer that make a nine-phase system and the equivalent of 20° phase shift which eliminate the 5th, 7th, 11th and 13th harmonics. The 24 pulse VFD has two 12-pulse rectifiers in parallel with two three winding transformers, thus having 15° phase shift. The benefit of this connection is that, theoretically, most of the low frequency harmonics are eliminated but the major drawback is the high cost.

An extensive literature review over the past thirty years leads to the fact that there are few articles that can compare and summarize the various VFD configurations. Table 2 provides a novel helpful comparative study between the various VFD configurations.

From Table 2, the following points can be extracted:

a. The 6 pulse VFD is the cheapest VFD but it creates the largest amount of harmonics. Accordingly, it could be used in the following cases:
   - Where small number and low ratings drives are present in the system
   - Where there are no strict harmonic limits imposed by the utility companies
   - Where minimum initial cost is required by the plant owner

b. The 24 pulse VFD is the most expensive drive but it produces the least harmonic distortion so it could be used in the following cases:
   - In the case of a high power single drive or large multi-drive installation (larger than 1 MW), a 24-pulse system may be the most economical solution with lowest harmonic distortion
   - Where there are strict harmonic limits imposed by the utility companies

The advantage of using a multi-pulse VFD is that the harmonics are eliminated from its source (not propagating inside the electrical network), thus avoiding excessive energy losses within the electrical system. On the other hand, the higher the number of pulses of a VFD the higher the drive cost and complexity.

The conclusion is that the selection of the optimal VFD configuration is a technical and economical compromise which mainly depends on the drive rating, project budget and customer and utility harmonic limits.

Table 2 A complete technical comparison between the various VFD configurations

Drive configuration	6 Pulse	12 Pulse	18 Pulse	24 Pulse
Harmonics created formula	$h_6 = 6n \pm 1$	$h_{12} = 12n \pm 1$	$h_{18} = 18n \pm 1$	$h_{24} = 24n \pm 1$
Harmonics created orders	5th, 7th, 11th, 13th, 17th, 19th …etc	11th, 13th, 23th, 25th, 35th, 27th…etc	17th, 19th, 35th , 37th …etc	23th, 25th , 47th , 49th …etc
Least harmonic order created	5th	11th	17th	23th
Input transformer	Not required	Required	Required	Required
Input transformer connection* **(*Connections may vary according to manufacturer)**	Not applicable	Primary: Star Secondary: double windings (Star / Delta)	Primary: Delta Secondary: Triple windings (Delta connected but phase shifted)	Four Input transformers (each Star/ Delta) but phase shifted from each other
Phase shift achieved* **(*Phase shift may vary according to manufacturer)**	Not applicable	30 °	20 ° or 15 °	15 ° or 7.5 °
Current THD (%)	25 – 40 %	9 – 11 %	3 – 4 %	1-2 %
Meet IEEE 519 limits	No	Maybe	Yes	Yes
Available ratings in the market (KW)	All (KW) ratings are available	All (KW) ratings are available	Available and economic for large power rating drives, (> 300 kW)	Available and economic for large power rating drives, (> 800 kW)
Overall dimensions (Relative to 6 pulse VFD)	100 %	150 % to 200 %	300 %	350 %
Installation options	Stand-alone installation or inside a standard switchgear	Stand-alone installation or inside a standard switchgear	Stand-alone installation	Stand-alone installation
Cooling	Air cooled	Air cooled	Air cooled or water cooled	Air cooled or water cooled
Complexity	Simple	Moderate	Complicated	Very complicated
Cost (Relative to 6 pulse VFD)	100 %	200 %	250 %	300 %

2.5 Passive harmonic filters

One of the most common and effective methods for control of harmonics in the industry is the use of passive filtering techniques that simply makes use of combinations of inductances, capacitances and resistances to form a trap for specific harmonic orders. Passive filters can be classified, according to their connections, into single-tuned, damped and high pass filters. Passive filters are designed (tuned) to provide a low impedance path to harmonic currents at a specific frequency called the tuning frequency (Fr) or as band-pass devices that can filter harmonics over a certain frequency bandwidth [7-9] thus preventing the flow of these harmonic currents into the electrical system. A shunt filter is said to be tuned to the frequency that makes its inductive and capacitive reactances equal.

2.6 Active harmonic filters (AHF)

Active harmonic filter (AHF) is an intelligent and interactive filter. The basic principle of the active filter is that it generates a current equal and opposite in polarity (180° phase shifted) to the harmonic current drawn by the nonlinear load and injects it to the point of common coupling (PCC). Accordingly, the active filter forces the source current to be pure sinusoidal. The characteristics of harmonic compensation are strongly dependent on the filtering algorithm used for extraction and calculation of the harmonic load current [10]. The current waveform generated from the active harmonic filter is produced by using a voltage source or current source inverter. There are two types of active filters, shunt active harmonic filter and series active harmonic filter. Series AHF's are not commonly used in the market because they are designed to carry the full load current and are insulated for full line voltage, hence their cost are much higher than shunt filters. Table 3 introduces a comprehensive comparison between the passive and active harmonic filters

Table 3 Comparison between the passive harmonic filter and the active harmonic filter

	Passive filters	Active filters
Harmonic studies required	Yes	No
Target harmonics	Only single harmonic order	From 2nd to 50th
Meet IEEE 519 limits	Sometimes, if properly sized	Yes
Possibility of overloading	Yes	No
Field expandable	Sometimes	Yes
Available voltages	LV and MV passive filters are available	Only LV AHF is available
Response to load changes	Slow	Very fast
Installation options	Indoor or Outdoor	Indoor only
Mainly defined by	Target harmonic order and the reactive power injected	RMS current
Probability of resonance	Yes	No
Maintenance	Easy	Difficult
Cost	Cheap	Very expensive

2.7 Hybrid harmonic filters

In order to extend the application range of the active filters, and to improve the performance of passive filters, another approach consists of combining both technologies within the same device called, Hybrid, filter [10]. The hybrid filter is composed of a combination of passive and active filters. The passive filter portion is tuned to the dominant harmonic frequency in the system and is supplying the required reactive power for power factor correction requirements. The active filter portion is dedicated for removing all other harmonic orders.

Each harmonic mitigation technique has many advantages and disadvantages as described earlier in this paper. Furthermore, Table 4 provides a novel helpful comparative study, in the form of a comparative table, between most of the harmonic mitigation solutions.

CONCLUSION

This paper provides comprehensive technical studies on most of the harmonics mitigation solutions for the industrial electrical power systems highlighting the merits and demerits of each technique to enable the design engineers, consultants and plant owners of selecting the optimum harmonic mitigating technique for their plants.

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Table 4 A complete technical study, in the form of a comparative table, between most of the harmonic mitigation solutions

Harmonic mitigation solution	**AC reactor**	**DC reactor**	**K-factor transformer**	**Multi-pulse VFD**	**Passive filter**	**Active filter**	**Hybrid filter**
Current THD (%)	< 40%	< 45%	Not Applicable (N/A)	< 11 %, (12 pulse VFD)	< 12 %	3- 5 %	5- 7 %
Meet IEEE 519 limits	Rarely	Rarely	N/A	Yes, (18 & 24 pulse)	Maybe	Yes	Yes
Power factor improvement	No	No	N/A	No	Yes	Yes	Yes
Attract upstream harmonics	No	No	N/A	No	Yes	No	Yes
Connection	Series	Series	Series	Shunt	Shunt	Shunt	Series & Shunt
Insertion difficulty	Difficult	Difficult	Difficult	Easy	Difficult	Easy	Difficult
Resonance occurrence risk	No	No	No	No	Yes	No	Yes
Field expandable	No	No	No	No	Yes	Yes	Yes
Require harmonic analysis studies	Yes	Yes	N/A	Yes	Yes	No	No
Available voltage levels	LV & MV	LV	LV & MV	LV & MV	LV & MV	LV	LV
Efficiency	Moderate	Moderate	Moderate	High	Moderate	High	High
Overall dimensions	Small	Small	Moderate	Large	Large	Large	Large
Installation options	Indoor or outdoor	Indoor (inside the VFD)	Indoor or outdoor	Indoor	Indoor or outdoor	Indoor	Indoor
Cooling	Air cooling	Air cooling	Air cooling	Air cooling or water cooling	Air cooling	Air cooling	Air cooling
Complexity	Simple	Simple	Simple	Complicated	Moderate	Very Complicated	Very Complicated
Cost	Low	Low	Moderate	Expensive	Moderate	Very Expensive	Very Expensive