Utilizing MATLAB-SIMULINK Based Technique for Teaching Advantages of Harmonic Eliminating Using Shunt Active Power Under Steady State to Graduate Students

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ABSTRACT

Harmonic current which is generated during connection of a non-linear load to system, if it multiplied by the network impedance it will distort the network voltage. This harmonic voltages and currents have undesirable effects, including the increase of dielectric losses and insulation stress, hysteresis losses, eddy-current losses, copper losses, overheating of transformers and cables, malfunction of system or plant components. In this paper description and definition of harmonics and their destroyer effects on power system is presented. Also the effect of harmonics mitigation using shunt active power filter under steady state is investigated. Due to educational purpose of this paper to teaching compensation advantages to graduate students the well-known software MATLAB-SIMULINK is used to simulate and investigate the effects of harmonics mitigation.

Keywords: Simulation, Matlab/Simulink, Harmonics, Shunt Active Filter, Educational Purpose, steady state operation

1. INTRODUCTION

Harmonic distortion (Figure 1) is the corruption of the fundamental sine wave at frequencies that are multiples of the fundamental. (e.g., 180 Hz is the third harmonic of a 60 Hz fundamental frequency; \( 3 \times 60 = 180 \)). Symptoms of harmonic problems include overheated transformers, neutral conductors, and other electrical distribution equipment, as well as the tripping of circuit breakers and loss of synchronization on timing circuits that are dependent upon a clean sine wave trigger at the zero crossover point. Harmonic distortion has been a significant problem with IT equipment in the past, due to the nature of switch-mode power supplies (SMPS). These non-linear loads, and many other capacitive designs, instead of drawing current over each full half cycle, “sip” power at each positive and negative peak of the voltage wave. The return current, because it is only short term, (approximately \( 1/3 \) of a cycle) combines on the neutral with all other returns from SMPS using each of the three phases in the typical distribution system. Instead of subtracting, the pulsed neutral currents add together, creating very high neutral currents, at a theoretical maximum of 1.73 times the maximum phase current. An overloaded neutral can lead to extremely high voltages on the legs of the distribution power, leading to heavy damage to attached equipment. At the same time, the load for these multiple SMPS is drawn at the very peaks of each voltage half-cycle, which has often led to transformer saturation and consequent overheating. Other loads contributing to this problem are variable speed motor drives, lighting ballasts and large legacy UPS systems. Methods used to mitigate this problem have included over-sizing the neutral conductors, installing K-rated transformers, and harmonic filters. Spurred on by the remarkable expansion of the IT industry over the last decade, power supply design for IT equipment has been upgraded via international standards. One major change compensates for electrical infrastructure stresses caused, in the recent past, by large clusters of IT equipment power supplies contributing to excessive harmonic currents within a facility [1]. Many new IT equipment power supplies have been designed with power-factor corrected power supplies operating as linear, non-harmonic loads. These power supplies do not produce the waste current of harmonics.

2. HARMONICS MODULE

This module consists of 5 weeks theoretical course was held in Borujerd Branch of Islamic Azad University. The most important contents of this module includes of harmonic principles and its difference with other power quality phenomena. The harmonics effects on power system are introduced, analyzed and finally the method of harmonics compensation and elimination based implementation of shunt active power filter are investigated. It also covers some examples in this area. The aim of this module is to introduce a helpful method to instructor for teaching the examples of harmonic distortions, its effects on power system and its mitigation and compensation with their results. Therefore, the author of this article has been using MATLAB-SIMULINK as an instructional tool to teach this subject. This method of instruction has enabled students to understand the harmonics
concept and the necessity of harmonics elimination and compensation subject.

The success rate of students in understanding the subject shows the ability of this method.

An essential feature of using MATLAB-SIMULINK is to incorporate the visualization and control of results in a graphical form on a computer screen. This is particularly important in the analysis or simulation of power networks because of their large size and wide geographical distribution. In order to better describe of harmonic concepts, at first four questions as follows are presented:

- What is harmonics?
- What are the effects of harmonics on power system?
- What is method of harmonics elimination?
- What is the performance of shunt active power in harmonic compensation?

This is a limited definition of reactive power. It would be said that Harmonics have frequencies that are integer multiples of the waveform’s fundamental frequency. Total harmonic distortion is a complex and often confusing concept to grasp. However, when broken down into the basic definitions of harmonics and distortion, it becomes much easier to understand. Imagine a power system with an AC source and an electrical load. Now imagine that this load is going to take on one of two basic types: linear or non linear. The type of load is going to affect the power quality of the system. This is due to the current draw of each type of load. Linear loads draw current that is sinusoidal in nature so they generally do not distort the waveform. Most household appliances are categorized as linear loads. Non-linear loads, however, can draw current that is not perfectly sinusoidal. Since the current waveform deviates from a sine wave, voltage waveform distortions are created. Waveform distortions can drastically alter the shape of the sinusoid. However, no matter the level of complexity of the fundamental wave, it is actually just a composite of multiple waveforms called harmonics.

This harmonics distorted voltages and currents have these disadvantages [2-8]:

- Failure, tripping or overheating of capacitors, filters and related equipment.
- Abnormally high noise levels in capacitors, cables, transformers and lightning equipment.
- Overheating of transformers, cables, switchgear, conductors, etc.
- An abnormally high rate of failures of thyristors and converter equipment.
- Frequent failures of capacitors in lighting equipment or tripping of associated low voltage circuit breakers.
- “Nuisance failures” of fuses.
- “Nuisance tripping” of protection relays, in particular sensitive earth fault relays or earth leakage relays.
- Apparent errors in electronic power transducers.
- Apparent inconsistencies in metering equipment.
- Interference with computer equipment.
- An abnormally high cable failure rate or an increase in cable failures.

3. EFFECTS OF HARMONIC DISTORTION ON POWER SYSTEMS

Once the harmonic sources are clearly defined, they must be interpreted in terms of their effects on the rest of the system and on personnel and equipment external to the power system. Each element of the power system must be examined for its sensitivity to harmonics as a basis for recommendations on the allowable levels. The main effects of voltage and current harmonics within the power system are [3-5]:

- Amplification of harmonic levels resulting from series and parallel resonances.
- Reduction in the efficiency of the generation, transmission and utilization of electrical energy.
- Ageing of the insulation of electrical plant components with consequent shortening of their useful life.
- Malfunction of system or plant components.

The effects of voltage distortion are:

- Thermal stress
- Load disruption
- Insulation stress

Harmonics increase the equipment losses and thus the thermal stress. The triple harmonics result in the neutral carrying a current which might equal or exceed the phase currents even if the loads are balanced. This dictates the derating or over sizing of neutral wires. Moreover, harmonics caused resonance might damage the equipment. Harmonics further interfere with protective relays, metering devices, control and communication circuits, and customer electronic equipment. Sensitive equipment would experience mal-operation or component failure.

Harmonic currents in the power distribution system can cause [6, 7]:

- Transformer secondary voltage distortion
- Overloaded neutrals and capacitors
- Telephone and communication system noise
- Increased power losses and thermal stress

Harmonics have the effect of increasing equipment copper, iron and dielectric losses and thus the thermal stress [8].

\[ P_t = P_{1} (1 + \text{THD}_I^2) = P_{1} (1 + \text{THD}_V^2) \Rightarrow \Delta P_{1} = \frac{\Delta P_{1}}{P_{1}} = \text{THD}_I^2 = \text{THD}_V^2 \]  

(1)

Iron losses are the losses in an iron core of a magnetic circuit. These losses consist of hysteresis loss and eddy-current loss. Hysteresis loss is due to the reversal of magnetization of an iron core, and depends on the volume and quality of the used
magnetic material, maximum value of the flux density and frequency of electric current [9].

\[ P_{pe} = P_e + P_s \]
\[ P_h = \sum_{k=1}^{\infty} P_{h_k} = \sum_{k=1}^{\infty} \sum_{i=2}^{\infty} \xi f_i B_{s_i} = \sum_{i=2}^{\infty} \sum_{k=1}^{\infty} B_{s_k} \]
\[ = P_s \sum_{k=1}^{\infty} \left[ \frac{1}{P_{i_k}} \right] \]
\[ \Rightarrow P_{ve} = P_v = \sum_{i=2}^{\infty} i \left[ \frac{1}{P_{i_k}} \right] = \sum_{i=2}^{\infty} i \]

Eddy-current loss is the power loss associated with the flow of eddy currents which create induced magnetic fields that oppose the change of the original magnetic field due to Lenz's law

\[ P_e = \sum_{k=1}^{\infty} P_{e_k} = \sum_{k=1}^{\infty} \frac{1}{\sum_{i=2}^{\infty} \xi f_i B_{s_i}} \]
\[ = P_s \sum_{k=1}^{\infty} i \left[ \frac{1}{P_{i_k}} \right] = \sum_{i=2}^{\infty} i \]

\[ \Rightarrow P_{ve} = P_v = \sum_{i=2}^{\infty} i \left[ \frac{1}{P_{i_k}} \right] = \sum_{i=2}^{\infty} i \]

4. MATHEMATICAL MODELING OF HARMONICS

Total harmonic distortion, or THD, based on the IEEE definition, is the summation of all harmonic components of the voltage or current waveform \( M_i \) compared against the fundamental component of the voltage or current \( M_1 \) [10]:

\[ THD = \sqrt{\sum_{i=2}^{\infty} M_i^2} \]

The end result is a percentage comparing the harmonic components to the fundamental component of a signal. The higher the percentage, the more distortion that is present on the mains signal.

The \( \text{rms} \) values of all the harmonics that can be represented as:

\[ \text{RMS} = \sqrt{\sum_{i=1}^{\infty} M_i^2} = M_1 \sqrt{1 + THD^2} \]

When the fundamental component of a signal is zero, then the THD will be infinite, so in this condition this parameter does not have a engineering concept, therefore the another definition must be presented for total harmonic distortion. This new definition is DIN and can be defined as a percentage of the \( \text{rms} \) (used by the Canadian Standards Association and the IEC), and is calculated as follows:

\[ DIN = \left[ \frac{\sum_{i=2}^{\infty} M_i^2}{\sqrt{\sum_{i=1}^{\infty} M_i^2}} \right] \]

The total power factor is called distortion power and results from the harmonic component of the current and voltages as follows [11]:

\[ PF = \frac{P}{S} = \frac{\sum_{h=1}^{\infty} V_h I_h \cos \phi_h}{\sqrt{\sum_{h=1}^{\infty} V_{h, \text{rms}}^2 I_{h, \text{rms}}^2}} \]

Where, \( h \) is the order of the \( h \)th harmonic and \( \cos \phi_h \) is the angle between the \( h \)th harmonic voltage and the \( h \)th harmonic current. It could be calculated easily as follows [12]:

\[ PF = \frac{1}{\sqrt{1 + THD^2}} \cdot \text{DPF} \]

Where, \( \text{THD}_1 \) demonstrates the total harmonic distortion of currents and \( \text{DPF} \) is the displacement power factor and is the cosine the angle of fundamental voltage and current component and assuming that for non-inductive or non-capacitive loads, the value can be considered as 1.

5. HARMONIC ELIMINATING USING SHUNT ACTIVE POWER

Shunt active power filter compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180°. This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor. The current compensation characteristic of the shunt active power filter is shown in Fig. 2.

Fig. 2. Basic compensation principle of shunt active power filter

6. DISCUSSION AND SIMULATION

The specifications of test system considered in this article to teaching graduate students and to illustrate the disadvantages harmonics voltage and current and their effects on power system equipment and familiar to advantage of harmonic compensation on power loss of reduction, are listed in Table 1 and 2 respectively.
For fundamental component:

\[ P_{avg} = 1 \times 1 \times \cos(0 - 38) = 0.78 \text{ p.u} \]

For 3rd harmonic:

\[ P_{3avg} = 0.023 \times 0.15 \times \cos(10 - 15) = 0.0034 \text{ p.u} \]

For 5th harmonic:

\[ P_{5avg} = 0.014 \times 0.27 \times \cos(14 - 53) = 0.0029 \text{ p.u} \]

For 7th harmonic:

\[ P_{7avg} = 0.028 \times 0.12 \times \cos(27 - 54) = 0.0029 \text{ p.u} \]

For 11th harmonic:

\[ P_{11avg} = 0.033 \times 0.37 \times \cos(31 - 65) = 0.011 \text{ p.u} \]

Therefore the total average power is:

\[ P_{avg} = \sum_{k=1}^{n} P_{kavg} = 0.78 + 0.0034 + 0.0029 + 0.0028 + 0.011 = 0.8001 \]

The total harmonic distortion of harmonic voltage and current are:

\[ THD_{V} = \sqrt{\frac{\sum_{k=1}^{n} V_{rmsk}^2}{V_{rms}^2}} = \sqrt{0.023^2 + 0.014^2 + 0.028^2 + 0.033^2} = 0.051 \times 100 = 5.1\% < 12\% \]

\[ THD_{I} = \sqrt{\frac{\sum_{k=1}^{n} I_{rmsk}^2}{I_{rms}^2}} = \sqrt{0.15^2 + 0.12^2 + 0.37^2} = 0.496 \times 100 = 49.6\% \]

As seen that:

\[ M = \frac{1}{\sqrt{1 + THD_{V}^2}} \times \frac{1}{\sqrt{1 + THD_{I}^2}} = \frac{1}{\sqrt{1 + 0.051^2}} \times \frac{1}{\sqrt{1 + 0.496^2}} = 0.91 \]

So: 0.91 × 0.78 = 0.716 i.e. \( M \times DP = PF_{true} \)

The increasing equipment copper loss is:

\[ \Delta P_{R-p,u} = THD_{I}^2 = 0.24 \rightarrow \Delta P_{R} = 24\% \]

The increasing equipment hysteresis loss is:

\[ P_{k-\mu} = \sum_{k=1}^{n} \left( \frac{V_{k}}{V_{i}} \right)^{n+6} = 1(1/1)^{16} + 3(0.023/1)^{16} + 5(0.014/1)^{16} + 7(0.028/1)^{16} + 11(0.033/1)^{16} = 1.082 \rightarrow \Delta P_{k} = 0.82 \times 100 = 8.2\% \]

The increasing equipment eddy-current loss is:

\[ P_{e-p} = \sum_{k=1}^{n} k \left( \frac{V_{k}}{V_{i}} \right) = 1^2(1/1)^2 + 3^2(0.023/1)^2 + 5^2(0.014/1)^2 + 7^2(0.028/1)^2 + 11^2(0.033/1)^2 = 1.179 \rightarrow \Delta P_{e} = 0.179 \times 100 = 17.9\% \]

7. SIMULATIONS AND RESULTS

In this section the influence of shunt active power filter on harmonic compensation is analyzed. As shown in Fig.3 the Matlab/Simulink simulation tool was used to develop a model that allowed the simulation and testing of the p-q theory calculations, which were implemented in the controller of the shunt active power filter for three-phase, four wire systems.
The load which used in the simulations in this paper for education purpose is presented in Fig.4.

The loads in each phase are:

- Phase a: A typical non-linear load constituted by a single-phase rectifier with a RC load on the DC side (non-sinusoidal current waveform);
- Phase b: An RL linear load (sinusoidal current waveform, delayed regarding to the phase voltage);
- Phase c: Another non-linear load, constituted by a single-phase rectifier with a RL load on the DC side (non-sinusoidal current waveform).

The behavior of the active filter is analyzed in steady-state operation. Figure 5 presents the load currents which is harmonic distorted in each phase. The active filter compensation currents and the source currents for the three phases and neutral wire are shown in Figures 6 and 7. It can be seen that, by action of the shunt active filter, the power supply phase currents become balanced, sinusoidal. Besides, the neutral wire current is eliminated.
The indices of harmonics have been calculated using developed simulation model as shown in Figure 10.

The methodology illustrated in this paper has explained to 30 senior undergraduate students in power system, all of them have passed power quality courses. The students employ the methodology and in the presence of instructor filled a questionnaire form. The questionnaire, comprising six questions, is listed in Table 5. The students graded them as 1 (poor), 2 (medium), 3 (good), and 4 (excellent). Figure 11 shows the global results obtained from the students’ questionnaire.

Comparing these two tables it is confirmed that the shunt active filter can compensate the power factor and the harmonic currents, turning then respectively into one and zero at power supply.

### 8. STUDENTS FEEDBACK

The methodology illustrated in this paper has explained for 30 senior undergraduate students in power system, all of them have passed power quality courses. The students employ the methodology and in the presence of instructor filled a questionnaire form. The questionnaire, comprising six questions, is listed in Table 5. The students graded them as 1 (poor), 2 (medium), 3 (good), and 4 (excellent). Figure 11 shows the global results obtained from the students’ questionnaire.

#### Table 5: Questionnaire Answered by the Students and Engineers

<table>
<thead>
<tr>
<th>Question</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The content of this practical is valuable for a student of engineering course</td>
<td></td>
</tr>
<tr>
<td>2. Are you understanding the concept of harmonics and its difference with other power quality phenomena</td>
<td></td>
</tr>
<tr>
<td>3. Are you more familiar with the influence of harmonics on power system operation</td>
<td></td>
</tr>
<tr>
<td>4. Are you more familiar with the influence of harmonics compensation on power THD and power factor</td>
<td></td>
</tr>
<tr>
<td>5. Are you more familiar with the influence of harmonics on decreasing iron and copper loss</td>
<td></td>
</tr>
<tr>
<td>6. Are you more familiar with the performance of shunt active filters in harmonics compensation under steady state</td>
<td></td>
</tr>
</tbody>
</table>

Table 6 gives the average scores for each question out of students’ feedback.

#### Table 6: Average Score Obtained From Students’ Answers

<table>
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<tr>
<th>Question</th>
<th>Average Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 1</td>
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<tr>
<td>Question 2</td>
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<tr>
<td>Question 3</td>
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<td>Question 4</td>
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<td>Question 5</td>
<td>3.75</td>
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<tr>
<td>Question 6</td>
<td>3.53</td>
</tr>
<tr>
<td>Total</td>
<td>3.34</td>
</tr>
</tbody>
</table>
9. CONCLUSION

Present article has outlined and illustrated a MATLAB-SIMULINK model to illustrate and investigate the effect of harmonics compensation on power system under steady state. The iron and copper power loss reduction dependence on the shunt active power filter capability in deceasing THD is non-linear. The improvement of power system condition is proportional to compensation duration by shunt active power filter. The method considerably reduces the time and cost needed to teach the subject. Therefore, it is very useful for educational purposes and useful preparatory exercises for student to learn the subject. The evaluation of the project involving more than 30 students indicates benefits of this project in teaching the subject. The following conclusions could be achieved regarding the studied active filter and its control system:

- It compensates dynamically the harmonic currents;
- It corrects dynamically the power factor;
- It compensates dynamically, and instantaneously, the zero-sequence current;
- It balances and reduces the values of the currents supplied by the source to the load;
- It turns the instantaneous three-phase power that source delivers to load into a constant value (the source only delivers conventional active power).

REFERENCES


[10]. W. Mack Grady and et.al, Harmonics and how they relate to power factor, Proc. of the EPRI Power Quality Issues & Opportunities Conference (PQA’93), San Diego, CA, November 1993.
