Mitigation and Improvement of Distorted Distribution System by Hybrid Passive Filter

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Abstract. The most important objective in electrical utility operation and control is to improve voltage quality in industrial power grids. Due to the use of electronic devices in the form of non-linear load, the system will get affected with harmonics. Harmonic has become the main issue for power quality, and to mitigate the distortion of harmonics and to improve the system condition, it is necessary to investigate modeling components. In this project, the harmonic analysis of the power system was performed using ETAP software, and the whole process was described in detail. For the work, firstly, the network is designed simply with 7 Buses modeled as a harmonic source to inject harmonic current through the power grid. The next step is to analyze the effect of harmonic current, the harmonic load flow analysis was performed, and the harmonic distortion was determined. To eliminate this harmonic distortion, various types of techniques have been followed. These are the design of symmetric filters, bank capacitors, etc. The overall results of filters without additional measures are discussed in detail to measure the efficiency of this harmonic analysis based on power quality measurements. It is found that the installed filter may mitigate the distortion by suppressing the Total Harmonic Distortion and waveform refinement.

1 Introduction

The optimal operation of electrical power systems is aimed at delivering power with better quality. In general, the loads are linear loads, where the current of the applied voltage is sinusoidal. However, some kinds of loads are nonlinear loads where the sinusoidal voltage entails a non-sinusoidal current that may inject distortion into the system [1]. These loads draw nonlinear since nonlinear loads cause non-sinusoidal currents or non-sinusoidal voltages named harmonic [2]. Harmonic effects devices connected to the electrical system may reduce lifetime [3]. Loads are preferably linear, according to developments in semiconductor technology. In the past 40 years, the number of nonlinear loads in the system has been increasing rapidly.

Nonlinear loads affect the system by generating harmonic voltage and current. Example of the load is a transformers, converter high-power induction motors, UPS systems and etc. Harmonic current and voltage also cause extra power loss, heat system elements, and damage to the system's installation components. The presence of high order frequency is very difficult to fix by using protection relays and may relays fail or even get damaged [4].

Variable frequency drives (VFDs) are increasingly used in all applications used in power electronic drives to meet energy efficiency and control performance under good conditions. The loads that have nonlinear characteristics may cause non-sinusoidal harmonic injection currents [5]. The harmonic reduction in the power system is the most important among other solutions, and filtering is the more extensive approach [6]. Reducing Harmonic can be done by using a power quality conditioner and filters (passive, active, and hybrid). Among these options, the passive filter is cost-effective, easy for user control, and provides an acceptable current harmonic cancellation.

There are many kinds of power system software that can be used to determine and analyze the Harmonic on power networks, such as Matlab, PSIM, or ETAP. In this research, the ETAP Software application was selected because it is simplified and easy to model harmonic sources. Electric Transient and Analysis Program (ETAP) is a completely integrated Electrical Engineering software solution. ETAP can provide the best tool for the study of harmonics in the power system. With ETAP, we can easily study the Harmonic analysis of any circuit's type. Also, ETAP helps us to study the Harmonic spectrums.

There are six types of harmonic filters provided by the ETAP program. These would have the advantage of minimizing harmonic distortion to meet the rules standard. The main objective of the project is to perform a Harmonic Study on a power system using ETAP software, analyze the system improvement or mitigation due to the application of filters into the system, and compare the results before and after adding the filter to the system [6].

To achieve this objective, the study is subject to the goals of following: (1) Modelling different types of power networks that will include Harmonic Sources in the power network, (2) Perform harmonic analysis on these power networks so that harmonic distortion can be easily identified, (3) Suppress the harmonic distortion and resonance conditions in the power network, design/test filters, (4) Identify possible violations of the distortion limits, (5) Comparison of the result before and after installing the filters, (6) Identify the factors that protect the power system equipment from Harmonic causes. All mentioned key issues will be taken according to the IEEE519 standard, where the Harmonic indices will be set accordingly in the software.

Designing harmonic filters to improve the power quality and fix the network system may face some challenges. Problems in this study can be formulated as follows: (1) Planning the design of circuits and collecting the data, (2) Installation and calibration of ETAP software to suit this research, (3) Creating and simulating the circuit equipment, and (4) Testing different sets and comparing the output results [7].

The objectives of this project are to propose the design of a Hybrid Passive Filter and to propose to form an ideal solution for two main types of analyses that could be performed during harmonic analysis voltage harmonic distortion and current harmonic distortion, in which the individual and total current and voltage harmonic distortions are calculated at the various buses then the results are compared with the relevant contractual limits on the power grid system.
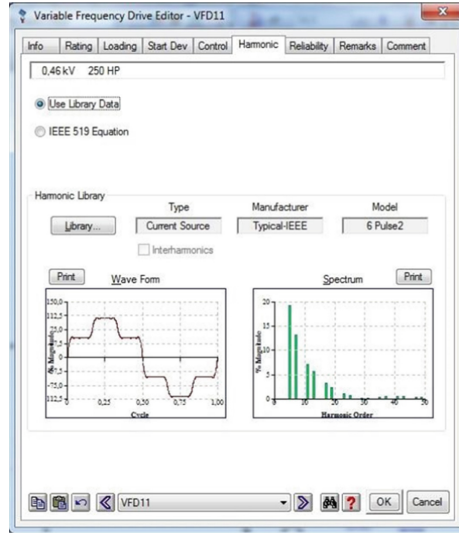
Fig. 1. Harmonic Editor page

2   Calculation of Harmonic Power Flow

For the purpose of system modeling, a single-line diagram needs to be initially developed from which harmonic source may be selected. The developed system may combine a pure power system and harmonic sources such as VFDs, chargers, UPS, etc. To model a nonlinear component as a harmonic current source, it may be directly selected from the library of the harmonic component via the library button and Harmonic Library Quick Pick Editor on the Harmonic page. The Harmonic page of a nonlinear load is shown in Fig. 1.

Once the single-line diagram of the electrical distribution system has been successfully developed with some nonlinear loads inclusive, the load flow calculation for fundamental and harmonic frequencies may be carried out. These calculations may be performed for various possible operating scenarios. By checking the individual and total voltage and current distortion levels at the interested system buses and checking the harmonic frequency spectrum, the plot of every individual harmonic value may be displayed. If the harmonic distortion results exceed the allowable limits, select an appropriate harmonic mitigation solution and the optimum insertion point for that solution, such as filters. To mitigate and improve the system condition, the calculation may be repeated after adding the harmonic filters to ensure compliance with the standard of harmonic limits.

3   Harmonic Indices

The result of harmonics is usually measured in terms of several indicators, as discussed in this section. For the harmonic order of i and maximum harmonic order N, the indices of harmonic are given as the followings.

Total Harmonic Distortion (THD) is the value obtained from the comparison of the RMS value of all components other than the fundamental harmonics to the fundamental component. The THD for voltage and current may be calculated using Eq. 1.

$$THD_V = \sqrt{\frac{\sum_{i \neq 1}^{N} V_i^2}{V_1}} \ THD_I = \sqrt{\frac{\sum_{a \neq 1}^{N} I_a^2}{I_1}} \tag{1}$$

where V_i and I_i is the amplitude of voltage and current at the h harmonic, and V_1 and I_1 is the fundamental component of voltage and current.

Individual Harmonic Distortion (IHD) measures the ratio of a given harmonic component to the fundamental component. The IHD for respective voltage and current is given by Eq. 2.

$$IHD_V = \frac{V_i}{V_1}, \ IHD_I = \frac{I_i}{I_1} \tag{2}$$

Root Mean Square (RMS) is the square root of the sum of the squares of the magnitudes of the fundamental harmonics and all the harmonics in the power system. For a power system without harmonics, the total RMS should be equal to the RMS fundamental component. The RMS of voltage and current are respectively given in Eq. 3.

$$RMS_V = \sqrt{\sum_{i=1}^{N} (V_i)^2}, \ RMS_I = \sqrt{\sum_{i=1}^{N} (I_a)^2} \tag{3}$$

4 International Harmonic Standards

The ETAP Harmonic Analysis module is fully provided the latest version of the following standards listed below:

- IEEE 519-2014 Standards, Recommended IEEE Practices, and Requirements for Harmonic Control in Electrical Power Systems.
- IEEE 519-1992, this document introduces many useful recommended practices for harmonics control in electrical networks. This document is widely used in the industrial sector and many consultants/clients use the limits shown in it as contractual limits within their specifications.

5 Harmonic Filter

In this project hybrid passive filter has been selected among the available harmonic mitigation solutions in power technology. The reason is its high efficiency, performance, simple configuration, and affordable price. Passive filter configuration consists of passive components such as inductors, resistors, and capacitors (RLC). The filter insertion point has been carefully studied as it dramatically affects the system's performance. Different types of passive filters exist in the industries, as shown in Fig. 2.
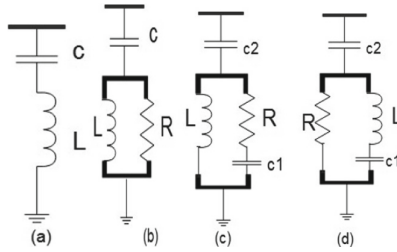
Fig. 2. (a) Single-tuned; (b) 2nd order high-pass; (c) 3rd order high-pass; (d) C-type.
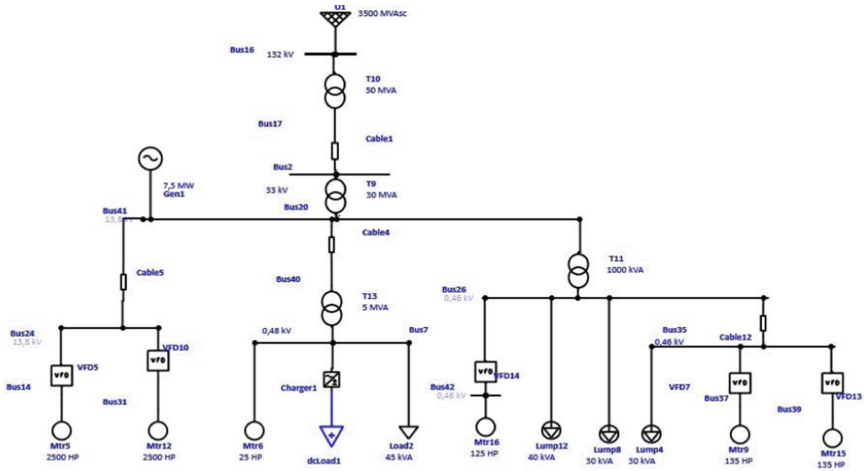
Fig. 3. The system for harmonic analyses using ETAP

6 System Design and Distortion Calculation

The project performed Harmonic analysis using ETAP to figure out harmonic current and voltage distortions in the power grid [8]. With harmonic calculation results in hand, the system is improved using hybrid passive filters to mitigate the harmonic distortion. The one-line diagram is shown in Fig. 3. The network consists of 7 main Buses, Bus 16, bus2, bus41, and bus 24, with high voltage ratings of 132, 33, and 13,8 kV. Bus 7, bus 26, and bus 35 as Low Voltages rating with 0.48 and 0.46 kV. The system is injected with six harmonic sources that generate harmonic distortion in the system. These are given in Table 1.

The external grid is connected to a 132 kV bus as high voltage, and the voltage level has decreased from 132 kV to 33 kV using 50 MVA-rated two-winding transformers. Then continued stepping down to MV 13,8 kV and the LV 0,48 and 0,46 kV. The values of Z% and X/R are typically provided from the ETAP library, and the five harmonic sources are VFDs installed with motors as a controller, and another harmonic source is a charger connected to the DC load. The harmonic spectrum, as given in Table 1, is taken

Table 1. Non-linear loads of the system

Load	Type	Location	Voltage
2 Toshiba PWMs	Adjustable Speed Drive	Bus 24	13.8 kV
1 Typical I-IEEE	6-pulse rectifier type 1	Bus 7	0.48 kV
1 Typical I-IEEE	6-pulse rectifier type 2	Bus 26	0.46 kV
2 Rockwell VFDs	6-pulse rectifier	Bus 35	0.46 kV

Fig. 4. The waveform and spectrum of harmonic source from ETAP

from the ETAP library. The example of waveform and a spectrum of a harmonic source taken from the library of ETAP is shown in Fig. 4.

The load flow result is shown on the one-line diagram as given in Fig. 5, which indicates some harmonic frequency with greater magnitude exceeding the Total Harmonic Distortion THD and Individual Harmonic Distortion IHD limit. On the other hand, the alert window shows that 5th, 7th, 11th, and 13th-order harmonics are contributing to different buses. The alarm window's harmonic commands exceed the predefined limit THD and IHD.

After harmonic analysis, the voltage waveforms and spectrum of the four distorted buses are displayed in Fig. 6, showing the waveform of buses 7, 24, 26, and 35, which are the most malformed. As expected, these buses are the most distorted since harmonic sources inject them.

7   Results and Discussion

Single-tuning filters were selected to suppress harmonic distortion at the power network [9]. Filter design is provided in the ETAP library, giving enough reactive power to the station network and minimizing losses at the fundamental frequency. This filter can typically size the parameter values based on filter modeling using the "Harmonic Filter
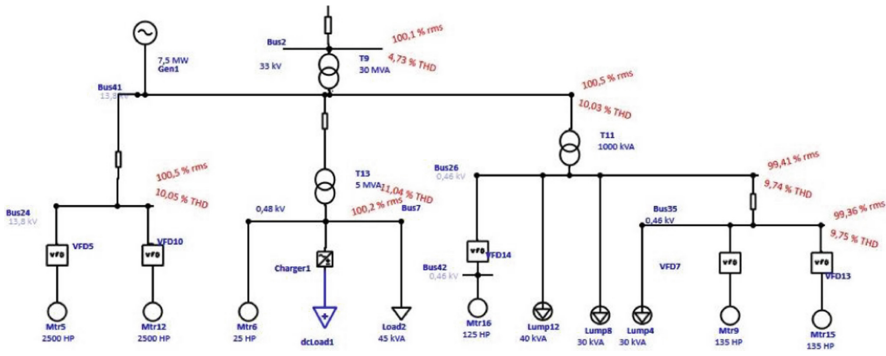
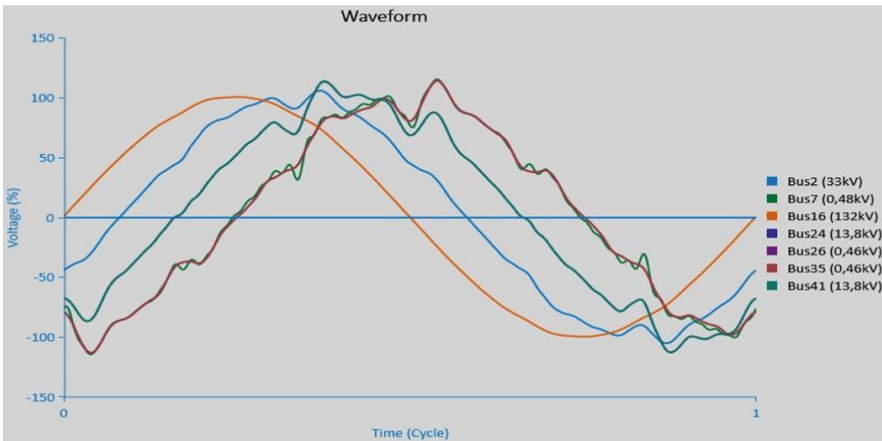**Fig. 5.** The harmonic analyses that shows some THDs exceeding the limit

Fig. 6. The waveforms of the distorted buses

Sizing" option. For calculating the parameter values of each filter, another page will open, and the required harmonic order in which harmonic distortion needs to be eliminated needs to be specified. The harmonic current for each filter size harmonic order must be given correctly. To size, the harmonic current, MVA, and power factor can be found in the single-line diagram, especially after running the load flow at the common coupling point where the harmonic source is connected to the primary power grid. After providing all the required parameters, the filter page is automatically updated. The process is shown in Fig. 7.

The filters (tuned filters of 5th, 7th, 11th, and 13th added in bus 24 & tuned 17th) were added to bus 7. The order can be executed through the same procedure when the order's filter size values are changed. The system is again analyzed and compared with the result of the pervious harmonic load flow analysis before adding the filter. The result of harmonic power flow on the single-line diagram is shown in Fig. 8.
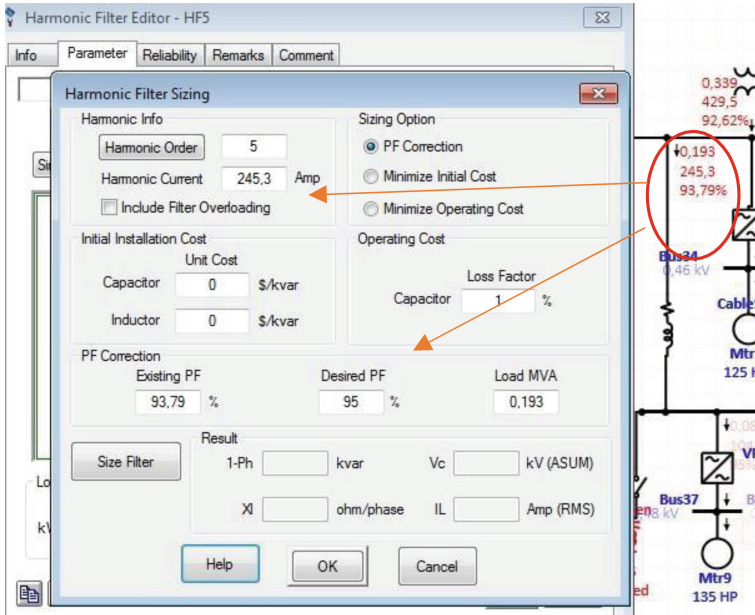
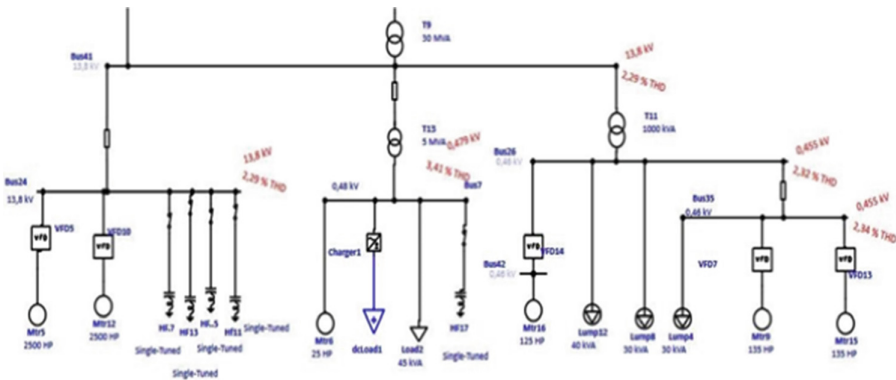**Fig. 7.** Filter design for the distorted system

Fig. 8. Harmonic power flow after installation of filters

For investigating the improvement, the buses with bad distortion displayed improvement due to filter installation. This is aimed to indicate the suppression the harmonic distortion. To have a clear picture of the buses after filter installation, the waveform of the buses will be separately shown. The improvement of the bus waveform is shown in Figs. 9, 10 and 11. It may be observed from the figures that the waveform is refined closer to sinusoidal. This indicates the improvement of the system because of filter installation. While the waveforms, as indicated by the figures, are not completely improved into purely sinusoidal, the improvement is remarkable. This may be seen if the figures are
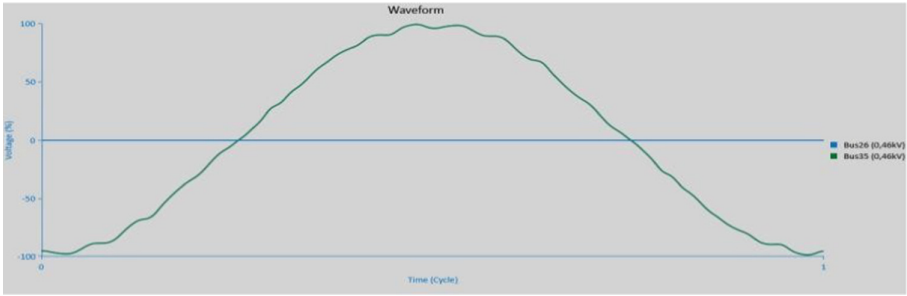
Fig. 9. Waveform of the bus 26 and 35 after installation of filters
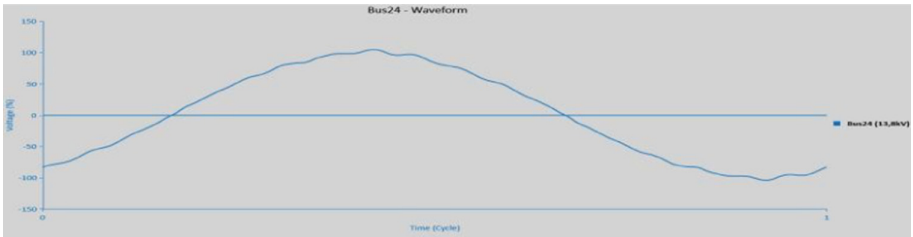
Fig. 10. Waveform of the bus 24 after installation of filters

Fig. 11. Waveform of the bus 7 after installation of filters

compared with those when the filters have not been installed yet, as given in Fig. 6. For further highlighting the improvements, the comparison before and after installation is given in Table 2.

It may be shown from Table 2 that the THD at the selected buses is significantly reduced after installation. It may also be shown from the table that the RMS of the selected buses is improved. This confirms that if the distortion is improved to an acceptable level. The mitigation of harmonic distortion may be further optimized by carefully determining the filter's size and location so that this may provide the best system improvement at an affordable cost. This may be carried out employing available soma methods.

Table 2. Operating condition of the selected bus before and after filter installation

Bus	K	V	RMS without filter (%)	THD without filter (%)	THD with filter (%)
35	0.460	99.36	98.03	9.75	2,33
26	0.460	99.41	98.08	9.74	2.32
24	13.8	100.49	100.1	10.05	2.29
7	0.480	100.18	99.7	11.04	3.41

8   Conclusion

A simple power network is modeled to analyze power system harmonics. The harmonic sources were modeled to create harmonic distortion in the power network. Once the Harmonic Load Flow study was run, harmonic distortions were shown on the one-line display and plotted curve. The components are modeled past the IEEE standards 519. The harmonic sources that were modeled from the harmonic library are Toshiba 2 PWM ASD, Typical IEEE 6 pulse1, Typical IEEE 6 pulse 2, and 2-Rockwell VFD 6 pulse. The single-tuned filter was designed from the predefined filter of the ETAP library. Display Alert is a practical option to display any component beyond its standard rating. The filters are intended considering THD and IHD exceeded in the alert display. In ETAP, it is easy to eliminate harmonic distortion for a specific harmonic arrangement by placing the harmonic value order and related parameters on the filter to resize the page. This filter design option is one of the most effective ETAP software tools. In ETAP, the user can create and save an unlimited number of study cases. Load flow calculations are performed and reported according to the study state settings defined in the network buses. Users can easily switch between study cases without the hassle of resetting study case options every time. This unique feature that most other packages do not have will save a similar amount of effort and time.

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