Volume 5 Nomor 2 Juli 2022 JJEEE e-ISSN : 2715-0887
p-ISSN : 2654-7813

Jambura Journal of Electrical and Electronics Engineering

Analysis and Mitigation of Harmonics Distortion with Optimization Capacitor Banks and Single-Tuned Passive Filters

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Received : March 2023
Approved : July 2023
Published : July 2023

***Abstract*—Electrical system power supplies always require a completely sinusoidal voltage signal. But for a variety of reasons, utilities often struggle to maintain these desired conditions. Deviations of voltage and current waveforms from a sinusoidal form are called harmonic distortions. Harmonic distortions in power networks are increasing due to the widespread use of non-linear loads. In this article we will analysis at a single-tuned passive filter and optimization using a capacitor bank. Load-current analysis determines the efficiency of the filter application by calculating the load bus voltage and total harmonic distortion (THD). To simulate the work, the Electrical Transient Analyzer Program (ETAP) software was used. This system was created specifically for this simulation and does not represent a real system. This model tests the effects of injecting harmonic currents into a power grid through a variable speed drive (VFD). The filter is attenuated with a capacitor bank.**

Keywords—Harmonics, Passive Filter, Capacitor Bank

I. INTRODUCTION

Many capacities are concerned about service dependability and power worth, especially as electrical equipment and programmed controls have become more sensitive [1]-[3]. Voltage fluctuations that can cause deviations include surges and spikes, sags, harmonic distortion, and transients. Harmonic distortion can cause sensitive equipment failure and other problems, as well as transformer and wiring overheating, interrupting circuit breakers, and reduced power factor [4],[5].

The role of electric voltage distribution to the power system is critical. Because of the generated harmonic currents, this goal is difficult to achieve [6]. They have a negative impact on the system and destabilize it. Harmonics must be reduced when they are produced to improve system performance. In two ways, we can understand how harmonics affect the power system [4], [7].

The first is that nonlinear loads produce harmonics, and the second is how harmonic current flows and produces harmonic voltage [3]. The nth harmonic (also known as simply the nth harmonic) of a signal is a sinusoidal component with a frequency of n times the fundamental frequency. The following is the equation for the harmonic expansion of a periodic function:

$$y(t) = Y_0 + \sum_{n=1}^{n=\sim} Y_n \sqrt{2} \sin(n\omega t - \emptyset_n) \qquad (1)$$

Where,

Y_0 = Point of DC components, generally zero and considered as such here in after
Y_n = rms point of the nth harmonics
ω = Angular frequency of the fundamental frequency
$\emptyset_n$ = Displacement of the harmonic component at t = 0.

Installing a harmonic filter can solve the problem of spurious frequencies and harmonics. There are two types of filters: active and passive. Active filters can significantly improve quality but are expensive. The design in question makes use of a single-tuned structure filter that promises clarity in terms of design and structure and has a higher economic cost [8]. The passive filter in question is composed of a choke and a capacitor that connect to a range of resonance tuned to the forthcoming harmonic frequency. The current model may be composed of several filters that function to exclude various harmonizers with distinctive properties. The purpose of passive harmonic filters is to repair imperfections caused by component waves or other variables that may perturb the operating frequency. Passive filters can solve the frequency error problem caused by power electronic or switching component used to control the speed of induction motors and other alternating loads [9]. In this research, a preliminary study was made on the design of a passive filter model, which is used to reduce harmonic distortions in power systems.

The first part presents the concept of harmonics. The second part is an analysis to understand the design of a single-tuned passive filter. Solutions to these technical problems are presented according to their effect on voltage total harmonic distortion (THDv) and harmonic spectrum.

II. RESEARCH METHODS

Figure 1 shows the methodology or approach used for further analysis. Literature search and research methods based on preliminary data from previous studies. Modeling used to reduce harmonic disturbances from the electrical system, and initial data collection and model simulation carried out by ETAP Power Station.

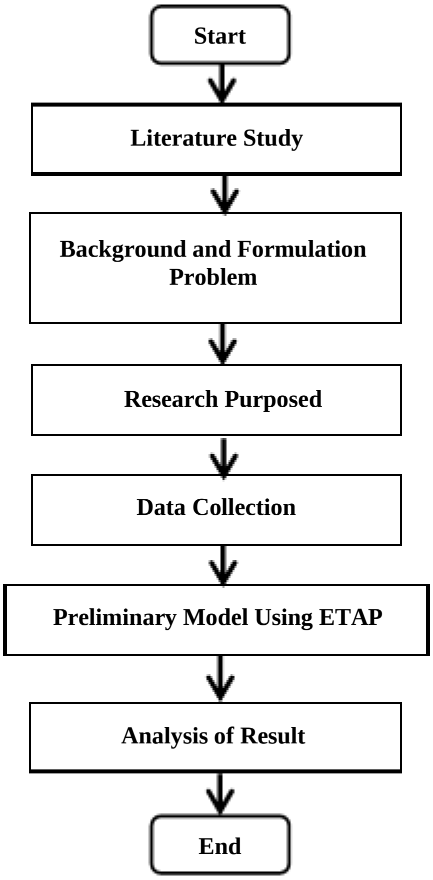


Figure 1. Flowchart of Research Methods

A. Harmonics Analysis

Harmonics are caused by voltage and current waveform distortion. Harmonics are defined as portions of the waveform that are integer multiples of the fundamental frequency. A harmonic source is a load that returns normal power to the source at harmonic frequencies. Harmonic currents appear to be injected into the grid by nonlinear loads on the consumer side [10]. Figure 2 shows a waveform with peaks corresponding to a secondary distribution level.

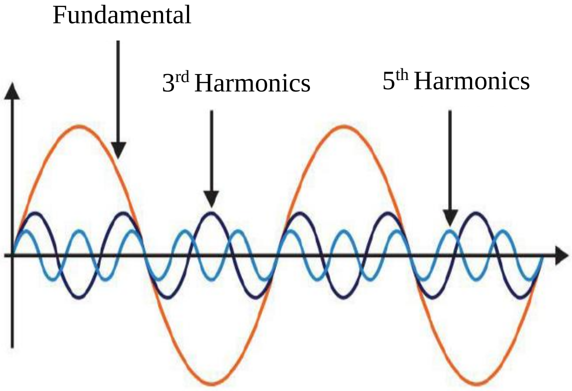


Figure 2. Harmonics Disturbance

B. Single-Tuned Passive Filter Calculation

Harmonic filters have the capability to contribute a substantial amount of reactive power for the purpose of power factor improvement [11]. By installing Qcom (kVAR) in an active power (kW), it becomes possible to enhance the power factor from PF_0 to PF_1 [12]:

$$Q_{com} = P[\tan(\cos^{-1} PF_0) - \tan(\cos^{-1} PF_1)] \quad (2)$$

The capacity of a single-tuned passive filter can be set to:

$$Q_f = Q_{com} \quad (3)$$

Using the following formula, the capacitor corresponding to the n^{th} harmonic filter can be roughly divided into several passive filters with a single alignment in parallel:

$$Q_{fh} = Q_{com} \frac{Ih}{\sum_{n=1}^{h} Ih} \quad (4)$$

Where I_h denotes the n^{th} harmonic current and Q_{fh} represent the capacity of the n^{th} harmonic filter. Also, the filter capacity Q_{fh} contains the capacity of capacitor Q_C and inductor Q_L. They have the following relationships [13]:

$$Q_C = \frac{h^2}{h^2 - 1} Q_f \quad (5)$$

$$Q_L = Q_C - Q_F \quad (6)$$

$$Q_L = \frac{1}{h^2} Q_C \quad (7)$$

Evaluate the capacitor reactance at fundamental frequency:

$$X_C = \frac{KV^2}{Q_C} \quad (8)$$

Calculate the reactor size providing the resonance:

$$X_L = \frac{X_C}{h_n 2} \quad (9)$$

The capacitance reactance value can be determined by:

$$X_C = \frac{1}{2\pi f C} \quad (10)$$

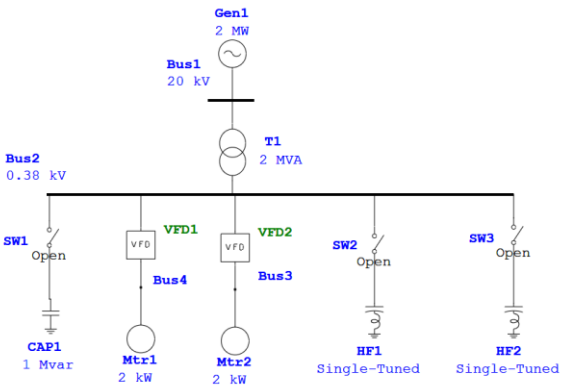


Figure 3. Single Line Diagram with Non-Linear Loads

Resonance will appear if the value of inductive reactance is the same as capacitive reactance:

$$X_L = X_C \tag{11}$$

The inductive reactance value of the filter can be obtained:

$$X_L = \frac{1}{(2\pi f)^2 C} \tag{12}$$

Calculate resistance of the reactor for a best quality factor:

$$R = \frac{X_n}{Q} \quad 30 < n < 50 \tag{13}$$

The characteristic reactance is:

$$X_n = X_{Ln} = X_{Cn} = \sqrt{X_L X_C} = \sqrt{L/C} \tag{14}$$

C. Determine the Value of the Quality Factor

The frequency at which the inductive and capacitive reactance of an ideal single-tuned passive filter is the same is called the tuning frequency [1]. The precision of the tuning is determined by the quality factor (Q) of the filter. It can be higher or lower. The low-pass filter is fine-tuned to one of the lower harmonic frequencies, with typical values between 30 and 60. A quality factor (Q) filter has a low resistance, typically between 0.5 and 5.5. The quality factor (Q) is a quantity that denotes the proportion of inductance or capacitance to resistance at the matched filter's resonance frequency. In the filter design, the quality factor may be calculated by dividing the reactance value (X) by the resistance value (R) [15].

$$Q = X/R \tag{15}$$

As shown in Figure 1, the passband (PB) of a filter is determined by the frequency at which the reactance of the filter equals its resistance. So the impedance angle is 45^0 and the magnitude is 2R. The relationship between quality factor and passband is expressed as:

$$Q = \omega_n / P_B \tag{16}$$

Where, ω_n is the tuned angular frequency (rad/s).

D. Determine the Value of the Tuning Factor (δ)

The tuning factor (δ) indicates how far the filter has detuned from the nominal tuned frequency. The configuration of the passive filter utilized can be affected by changes in the main frequency, capacitance, and inductance brought on by aging and temperature, as well as initial adjustments brought on by manufacturing tolerances and erroneous tuning steps. The formula gives the total detuning in units of the nominal tuning frequency (16) [16].

$$\delta = (\omega - \omega_n)/\omega_n \tag{16}$$

Moreover, the 2% change of inductance value (L) or capacitance value (C) causes the same detuning as change of 1% system frequency. Therefore, δ is often expressed as

$$\delta = \frac{\Delta f}{f} + \frac{1}{2} + \left(\frac{\Delta L}{L} + \frac{\Delta C}{C}\right) \tag{17}$$

Table 1 shows the percentage error for each value of frequency (*f*), inductor (L) and capacitor (L) for single-tuned passive filters design.

TABLE 1. ANTICIPATED ERROR

Items	Error
Frequency	Δf : 2%
Inductance (L)	ΔL : $-10 \sim +20\%$
Capacitance (C)	ΔC : $-4.5 \sim +6.5\%$

E. Passive Filter Type Single-Tuned Design Implementation

Automatic sizing of harmonic filters is provided by the harmonic package, which requires only harmonic orders and harmonic currents. A desired model or harmonic analysis of the power system can be used to obtain the desired harmonic order current magnitudes [17], [18]. However, automatic dimensioning only compensates for reactive power through filters. A capacitor bank must be used as it cannot provide the necessary compensation. The filter sizing feature is disabled to achieve an optimal configuration between the capacitor bank and the harmonic filter, but the harmonic order and current strength should be set [19], [20].

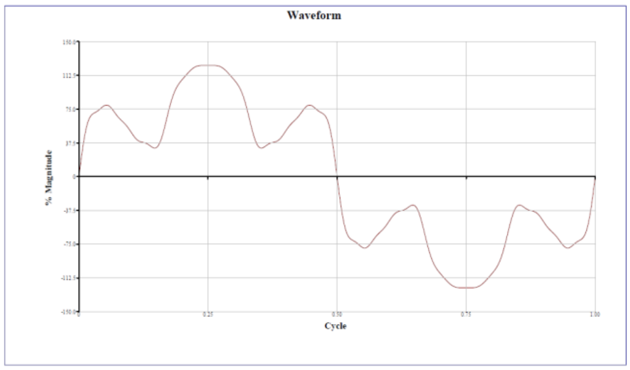


Figure 4. VFD_1 Waveform

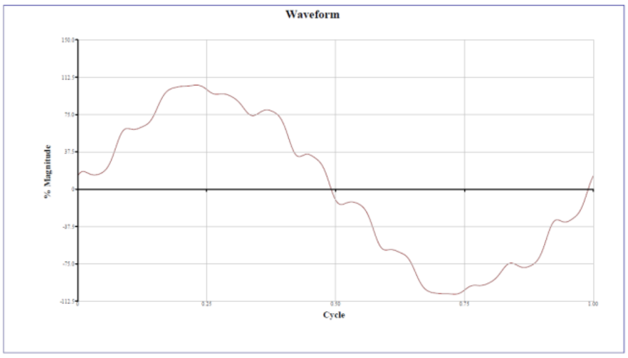


Figure 5. VFD$_2$ Waveform

A single-line concept without power factor correction and filtering is shown in Figure 3. A load flow analysis was performed to determine the power value required for power factor (PF) correction. The waveforms generated by the variable frequency drives (VFD) with 6 pulses on VFD$_1$ and 12 pulses on VFD$_2$ are shown in Figures 4 and figure 5. If you pay attention to these waveforms, you will notice that they can cause distortion in the fundamental waves, resulting in harmonic distortion in the electrical system.

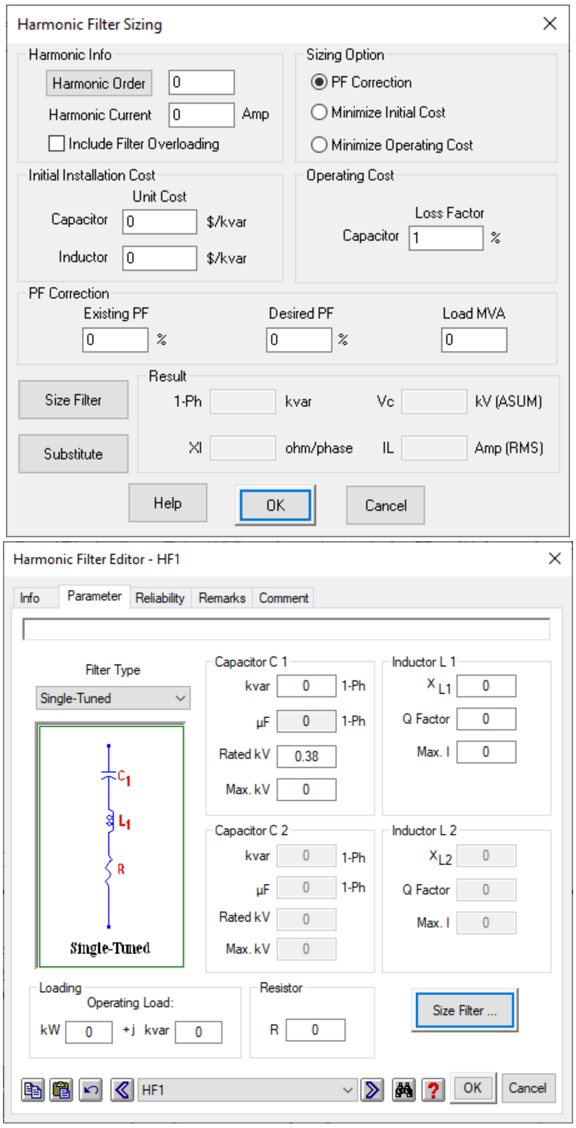


Figure 6. Single-tuned passive filter sizing

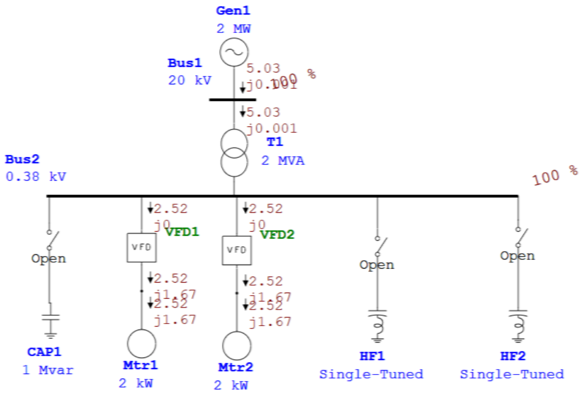


Figure 7. Load Flow Analysis

After determining the order of harmonics and harmonic currents, set the parameters obtained from the design on the harmonics filter sizing and harmonics filter editor menus as shown in Figure 6. The default filter type is simply adjusted and the parameters value are set in the specified range. Figure 7 shows the power flow simulation results. The absence of issues during data collection implies that the electrical system is operating normally when the design has been simulated.

III. Result and Analysis

In this result, the passive filter used is installed on a bus that has a voltage harmonic value and a current harmonic value that exceeds the standard limit. The standard used by IEEE Std. 519-1992 [16]. There are two criteria used in the analysis of harmonic distortion:

- First is the limitation for current distortion. The standard for voltage 120 V – 69 KV without considering the I_{SC}/I_L value is 5%.
- Second is the limitation for voltage distortion. The standard for voltage 69 kV and below is 5%.

A. Simulation Result

This will be used later as a reference for calculating the total harmonic distortion of the system used to design passive filters to reduce the total harmonic distortion caused by the switching components of the power electronic device. To identify the harmonics brought on by the operation of VFDs, harmonic analysis is carried out in the ETAP Power Station program. The passive filter design for the 5th and 7th order uses single-tuned passive filter.

a) Determine the reactive power compensation value.

$$Q_{com} = P[\tan(\cos^{-1} PF_0) - \tan(\cos^{-1} PF_1)] = 389.37\ KVAR$$

b) Determine the value of the capacitor

$$X_C = \frac{(V_{L-L})^2}{Q} = 0.017\ ohm$$

$$C = \frac{1}{2\pi f X_C} = 0.18\ \mu F$$

c) Determines the value of the inductor

$$X_L = X_C$$

$$L = \frac{1}{\omega^2 C} = 0.444\ H$$

$$X_L = 2\pi f L = 139.49\ Ohm$$

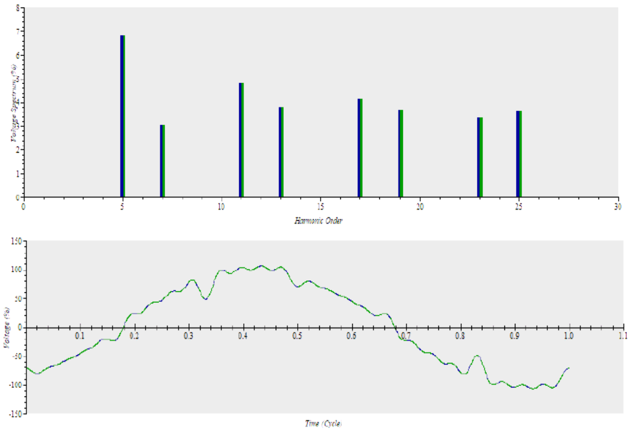


Figure 8. Spectrum and Waveform in Bus 2

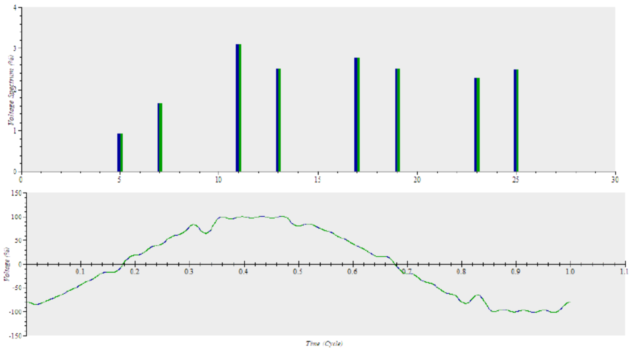
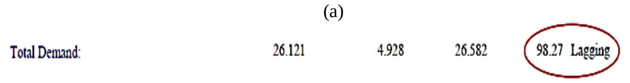


Figure 9. Spectrum and Waveform after Installing Passive Filter

(a)



(b)

Figure 10. Power Factor report: a) Before Improvement b) After Improvement

Once designed and calculated, these values are entered into the existing parameters of the single-tuned passive filter of Bus 2. Mathematical calculations with technical data passive filter specifications and measurement results per load are available. Table 2 below shows the specifications for a single-tuned passive filter.

TABLE 2. SPECIFICATION SINGLE-TUNED PASSIVE FILTER

SPECIFICATION SINGLE-TUNED PASSIVE FILTER					
Q_{VAR} (KVAR)	C (μF)	X_L (OHM)	R (OHM)	KV RATED	Q_{FACTOR}
389.37	0.18	139.49	0.029	0.38	30

After installing a simple tuned filter on bus 2, the spectrum graph or waveform should be retested and verified. Simulation results are shown in figure 9. Compared to the harmonic spectrum in Figure 8, the total harmonics distortion (THD) in figure 9 is below the specified criteria of 5%. figure 9 shows the resulting waveform after using a single-tuned passive filter. This shows a better result than figure 8, which has a shape like that of a pure sine wave.

B. Harmonics Reduction using Single-Tuned Passive Filter

Harmonics reduction using passive filters type single-tuned provide harmonic rejection and can be used as a power factor (PF) correction. The remaining reactive power is compensated by a capacitor bank with a capacitor bank value of 1 Mvar. The installation of the capacitor bank can strengthen harmonics, so additional filters are needed to be installed in the electrical system.

A quality factor (Q) linked to a percentage that represents the degree of harmonic current reduction determines the tuning accuracy. All filters fall into one of several categories of high or low quality, depending on the application: (i) Quality factor value depends on resistance. To increase the quality factor, the resistance must be decreased. (ii) Quality factor is inversely proportional to bandwidth. As a result, the quality factor determined the filter's frequency selectivity. For example, a high quality factor results in a narrow bandwidth and accurate frequency selection.

TABLE 3. COMPARISON THD VALUE

Line	Before		After	
	THDi (%)	THDv (%)	THDi (%)	THDv (%)
Bus 2	13.87	6.9 %	10.24	3.3%

Capture banks and passive filters contribute to power factor correction, increasing power factor up to 98% which can be observed from the before and after reports of power quality improvement in figure 10. In addition to their primary function of filtering specific harmonics, the percentage contribution of each filter to the power factor improvement was an important issue. Table 3 compares the improvement in current and voltage total harmonic distortion (THD) measurements before and after installing the filter. Total Harmonic Distortion (THD) is reduced to 3.3% according to the IEEE 519-2014 standard. The capacitor bank compensates for the remaining reactive power. The installation of this capacitor bank is the cause of the harmonics produced are getting bigger, so it needs more filters to be installed by adjusting the 7^{th} and 11^{th} harmonics. As before, the capacitor banks for the 7^{th} harmonic and after have low impedance to ground.

IV. CONCLUSION

The result of this work is to design a simple tuning filter and test it on a simple model using ETAP software. Analysis of a single-tuned passive filter to overcome harmonic variations resulting from the use of capacitor banks used for power factor correction. After conducting the simulation, some results were obtained as described below. 1) The installation of the Capacitor Bank is functioning properly, able to increase the value of the power factor from 73.56% to 98.27%, 2) The installation of passive filters succeeded in reducing the value of harmonics in the 7th and 11th order to 3.3%, 3) The value of the Q factor determines the success of the passive filter to reduce harmonics.

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