Analysis And Implementation Of Triple-Tuning Filters For Harmonic Reduction In Electrical Power Systems

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Abstract— This research aims to develop an effective solution to reduce harmonics through the design and implementation of a triple-tuning filter. High harmonic levels, which exceed the IEEE 519-2014 standard limits, can reduce system efficiency and power quality. The research method includes a literature study and simulation using MATLAB software. This simulation designs a triple-tuning filter with three LC resonance branches to suppress fifth, seventh, and eleventh order harmonics. The prototype design was tested based on electrical load condition data at the Electrical Engineering Department Building of Medan State University. The simulation results show that the triple-tuning filter significantly reduces the Total Harmonic Distortion (THD) value. The initial THD value of 31.8 percent was successfully reduced to below the standard limit of five percent. In conclusion, the triple-tuning filter has been proven to be an effective and applicable solution in harmonic mitigation in power systems, while also providing practical and academic contributions in the field of Electrical Engineering.

Keywords—Harmonics, Triple-Tuning Filter, Total Harmonic Distortion (THD)

I. INTRODUCTION

The electrical power system is not immune to harmonics problems. Harmonics are one of the main problems that can cause equipment performance disturbances, power loss, and damage to system components, as well as shorten the life of electrical equipment [1]. According to the IEEE 519-2014 standard, harmonic distortion must be minimized to maintain power quality and stability [2]. The main sources of harmonics are non-linear electronic devices, such as rectifiers and inverters, which produce currents with non-sinusoidal waveforms.

To address this, passive filters such as single-tuned and double-tuned have been widely implemented due to their relatively low cost. However, these conventional passive filters have limitations in simultaneously reducing harmonics at multiple frequencies, especially in systems with complex harmonic spectra [3].

The use of triple-tuned filters is gaining traction as a more effective solution. These filters are designed to simultaneously reduce three primary harmonic frequencies and demonstrate superior performance compared to single-tuned and double-tuned filters [4]. This study aims to analyze the effectiveness of the triple-tuning filter, design its optimal parameters, compare its performance with other filters, and assess its impact on the efficiency of the electric power system.

II. MATERIALS AND METHODS

A. Research Design and Data Collection

This research uses an experimental method with a quantitative approach. The case study was conducted on the electric power system in the Electrical Engineering Education Department Building, Medan State University. The initial stage was the collection of primary data on system conditions using a Power Quality Analyzer (PQA). Initial measurement results showed the system's Total Harmonic Distortion (THD) of 31.8%, with dominant harmonics in the 3rd (28.3%), 5th (13.27%), 7th (9.27%), and 11th (5.97%) orders. This data became the basis for filter design.

B. Filter Design and Simulation

Passive filter design begins by determining the reactive power compensation requirements (Q_c) to improve the power factor from 0.8 to 0.95, based on the measured active power (P) [5]:

$$Q_c = P[\tan(\cos^{-1} p\,f_1) - \tan(\cos^{-1} p\,f_2)] \quad (1)$$

From the Qc value, the capacitive reactance value (X_c) required at the fundamental frequency (f_0) is calculated using the equation:

$$X_c = \frac{V^2}{Q_c} \quad (2)$$

The capacitance value (C) is then obtained from:

$$C = \frac{1}{2\pi f_0 X_c} \quad (3)$$

For a filter tuned at the nth harmonic order (n), the inductor reactance value (X_L) is determined to resonate with X_c [6]:

$$X_L = \frac{X_c}{h_n^2} \quad (4)$$

So the required inductance value (L) is:

$$L = \frac{X_L}{2\pi f_0} \quad (5)$$

This basic calculation became the basis for developing a more complex triple-tuning design, consisting of three parallel LC branches designed to resonate at the 5th, 7th, and 11th orders [7][8][9].

The total harmonic distortion (THD) percentage of voltage and current is formulated as follows [10]:

$$THD_I = \frac{\sqrt{\sum_2^h I_h^2}}{I_1} \times 100\% \quad (6)$$

Where:

I_h: harmonic component of the current h

I_1: fundamental frequency current (RMS)

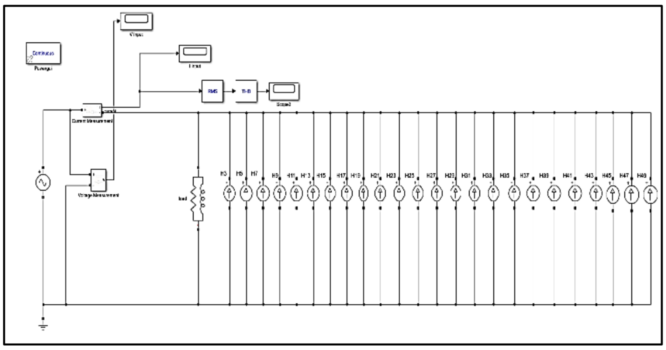
C. Simulation and Optimization Models

The design and testing of the filter effectiveness were carried out through simulations using MATLAB Simulink software. To determine the optimal component values (L and C) in the three branches of the triple-tuning filter, this study applied a metaheuristic optimization method [4]. Three optimization algorithms were tested, namely Ant Rider Optimization (ARO), Ant Lion Optimizer (ALO), and Whale Optimization Algorithm (WOA). The objective function of these optimizations is to achieve THD minimization.

III. Results and Discussion

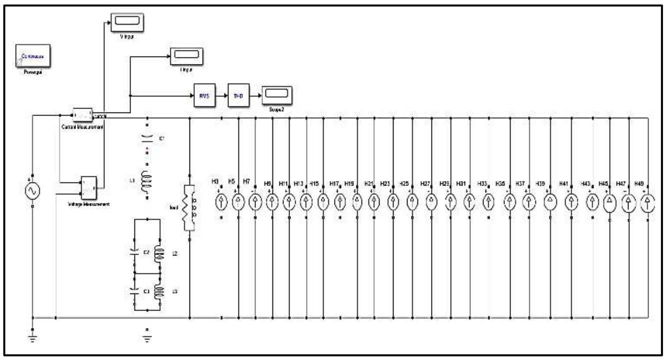
A. System Simulation Model

The power system model and triple-tuning passive filter were designed in MATLAB Simulink. Figure 1 shows the power system simulation model before the filter was installed. This model represents the load at the research site and the identified harmonic sources (H3, H5, H7, H9, H11, etc.).



(Figure 1. Simulink Model Design Before Installing the Triple-Tunning Filter)

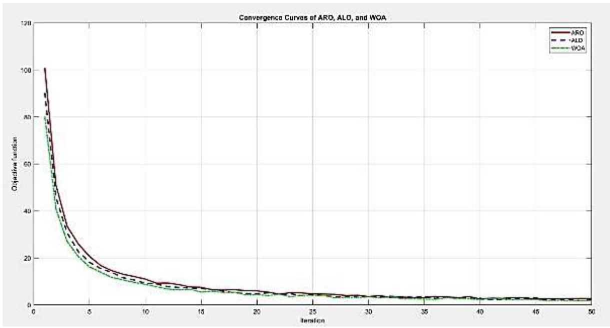
Figure 2 shows the same model design after the triple-tuning filter is installed. This filter consists of three parallel branches (C1-L1, C2-L2, C3-L3), which are installed before the load to absorb harmonic currents.



(Figure 2. Simulink Model Design After Installing Triple-Tunning Filter)

B. Filter Parameter Optimization

The metaheuristic optimization process is carried out to obtain the optimal component parameters in the three filter branches in Fig. 2. The convergence curves of the three algorithms (shown in Fig. 3) show that the WOA algorithm achieves the fastest convergence with the lowest objective function value.



(Figure 3. Convergence Curves of ARO, ALO, and WOA Algorithms)

A comparison of the performance of the three algorithms is presented in Table 1. The WOA algorithm produces the lowest THD, which is 3.8%, with the fastest computation time. Based on the consideration that the main objective of the research is THD minimization, the WOA algorithm is selected as the most optimal. The parameters of the optimal triple-tuning filter components resulting from WOA optimization are shown in Table II.

TABLE 1. COMPARISON OF METAHEURISTIC ALGORITHM OPTIMIZATION RESULTS

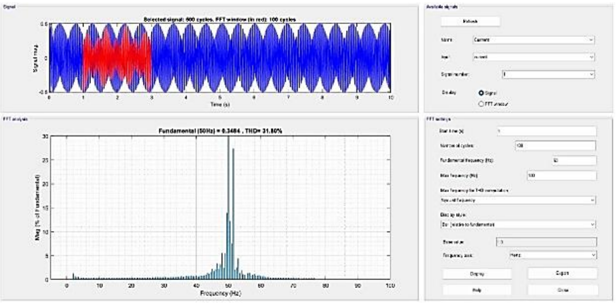
Algorithm	**Reactive Power (VAR)**	**Power Loss (W)**	**THD (%)**
ARO	2000	0,8	4,5
ALO	2100	0,9	4,1
WOA	1980	1,0	3,8

TABLE 2. TRIPLE-TUNING FILTER OPTIMIZATION RESULT PARAMETERS

Component	Valrus (SI Units)	Value (Practical Units)
C1	$1{,}37016 \times 10^{-5}$ F	13,70 µF
L1	$2{,}57607 \times 10^{-2}$ H	25,76 mH
C2	$9{,}43678 \times 10^{-6}$ F	9,44 µF
L2	$3{,}50972 \times 10^{-2}$ H	35,10 mH
C3	$5{,}65335 \times 10^{-5}$ F	56,53 µF
L3	$2{,}91233 \times 10^{-3}$ H	2,91 mH

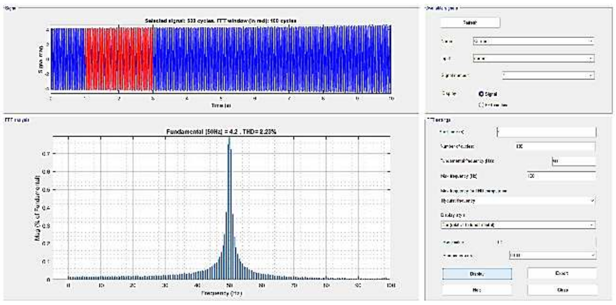
C. Filter Performance Simulation Results

The filter performance with the optimal parameters from Table 2 was then simulated using the model in Figure 2. Fig. 4 shows the FFT analysis results of the simulation model before the filter was installed (as per Fig. 1). These results confirm the initial condition of the system with a THD of 31.8%.



(Figure 4. Wave Simulation Results Before Installing the Triple-Tunning Filter*)*

After the triple-tuning filter is installed, the waveform becomes much more sinusoidal, as shown in Figure 5. The THD value dropped drastically to 2.23%.



(Figure 5. Waveform Simulation Results After Installing the Triple-Tuning Filter)

The reduction results for each harmonic order are summarized in Table 3. It can be seen that the most effective filter reduces the 11th order harmonics (79.9% reduction), followed by the 5th order (73.6% reduction) and the 7th order (73.0% reduction).

TABLE 3. HARMONIC REDUCTION RESULTS AFTER INSTALLING THE TRIPLE-TUNING FILTER

Harmonious Order	Before Filter (%)	After Filter (%)	Reduction (%)
3	28,30	15,00	47,0
5	13,27	3,50	73,6
7	9,27	2,50	73,0
9	7,29	3,50	52,0
11	5,79	1,20	79,9
13	5,10	2,55	50,0
19	3,52	0,01	99,7
21	3,13	0,00	100,0
23	2,95	0,00	100,0
25	2,58	0,00	100,0
27	2,46	0,00	100,0
29	2,29	0,00	100,0
31	2,14	0,00	100,0
33	2,14	0,00	100,0
35	2,05	0,00	100,0
37	1,93	0,00	100,0
39	1,75	0,00	100,0
41	1,72	0,00	100,0
43	1,6	0,00	100,0
45	1,5	0,00	100,0
47	1,47	0,00	100,0
49	1,34	0,00	100,0
Total THD	31,8	2,23	92,98

D. Discussion

The simulation results demonstrate the significant effectiveness of the triple-tuning filter in suppressing harmonic distortion. The reduction in THD from 31.8% calculated using equation (6) (seen in Figure 4) to 2.23% (seen in Figure 5) demonstrates the success of the filter design in meeting the IEEE 519-2014 standard [2].

This success is achieved because the filter design (in Fig. 2) provides three simultaneous low-impedance paths at the target frequencies (250 Hz, 350 Hz, and 550 Hz). The analysis in Table 3 confirms the precision of this design, where the target harmonics (11th, 5th, and 7th orders) experience the most drastic reduction.

Interestingly, the 3rd-order harmonics, which were not part of the design target, also experienced a significant reduction of 47.0%, indicating an additional positive impact from the implementation of this filter. The advantage of the triple-tuned filter is evident in its ability to handle a wider range of complex harmonic spectra compared to conventional single-tuned or double-tuned filters.[4]. In addition to reducing harmonics, as a passive filter containing capacitive components, its implementation also contributes to reactive power compensation and system power factor improvement.

IV. Conclusion

Filter *triple tuning* was successfully designed with optimal parameters using three LC branches tuned at the 5th (250 Hz), 7th (350 Hz), and 11th (550 Hz) order harmonic resonance frequencies. This design is proven to be effective in providing a low impedance path for the three dominant harmonics. The triple-tuning filter shows superior performance compared to single-tuning and double-tuning filters in reducing complex harmonics. MATLAB simulations prove a reduction in Total Harmonic Distortion (THD) from 31.8% to 2.23%, thus meeting the IEEE 519-2014 standard. The implementation of the triple-tuning filter not only suppresses harmonic distortion, but also contributes to improving the power factor and overall power system efficiency.

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