Design and Implementation of Hybrid Filter for Harmonic Reduction and Damped Resonances in Non-Linear Loads

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Abstract. The use of Power Factor Correction (PFC) is generally used to increase the power factor in a system plan. However, the system will be dangerous if there are non-linear loads on the system that causes resonance risk. The impedance of the capacitor bank for PFC can interact with the non-linear loads and the impedance of the up-transformer which causes series and/or parallel resonances. Resonance causes surges in currents and voltages at harmonic frequencies. This problem can be solved by adding a detuned reactor filter in PFC. However, the implementation of detuned LC passive filters can’t reduce all harmonic components. This paper presents a hybrid filter consisting of a detuned LC passive filter and an active filter to reduce harmonics, avoid the system from resonance risk, and to improve the power factor. This system using 5Kvar of capacitor bank and a 14% detuned reactor filter combined with an active filter. The results of power quality increasing the power factor from 0.6 to 0.88, THDi is reduced from 49.5% to 18% after using a hybrid filter.

1. Introduction

Installing capacitor banks are commonly used for power factor improvement. Good quality electric power if the value of pf> 0.85, a constant voltage even though the loads are variable, constant frequency, sinusoidal waveform (not distorted) [1], [2], [3].

On the other hand, the use of non-linear loads on the electric power system is increasing and these loads produce non-sinusoidal waves. This causes harmonics in the electric power system [4] Harmonics are generated due to the presence of nonlinear/ power electronic loads in the power systems such as AC/DC variable power sources, Variable Frequency Drives (VFD), welding machine Switched Mode Power Supplies (SMPS), arc furnaces etc. All non linear loads are major source for harmonic problems [5], [6]. Harmonics are the pure sinusoidal voltages and currents waveforms of frequencies which are basically integer multiples of the fundamental frequency of the power supply system. Harmonics have lots of bad effects on power system equipment and hence need several types of filters to obtain sinusoidal waveforms which in turn substantially improve the PQ of the distribution system [7]. Harmonic current producing loads cause additional losses in capacitors, transformers, power cables, also induce harmonic voltage drops at the supply transformers, and even damage the loads [8].

In industrial installations, PFC circuitries are often used to compensate reactive power. Typically, switched capacitor banks are connected in parallel to the loads. There are many connection types of capacitor banks such as delta, grounded Y, ungrounded Y [9]. But, seen from the load side the capacitance of the PFC and the source inductance create a parallel resonant circuit, and that one the most serious problems is called harmonic resonance. Harmonic resonance contributes to significant
amplification of voltage and current harmonics. This phenomenon is caused by series and/or parallel harmonic resonance between capacitors and system inductances such as load, line inductances, and up transformer. Normally, add reactors series with capacitors that called detuned LC passive filters are deployed to provide low impedance for dominant harmonic current and improve power factor for inductive loads [8], [10], [11]. Detuned LC passive filters also can dump the resonances. However this type of passive filter is commonly used to eliminate current harmonic when it is connected in shunt with the load, but it has some drawbacks due to which the performance is not up to the mark as follows. Meanwhile, active power filters mitigate harmonics with much better accuracy, but their cost is relatively more expensive than passive filters. This disadvantage excludes them from usage in cost-sensitive applications [12], [13]. To minimize this drawbacks, various types of hybrid topologies were presented and successfully implemented in recent years. These topologies mitigate the harmonic currents relatively well, while their cost is considerably reduced comparing to an active power filter installation individually.

In the implementation of detuned filter is not enough to reduce harmonics generated by non-linear loads, so it needs to be added with active filters to eliminate harmonics that still exist. This paper presents a hybrid filter to improve the performance of the passive filter to reduce harmonics and dump the resonances. The hybrid filter is constructed by detuned LC passive filters for PFC and an active filter for harmonics reduction in parallel connection so that the harmonics that still appear on the system are allowed by the IEEE 519-1992 standard [13]. The function of detuned reactor filters in hybrid filters is to protect the bank capacitor from resonance due to the use of non-linear loads or from active filter signals. While the active filter on the hybrid filter serves to reduce the harmonics that still appear on the system.

2. Modelling and Design of Hybrid Filter

In this experiment, the type of hybrid filter is combined with detuned passive filter and active power filter in parallel configuration (Figure 1). The parallel detuned passive filter can reduce the fundamental reactive current passing through the Hybrid Filter so that the required rating of the active part of the hybrid filter can be lower. Passive filter supply reactive power compensation, so the power factor can be increased. This system used non-linear load and inductive load as linear load. This research took measurement data at Laboratorium Sistem Tenaga Listrik of Politeknik Elektronika Negeri Surabaya. From the measurement data obtained the initial parameters as in the following Table 1. These data are used to design the value of bank capacitors, detuned reactor filters, and active filter.

![Figure 1. Hybrid Filter Plan](image-url)
Table 1. Measurement without filter

| Parameters | Value     |
|------------|-----------|
| V_{LL}     | 381,19V   |
| V_{LN}     | 221 V     |
| I          | 21,58 A   |
| P          | 5,85 kW   |
| S          | 9,5 kVA   |
| pf         | 0,6       |
| THD_i      | 2,18%     |
| THD_v      | 49,25%    |

Figure 2. Hybrid Filter Panel System

2.1. Design of Capacitor Bank
The most common method for improving power factor is shunt capacitors. The capacitor method is most economical and practical for the existing plants [14]. From the measurement results based Table. 1, the calculation is needed for the amount of bank capacitor requirements. From the measurement results, the pf value is 0.6 and will be corrected to 0.9.

The rating of capacitor bank can be found by following equation below [14], [15].

\[ Q_c = P (\tan \theta_1 - \tan \theta_2) \]  

Because of the plan is equipped with a 14% detuned filter, there will be a shift in the resonant frequency and the voltage from capacitor bank rising. So the rating value of capacitors will also rise [3].

\[ U_c = U_N \left( \frac{100}{100 - \%p} \right) \] (2)

\[ p = \text{detuned factor} \]

\[ Q_{c\text{ final}} = \frac{Q_c}{(1 - p)} \] (3)

\[ C_\Delta = \frac{Q_c}{6\pi f V^2} \] (4)

\[ C_Y = \frac{Q_c}{2\pi f V^2} \] (5)

\[ U_c = U_N \left( \frac{100}{100 - \%p} \right) \] (6)

From the equation above, 5.8Kvar of capacitor banks is needed with the maximum rating voltage 441V. The capacitor bank will be installed in delta connection. This PFC has 6 step capacitor bank, so the rating is 7µF capacitor bank in delta connection.
Table 2. Capacitor bank rating design

| Capacitor Bank Rating |
|----------------------|
| $Q_C$                | 5.8KVar  |
| $C_{\text{delta}}$  | 40 $\mu$F |
| $C_{\text{wye}}$    | 120 $\mu$F |
| $V_{\text{max cap}}$| 441V     |

2.2. Design of Detuned Reactor Filter

Detuned reactors are components that consist of an impedance coil (inductor) mounted in series with a capacitor bank that has increased its voltage range. The installation of the detuned reactor is used to protect the capacitor bank from damage due to excess voltage or current because the harmonics are too high [16].

From the results of measurements that have been made, there is a 3rd harmonic in the system. So, a 14% detuned factor is chosen to avoid resonance risk at the 3rd harmonics ($f = 150$Hz) so that the resonance system is shifted under that frequency. The result is a resonant frequency of the system with $p=14\%$ is shifted to 134Hz according to Table 3 and equation (8).

Figure 2 is an algorithm to determine the value of detuned factor that is needed by the system plan [15].

![Algorithm](image)

**Figure 4.** The algorithm determines the detuned factor

The rating of detuned reactor (inductor) can be found by following equation (7) or based from Table 3 below.
Table 3. Detuned Factor and Shifting Frequency

| p     | \( f_{res} \) |
|-------|---------------|
| 5%    | 223 Hz        |
| 5,5%  | 213 Hz        |
| 5,67% | 210 Hz        |
| 6%    | 204 Hz        |
| 7%    | 189 Hz        |
| 8%    | 177 Hz        |
| 12,5% | 141 Hz        |
| 14%   | 134 Hz        |

\[ p = \left( \frac{f_n}{f_{res}} \right)^2 \times 100 \] (7)

\[ L = \frac{p}{100 \times 4 \times \pi^2 \times f^2 \times C} \] (8)

From the following equation above, the rating of reactor is 70mH for each step in PFC. The reactors are installed series with capacitor bank.

Figure 5. 14% Detuned Reactor Filter

Table 4. Inductor rating design

| Detuned reactor filter rating design |
|--------------------------------------|
| L                  | 70mH |
| p (factor detuned)   | 14%  |
| \( f_{res} \) of detuned filter | 134Hz |
2.3 Active Harmonic Filter for Hybrid Filter

The active filter for hybrid filter works as a current source, compensating for harmonic currents due to the use of non-linear loads [17]. The principle is to inject a compensation current of the same magnitude as the harmonic current so that the harmonic current is eliminated. The active filter aims to produce sinusoidal currents with the equation \( I_S = I_L - I_F \) [18]. If the non-linear load current is the sum of the \( I_{Lh} \) fundamental current component and the \( I_{LF} \) harmonic current, as in the equation below:

\[
I_L = I_{Lf} + I_{Lh} \tag{9}
\]

Then the current compensation by the active filter is:

\[
I_f = I_{Lh} \tag{10}
\]

\[
I_S = I_L + I_f = (I_{Lf} + I_{Lh}) - I_{Lh} = I_{Lf} \tag{11}
\]

Tuned passive filters have some disadvantages e.g. performance of these filters is affected due to varying impedance of the system and with the utility system, the series and parallel resonances may occur, which causes increase of current harmonics in the supply. Therefore, alternate solution of harmonic mitigation, called hybrid harmonic filter has been introduced. Hybrid harmonic filter provides the combined advantages of active harmonic filter and passive filters assuring PQ with improved performance [19].

![Active Filter Diagram](image)

**Figure 6.** Active filter diagram

Capacity of active filter can be found by following equation below:

\[
I = THDi \times I_{load} \tag{12}
\]

\[
I = 49,25\% \times 21,58A
\]
\[ I = 10.62A \]

This active filter has rated current 50A. In this experiment, it works by injecting 10.62 Ampere of harmonic currents or 21% from its rated.

3. Experiment and Analysis

This study is combining the detuned filter with the active filter. Before installing a hybrid filter, the voltage source remains sinusoidal but there is a distortion in the current source. The values of THD\textsubscript{v} and THD\textsubscript{i} in the system are 2.18% and 49.25%. The THD\textsubscript{v} is still allowed according to standard for voltage <69kV which must be below 5%, while the THD\textsubscript{i} value exceeds the allowed standard IEEE 519-1992 which exceeds 20%. The value of the power factor before installing a hybrid filter is 0.6.

![Figure 8. Waveforms of voltage and current without hybrid filters](image1)

![Figure 9. Measurement with harmonic analyser – Hybrid OFF](image2)

Then for the use of active filter combined with a 14% detuned filter, the results are THD\textsubscript{v} decreased to 1.97% from 2.18% and THD\textsubscript{i} decreased to 18.30% from 49.25%. This THD\textsubscript{i} value is allowed by IEEE 519-1992 standards [13].

![Figure 10. Waveforms of voltage and current after installing hybrid filter](image3)
Table 5. THD and Power Factor

| Parameters | Hybrid Filter OFF | Hybrid Filter ON |
|------------|------------------|------------------|
| THDi       | 49,25%           | 18,30%           |
| THDv       | 2,18%            | 1,97%            |
| Power Factor | 0,6       | 0,88             |

For more details about the harmonic value of the measurement results can be seen in Table 6 and Table 7. Meanwhile, the value of the power factor increased from 0,6 to 0,88 after installing hybrid filter.

Table 6. Comparison of Voltage Harmonics

| Order of harmonics | Hybrid Filter OFF | Hybrid Filter ON |
|--------------------|------------------|------------------|
| 3                  | 0,43%            | 0,43%            |
| 5                  | 1,18%            | 1,08%            |
| 7                  | 0,74%            | 0,73%            |
| 9                  | 0,34%            | 0,45%            |
| 11                 | 0,88%            | 0,78%            |
| 13                 | 0,46%            | 0,22%            |
| 15                 | 0,47%            | 0,13%            |
| 17                 | 0,84%            | 0,85%            |
| 19                 | 0,43%            | 0,37%            |
| 21                 | 0,12%            | 0,12%            |
| 23                 | 0,03%            | 0,08%            |
| 25                 | 0,02%            | 0,12%            |
| 27                 | 0,04%            | 0,04%            |
| 29                 | 0,05%            | 0,03%            |
| 31                 | 0,01%            | 0,05%            |
| 33                 | 0,02%            | 0,02%            |
| 35                 | 0,01%            | 0,04%            |
| 37                 | 0,02%            | 0,02%            |
| 39                 | 0,01%            | 0,01%            |
| 41                 | 0,02%            | 0,02%            |
| 43                 | 0,01%            | 0,03%            |
| 45                 | 0,02%            | 0,03%            |
| 47                 | 0,01%            | 0,01%            |
| 49                 | 0,02%            | 0,02%            |
Table 7. Comparison of Current Harmonics

| Order of harmonics | Hybrid Filter OFF | Hybrid Filter ON |
|-------------------|-------------------|------------------|
| 3                 | 9.04%             | 5.14%            |
| 5                 | 6.85%             | 2.58%            |
| 7                 | 2.38%             | 1.45%            |
| 9                 | 0.49%             | 0.34%            |
| 11                | 0.41%             | 0.47%            |
| 13                | 0.41%             | 0.18%            |
| 15                | 0.59%             | 0.20%            |
| 17                | 0.60%             | 0.50%            |
| 19                | 0.22%             | 0.13%            |
| 21                | 0.28%             | 0.14%            |
| 23                | 0.23%             | 0.18%            |
| 25                | 0.37%             | 0.04%            |
| 27                | 0.12%             | 0.03%            |
| 29                | 0.18%             | 0.13%            |
| 31                | 0.04%             | 0.03%            |
| 33                | 0.03%             | 0.03%            |
| 35                | 0.15%             | 0.05%            |
| 37                | 0.08%             | 0.06%            |
| 39                | 0.06%             | 0.01%            |
| 41                | 0.13%             | 0.05%            |
| 43                | 0.07%             | 0.04%            |
| 45                | 0.05%             | 0.01%            |
| 47                | 0.08%             | 0.03%            |
| 49                | 0.04%             | 0.01%            |

THDi 49.25% 18.30%

4. Conclusion
The hybrid filter of this experiment, hybrid filter is installed in parallel topology. The detuned passive filter can reduce the fundamental reactive current passing through the hybrid filter so that the required rating of the active filter of the hybrid filter can be lower.

The results of the study concluded that the hybrid filter can reduce harmonics and improving the power factor in the system plan. Without filters, THDi was 49.25% and after installing a hybrid filter with a 14% detuned filter THDi dropped to 18.30% which this value is allowed by IEEE 519-1992 standard. THDv dropped from 2.18% to 1.98% after installing the hybrid. The power factor increases from 0.6 to 0.88 after a hybrid filter was installed.

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