Reference Current Generation for Active Power Filtering in Single-Phase Power System

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Abstract. The study presents a new proposed reference current generation algorithm based on the synchronous reference frame (SRF) conventional algorithm in single-phase power system for an active power filtering. Shunt active power filter (SAPF) is often used as it can mitigate harmonic currents in the AC networks due to its superiority in dynamic-state conditions. The reference current generation algorithm is the most important control algorithms to control SAPF as it has the simplest implementation features. A proposed STF-based fundamental component identifier (STF-FCI) algorithm is implemented for the major improvements such as the removal of the unnecessary cosine function to reduce complexity of algorithm, employment of self-tuning filter (STF) to extract accurate fundamental component and to generate a sinusoidal reference current. The purpose of developing STF-FCI algorithm is to replace low pass filter (LPF) with a mean as it can generate a fast and accurate fundamental reference current to operate the SAPF in reducing the harmonics content of the power system and provide a fast response time in the dynamic-state conditions. This paper is presented under both steady-state which is capacitive (RC) load or inductive (RL) load as well as dynamic condition where capacitive load change to inductive load. The performance of steady-state condition will be evaluated in terms of THD values, ripple factor, power factor and phase difference. Under dynamic-state condition, the dynamic speed will be evaluated to capture the speed of the amplitude change in nonlinear load in a period of time. MATLAB-Simulink is used to design and evaluate the proposed STF-FCI algorithm with mean algorithm and LPF algorithm for comparison purpose. The simulation results had shown the major improvement when THD values, ripple factor, power factor and phase difference are reduced. The response time of the changing load is shorter by using mean algorithm compare to LPF algorithm. The simulation results obtained proved success when the proposed STF-FCI algorithm using mean algorithm are much better than LPF algorithm in steady-state and dynamic conditions under two voltage conditions i.e. ideal and distorted voltage.

1. Introduction

Power quality defined as the ability of power grid to supply a constant voltage and power flow stability for power supply. Power quality played a crucial part for electrical equipment so that the device can function effectively to provide a perfect output value without significant loss, and being able to consume the energy that supplied to it. A good power quality of electrical equipment has a very low harmonic distortion and can withstand the interruption easily. Power quality issues are the main concern that had to be considered as the harmonics disturbance will degrade the power factor, causes voltage flickers, electrical noises, power interruptions and etc. of the overall power system. Those harmonics may cause the disturbance, stress and
unwanted losses in the system and degrades the quality network of voltage and current [1]. Single-phase shunt active power filter (SAPF) mainly used to reduce the unwanted harmonic distortion from nonlinear loads as well as to aid the improving of filtering efficiency and the power quality [2]. Single-phase networks are chosen instead of three-phase networks as three-phase networks already have the ability to cancelled out the harmonics as the harmonic issues in single-phase is worse compare to three-phase system, hence, a more appropriate control algorithm can be developed to compensate the harmonic [3]. Since the three-phase system will not have higher THD, the proposed control algorithm that is used in single-phase can be applied to three-phase also. Single-phase and nonlinear load are chosen as the worst condition representation to test for the effectiveness of SAPF for harmonics mitigation. Besides, when design the control algorithms of SAPF, a proper synchronization method and careful considerations needs to be applied such as compensating current, harmonic detection methods, and different types of control algorithm [4].

Figure 1 shows the SAPF circuit connection. The full-bridge inverter which represents the SAPF is connected in between an AC main source with a nonlinear load via common coupling (PCC) point. The nonlinear load that is commonly connected to purely resistive (R), capacitive (RC) or inductive (RL) loads. When there is harmonic contamination available, the SAPF will inject the compensating currents (180º phase shifted) to cancel out the unwanted harmonic [6]. The amount of compensating currents had to be injected correctly by SAPF so that the operation of SAPF is in phase with power system and source current is in sinusoidal waveform.

The structure of SAPF is constructed by four control algorithms such as reference current generation algorithm, switching algorithm, DC-link voltage regulation algorithm and synchronizer algorithm to create an effective performance of SAPF to mitigate the harmonic distortions. The control algorithms which work together in synchronization has to be accurate and fast so that the SAPF in power quality mitigation will achieve an optimum performance. The working principle of SAPF works in this way. First, the synchronizer applies PLL technique to process the source voltage for the generation of the reference phase angle such as cosine and sine angle to the reference current generation algorithm. Then, reference current generation algorithm receives the current load and DC current from DC-link capacitor voltage regulation. The DC-link capacitor voltage regulation algorithm applies the proportional integral (PI) method to control the DC-link voltage. Next, the switching algorithm which apply hysteresis technique is to compare the current error so that proper switching pulses is done. A desired injection current will be produced for the harmonic’s
mitigation. The $i_{dc}$ (from the DC-link capacitor voltage regulation algorithm) will regulate the magnitude of reference current so that potential losses can be regulated and appropriate amount of real power is drawn [6]. The reference current generation algorithm plays the most important parts. If the algorithm able to provide an efficient and accurate reference current, then it will extract the precise and fast current harmonics to the SAPF for the generation of injection current to eliminate the harmonic.

Self-tuning filter (STF) can be used in both SRF and PQ theory [7]. The design of STF is simple and straightforward without the additional needs for practical implementation and is used in the new proposed algorithm. STF technique is normally works well in distorted voltage source condition specially to enhance the performance of synchronizer algorithm as STF can manage to generate a sinusoidal voltage from a distorted voltage source [7].

The main objective of this paper is to propose a mean algorithm and LPF algorithm in STF-FCI algorithm for comparison purposes. Both of the algorithms are tested under two voltage conditions which is ideal and distorted voltage source. The results for the test are focusing on the accuracy and the speed which is under the steady-state condition and dynamic-state condition. Under the steady-state conditions, the few parameters such as THD values, ripple factor, power factor and phase difference of inductive and capacitive loads are being evaluated. The effectiveness of the reference current generation depends on the THD values and must maintain below a 5% THD limit set according to IEEE standard 519 [8]. The ripple factor, power factor and phase difference must be as low as possible so that the SAPF can provide a superior performance in reducing the harmonics. Under dynamic conditions, the performance and flexibility of SAPF will be observed such as the dynamic speed of the load changing. For example, the sudden switched of connected load from capacitive to inductive, then the speed response of the algorithm should be as low as possible to prove the effectiveness of the algorithm. The implementation of mean block is to replace the 15 Hz cutting frequency of second order Butterworth-type LPF in the benchmark model. The working principles of this algorithm will be studied thoroughly and MATLAB-Simulink is used to compare and evaluate the effectiveness and the design concept for both of the algorithms.

2. Methodology

In this section, the method to conduct research on the new proposed algorithm which is STF-based fundamental component identifier (STF-FCI) algorithm will be discussed. MATLAB-Simulink 2020b is used to test the effectiveness for the design concept of the STF-FCI algorithm which use mean algorithm and LPF algorithm for comparison purposes. Both of the algorithms will be tested with distorted or ideal voltage source and in a steady-state and dynamic condition.

2.1 STF-based fundamental component identifier (STF-FCI) algorithm

The main purpose of choosing STF in this reference current algorithm is that it can help to separate the harmonic components from the distorted load currents. The main purpose of STF is to accept only the fundamental component before passing through the filtering process to obtain an accurate reference current [7]. Mean block is used to replace LPF as LPF has several drawbacks such as LPF has to be tuned a lot to get the desired results while mean block can eliminate the need for tuning. Besides that, by using a mean block can greatly reduce the ripple currents in the system which will result to lower noise to the application compared to the LPF. The benefits of using mean over LPF will be explained detail in section below.
As shown in figure 2, the STF-FCI algorithm contains two filters which are self-tuning filter (STF) and a mean to get a better reference current waveform with a perfect magnitude. In single-phase, the load current can be directly converted into $\alpha\beta$-frame as shown in equation (1) [5].

$$\begin{bmatrix}
  i_{L_{\alpha}} \\
  i_{L_{\beta}}
\end{bmatrix} =
\begin{bmatrix}
  i_{L_{\alpha}(\omega t + \phi)} \\
  i_{L_{\beta}(\omega t + \phi + \pi/2)}
\end{bmatrix}$$

(1)

When the 90-degree phase shifted of load currents is transform, the $\alpha\beta$-frame in load current is separated into harmonic and fundamental components shown in equation (2) [5].

$$\begin{bmatrix}
  i_{L_{\alpha}} \\
  i_{L_{\beta}}
\end{bmatrix} =
\begin{bmatrix}
  i_{L_{\alpha}(\text{fund})} + i_{L_{\alpha}(\text{har})} \\
  i_{L_{\beta}(\text{fund})} + i_{L_{\beta}(\text{har})}
\end{bmatrix}$$

(2)

where $i_{L_{\alpha}(\text{fund})}$ represents the fundamental and $i_{L_{\alpha}(\text{har})}$ represents the harmonic components of load currents.

Next, the $\alpha\beta$-frame of load currents is extracted when it passes through the STF. STF will do it part to separate the fundamental components of load currents. Hence, the transfer function of STF [9] to obtain only the fundamental components in $\alpha\beta$-domain are shown in equation (3).

$$\begin{bmatrix}
  i_{L_{\alpha}(\text{fund})(s)} \\
  i_{L_{\beta}(\text{fund})(s)}
\end{bmatrix} = K \begin{bmatrix}
  i_{L_{\alpha}(\text{fund})(s)} - i_{L_{\alpha}(\text{fund})(s)} \\
  i_{L_{\beta}(\text{fund})(s)} - i_{L_{\beta}(\text{fund})(s)}
\end{bmatrix} + \frac{2nf_{c}}{s} \begin{bmatrix}
  -i_{L_{\beta}(\text{fund})(s)} \\
  i_{L_{\alpha}(\text{fund})(s)}
\end{bmatrix}$$

(3)

where K stands for the parameter gain, and fc is the cutting frequency. The K can be adjusted in a fixed range of 20-100 and the fc is fixed at 50Hz [10]. The selected values of K will greatly affect the filtering performance of STF so it is important to set the values according to the requirements for selectivity and dynamic response.

If STF is in used, a simplified synchronizer is needed as only the sine component is in used. This is because synchronizer use PLL technique to generate reference phase angle such as cosine. The cosine component which is an even function is removed as the sine function can already be used to represent the characteristics of odd function. Once the fundamental components are extracted, the magnitude of fundamental load current [9] can be obtained by using the formula as shown in equation (4) below:

$$I_{L_{\text{fund~mag}}} = \sqrt{i_{L_{\alpha}(\text{fund})}^2 + i_{L_{\beta}(\text{fund})}^2}$$

(4)
2.2 Further improvements

Although the previous algorithm used LPF technique had been accepted as it can successfully perform well by cancelling the harmonics and reduce the THD as well as ripple currents, there are still some drawbacks and weaknesses which will reduce the performance quality of the reference current generation. Therefore, a new proposed STF-FCI algorithm that use mean technique is implemented to further improve the flaws and unnecessary features. Mean block plays an important role to identify the fundamental component so it is known as “fundamental component identifier” in detecting the desired fundamental dc component. Although LPF with lower cut off frequency can provide better THD values with lesser ripples, but it suffers a slow dynamic speed. However, a higher cut off frequency LPF suffer higher THD which results to more ripples, it can provide a better dynamic response of the algorithm [9]. Hence, the use of mean can eliminate this difficult task and tough decision for tuning the LPF in order to get a better filtering feature. Table below shows the benefits of using mean block over the LPF.

| Characteristics          | LPF                                      | Mean                                      |
|--------------------------|------------------------------------------|-------------------------------------------|
| Ripple                   | Has higher ripple content.               | Has almost zero ripple content.            |
| Tuning                   | Required to tune the cut-off frequency to get desired results. | Not required.                             |
| Complexity               | Higher complexity.                       | Less complex and straightforward.         |
| Dc component detection   | Suffer some delay due to improper tuning. | Able to detect accurately as do not need to tune. |

After the magnitude of fundamental load current is obtained from the previous equation (4), it will pass through a mean block to filter and obtain the desired fundamental magnitude load current, \(I_{L(fund\_mag)}\) with no ripple as shown in equation (5).

\[
I_{L(dc)} = I_{L(average)} = \frac{1}{T} \int_0^T I_L \, dt
\]

\(I_{L(average)}\) means the average value while \(T\) means time period of signal.

The algorithm will produce an output of sinusoidal reference current which shows that cosine function is unnecessary. The reference current generation can be obtained by multiplying synchronization phases, \(sin(\omega t)\) and dc-link charging current \(I_{dc}\) obtained from dc-link capacitor voltage regulation algorithm.

\[
i_{s\_ref} = \left[ I_{L(fund\_mag)} + I_{dc} \right] \sin(\omega t)
\]

By applying the equation (6), a desired reference current is produced which can be generated under ideal and distorted voltage source conditions. Thus, the STF-FCI algorithm works effectively to enhance the harmonic mitigation process.

2.3 Simulation parameter

The AC voltage source will be following the standard voltage rating in Malaysia where the supply voltage is 230 V and with a 50 Hz frequency. The range for the limiting inductor can be tune from 3mH to 5mH. The common switching frequency reported in the literature is 25 kHz, hence this frequency is applied in this work [7]. Table below shows the suggested parameter values for simulation of SAPF.
Table 2. Simulation parameters.

| Simulation parameter       | Value                        |
|----------------------------|------------------------------|
| Voltage source             | 230 Vrms, 50 Hz              |
| DC-Bus capacitor           | 3300 μF (each)               |
| DC-Bus reference voltage   | 500 V                        |
| Limiting inductor          | 5 mH                         |
| Switching frequency        | Switching frequency          |

3. Simulation results and discussion

The simulation results of STF-FCI algorithm is done by using the SimPower System toolbox which can be found in MATLAB-Simulink. The experiment is conducted under two conditions which is steady-state and dynamic-state. There will be two forms of nonlinear load connected under two voltage conditions i.e. ideal and distorted voltage source when simulated. The first nonlinear load is RL load which consist of a 20Ω resistor and 50mH inductor connected in series. The second nonlinear load is RC load consists of a 20Ω resistor and 1100µF capacitor connected in parallel. The effectiveness of the algorithm is observed based on the percentage of THD, ripple current, power factor and phase difference under steady-state condition. The values of THD should not be lower than 5%. In the meantime, under dynamic-state condition will have the changing of the nonlinear load where capacitive load is changed to inductive load. The performance parameter such as response time is analysed and should be as low as possible. Comparison analysis will be made based on the STF-FCI algorithm before installing SAPF and after installing SAPF to show that the effectiveness of SAPF to reduce the harmonics.

3.1 Comparison for steady-state and dynamic-state conditions

Steady-state and dynamic-state is mainly focus on the accurateness and the speed. Accuracy is analysed based on the THD performance and ripple current while speed is analysed when the load is suddenly connected to the network. The filter used in the new proposed STF-FCI algorithm is a mean block and compared with the STF-FCI algorithm which used LPF filter. The percentage of ripple current can be measured based on the waveforms obtained and comparison is made in section 3.2. The ripple factor percentage formula is the ratio of the maximum peak current minus the minimum peak current to the average value. Ripple current can be found by subtracting maximum peak current to minimum peak current. Ripple current is directly proportional to ripple factor. The formula to calculate percentage of ripple factor is written in equation (7).

\[
\text{Ripple factor} \ (\%) = \frac{\text{Max peak} - \text{Min peak}}{\text{Average value}} \times 100
\]

(7)

Figure 3 shows the simulation waveforms of single-phase voltage source, load current, injection current and source current for the capacitive load while figure 4 shows the simulation waveform for inductive load. The source current of capacitive load is higher than inductive load.
Figure 3. Simulation waveforms when capacitive load connected include (a) Voltage source, $V_s$ (b) Load current, $I_L$ (c) Injection Current (d) Source current, $V_s$.

Figure 4. Simulation waveforms when inductive load connected include (a) Voltage source, $V_s$ (b) Load current, $I_L$ (c) Injection Current (d) Source current, $V_s$. 
3.2 Steady-state condition

The STF-FCI algorithm is analysed under inductive and capacitive load with ideal or distorted voltage connected to it. Based on the results finding, the THD values are higher when there is no SAPF connected for inductive or capacitive loads. However, after installing the SAPF, the THD for each nonlinear load either with ideal or distorted voltage source connected has been greatly reduced to below 5%. This proves that the effectiveness of the reference current generation algorithm can reduce the unwanted harmonics while maintaining the value of THD.

Besides that, power factor also plays an important part in maintaining the efficiency use of electricity. According to the power factor surcharge rules and policy, the power factor should maintain above 0.9 when the supple voltage is more than 132kV. If the voltage supply is below 132kV, the power factor should maintain at least 0.85 and more. A high-power factor index will not cause a power factor surcharge [11]. To calculate the power factor obtained through the THD values, the formula is as shown in equation (8).

\[
P_F = \frac{1}{\sqrt{1+THD^2}} \times \cos\theta \tag{8}
\]

According to table 3,4,5 and 6, before installing the SAPF, the power factor can be seen lower than 0.85, and this shows an electricity wastage where power factor surcharge will occur. When the SAPF is installed, the source current can work in line with voltage source for either capacitive or inductive loads, hence the power factor is almost equal to one. The power factor increases from <0.911 (before install SAPF) to >0.999 (after install SAPF). By achieving an almost unity power factor, the phase difference of each nonlinear loads has also been greatly reduced comparing the before and after installing the SAPF. The minimum phase difference can be accomplished when the STF-FCI algorithm is used by either connecting LPF or mean block.

| Table 3. Ideal voltage source connected with capacitive load. |
|-------------------------------------------------------------|
| **Before installing SAPF**                                  |
| **Filter**        | **THD (%)** | **Power Factor** | **Phase Difference (°)** |
| Mean             | 94.92       | 0.721            | 6.6                      |
| 15 Hz LPF        | 94.72       | 0.721            | 6.6                      |
| **After installing SAPF**                                 |
| **Filter**        | **THD (%)** | **Power Factor** | **Phase Difference (°)** |
| Mean             | 2.81        | 0.999            | 0.1                      |
| 15 Hz LPF        | 2.80        | 0.999            | 0.1                      |
Table 4. Ideal voltage source connected with inductive load.

| Filter     | Before installing SAPF |  |
|------------|-------------------------|---|
|            | THD (%) | Power Factor | Phase Difference (°) |
| Mean       | 39.43   | 0.911        | 11.6                  |
| 15 Hz LPF  | 39.43   | 0.911        | 11.6                  |

| Filter     | After installing SAPF |  |
|------------|-----------------------|---|
|            | THD (%) | Power Factor | Phase Difference (°) |
| Mean       | 4.81    | 0.999        | 0.0                   |
| 15 Hz LPF  | 4.89    | 0.999        | 0.0                   |

Table 3 and 4 shows the results of the workbench model with ideal voltage source connected to it while table 5 and 6 are connected with distorted voltage source. Both has the same concept when SAPF is not yet install, the THD, power factor and phase difference will be very high. All these parameters will be reduced when SAPF is install. Therefore, the experiment proves that when installing SAPF which utilized the reference current generation algorithm that contain either mean or LPF as filter has work effectively in reducing the THD, minimize the phase difference as well as achieve an almost unity power factor.

Table 5. Distorted voltage source connected with capacitive load.

| Filter     | Before installing SAPF |  |
|------------|-------------------------|---|
|            | THD (%) | Power Factor | Phase Difference (°) |
| Mean       | 85.80   | 0.758        | 3.2                   |
| 15 Hz LPF  | 85.80   | 0.758        | 3.2                   |

| Filter     | After installing SAPF |  |
|------------|-----------------------|---|
|            | THD (%) | Power Factor | Phase Difference (°) |
| Mean       | 2.49    | 0.999        | 0.0                   |
| 15 Hz LPF  | 2.57    | 0.999        | 0.0                   |

Table 6. Distorted voltage source connected with inductive load.

| Filter     | Before installing SAPF |  |
|------------|-------------------------|---|
|            | THD (%) | Power Factor | Phase Difference (°) |
| Mean       | 41.60   | 0.911        | 9.2                   |
| 15 Hz LPF  | 41.60   | 0.911        | 9.2                   |

| Filter     | After installing SAPF |  |
|------------|-----------------------|---|
|            | THD (%) | Power Factor | Phase Difference (°) |
| Mean       | 4.74    | 0.999        | 0.0                   |
| 15 Hz LPF  | 4.76    | 0.999        | 0.1                   |
Figures 5 and 6 show the reference current generation algorithm applying the new propose STF-FCI technique in detecting the ripple current and ripple factor for capacitive and inductive load under both ideal and distorted voltage source. From the ideal voltage source, STF-FCI algorithm which used 15 Hz LPF suffer 1.4mA of ripples while STF-FCI algorithm that used mean as filter suffers zero ripple when an inductive load is connected in figure 5(a). When the nonlinear load is change to capacitive load, there is not a big change where the 15 Hz LPF still suffer 0.0341A of ripples current and the mean has zero ripple in figure 5(b). The simulation results are almost the same when a distorted voltage source is connected to it, where the 15Hz LPF suffered more ripple than a mean in figure 6 (a) and (b). Overall, by using the mean algorithm, all the simulation results in both voltage conditions have fulfilled the desired constant values despite the nonlinear loads connected. These results prove that the mean which is known as fundamental component identifier (FCI) can distinguish the fundamental component more accurately compared to a 15Hz LPF.

![Figure 5. Ripple current of reference current generation when ideal voltage source connected in (a) inductive (b) capacitive.](image-url)
3.3 Dynamic-state condition
Under dynamic-state condition, there are only one changing load which is capacitive to inductive load but with two voltage conditions i.e. ideal and distorted voltage source. Figures 7 and 8 shows that the mean block has superior performance of dynamic behaviour for reference current generation performed by SAPF compared to when using 15Hz LPF. The proposed STF-FCI algorithm using mean as filter shows the best response time (0.03s) compared to the 15Hz LPF with longer response time (0.04s). To conclude, mean can perform better for SAPF as compared to LPF as it can provide lower ripple current and shorter response time while maintaining THD below 5% based on the simulation on steady-state and dynamic condition above.
Figure 7. Simulation waveforms with ideal voltage source connected include (a) Voltage source, $V_s$ (b) Load current, $I_L$ (c) Source current, $I_s$ by using 15Hz LPF (d) source current by using mean.

Figure 8. Simulation waveforms with distorted voltage source connected include (a) Voltage source, $V_s$ (b) Load current, $I_L$ (c) Source current, $I_s$ by using 15Hz LPF (d) source current by using mean.
4. Conclusion
In conclusion, this paper summarizes a new proposed STF-FCI algorithm based SAPF which applies the mean algorithm. Comparison has been made between the type of filter used in STF-FCI algorithm, such as mean block and a 15Hz LPF. There are almost similarities of these filters used where the power factor, phase difference and the THD values obtained are almost the same. However, mean block is still more superior compared to a 15Hz LPF in terms of the ripple current and response time. When there is less ripple current in the system, this means the system will have lesser noise. The used of mean block in STF-FCI algorithm has bring more benefits as it does not require to tune and the algorithm has become more simplicity. Overall, the STF-FCI algorithm that used mean block as its filter has more advantages where the response time is shorter and the ripple current is lower while it can maintain the THD of below 5%.

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