Simulation and Analysis of a Three-phase Shunt Active Power Filter

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Abstract:

This work presents the results of a simulation-based analysis of a three-phase shunt active power filter (SAPF) for power quality improvement. The power quality of power systems is degraded when non-linear loads are present at the consumer end. Harmonics induced by non-linear loads can be reduced with the SAPF. Workspace for MATLAB-Simulink is used to model and simulate the SAPF system under inquiry. The ultimate goal of this research is to reduce the system's total harmonic distortion to meet industry requirements.IEEE-519 defines it.

Keywords: Total Harmonic Distortion (THD) Reduction, Reactive Power Compensation, Shunt Active Power Filter (SAPF), and Power Quality Improvement.

I. INTRODUCTION

In the electrical power sector, power quality is crucial because it allows us to determine how efficiently the load uses the electric power. Poor power quality causes power loss, harmonic generation owing to non-linearity, and a decrease in the efficiency and life of the electric equipment used in power systems. Power electronic devices that are non-linear in behaviour and generate harmonics in the power system are used in this period for efficient power regulation. Harmonics have a variety of effects on the power system, including excessive heating of capacitors used for power factor improvement, overheating of transformers and motors, and synchronisation issues in generating units [2], [3].

Prior to the development of the shunt active power filter, passive filters (or LC-filters) were routinely used to deal with power quality issues (SAPF). Passive filters also have a number of drawbacks, including their bulkiness, the fact that they only provide set compensation, and the fact that they can only be built and operated for a single fundamental frequency. However, due to the non-dynamic nature of passive filters, scientists and engineers worked to find more acceptable solutions, eventually resulting in the SAPF, which uses advanced control techniques. Line reactors, isolation and phase-shifting transformers, and other types of equipment are used to improve power quality in addition to active and passive filters [4].

The SAPF is built around a PWM-controlled voltage source inverter (VSI) that is connected to the load in parallel, hence the name "Shunt Active Power Filter." The SAPF's major components are VSI, a DC-Link Capacitor, and integrated control circuitry. The efficiency of SAPF is largely determined by the reference current generation technology and the control methods used to reintroduce the appropriate compensation current.

SAPF can employ time-domain techniques like Hysteresis current control, PI-control, and sliding mode control, or frequency domain methods like fast Fourier transform (FFT), discrete Fourier transform (DFT), and recursive discrete Fourier transform (RDFT) (RDFT). However, frequency domain approaches require a lot of memory and processing power, and the results for transitory conditions aren't very precise. Time-domain approaches, on the other hand, are simple to implement and understand, needless calculation, and are extensively used to generate the reference current. SAPF [4], [5] are the ones who employ hysteresis control the most.

2. SHUNT ACTIVE POWER FILTER (SAPF)

By comparing the load current and source voltages to the reference current waveform and then generating the 'anti-harmonics' with the help of a power converter, the Shunt Active Power Filter adjusts to variations in the sinusoidal waveform. Reactive power can also be adjusted using SAPF. Because we don't have to redesign the entire filter in response to changes in load conditions, SAPF is preferable over passive filters.

A.WORKING OF SHUNT ACTIVE POWER

The SAPF operates by detecting harmonics in the power system and then producing anti-harmonics that are identical in amplitude to the harmonics in the power line but 180 degrees out of phase. SAPF is connected in parallel to the non-linear load and assists in achieving only sinusoidal current at the receiving end (fundamental component). Figure 1 depicts SAPF in action in a circuit where iL stands for load current, is for source current, and iF stands for compensation current (or filter current at the power converter output) [7].

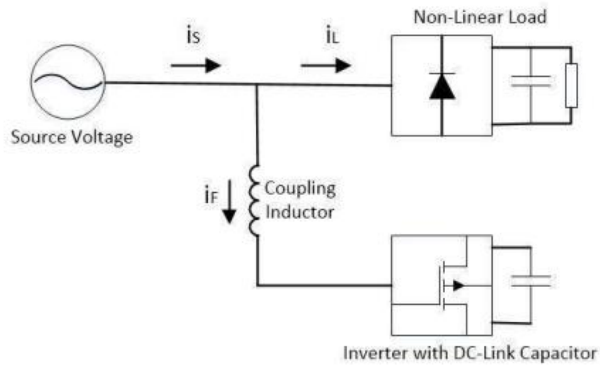

Figure 1.Single Line Diagram of SAPF

The voltages vS and VDC represent the measured source voltage and the voltage on the SAPF's DC side, respectively. Using vS, VDC, and iL, the SAPF controller generates the reference current Iref in real-time time. SAPF can be subjected to two major parts:

1) Power Circuit
2) Control Circuit

SAPF uses control techniques such as p-q theory, d-q transformation, sliding mode control method, unity power factor method, DSP algorithms, and so on to keep track of load current and generate compensating current in real-time. We shall use pq theory, Clarke Transformation, and a hysteresis band current controller among these [8], [9].

B. DC-Link Capacitor

The DC-link capacitor is used for the following purposes:

1) It maintains a relatively constant DC voltage on the dc side of the VSI with very little ripples.
2) It works as an energy storage element during the transitory phase, supplying the real power demand of the load from the source.

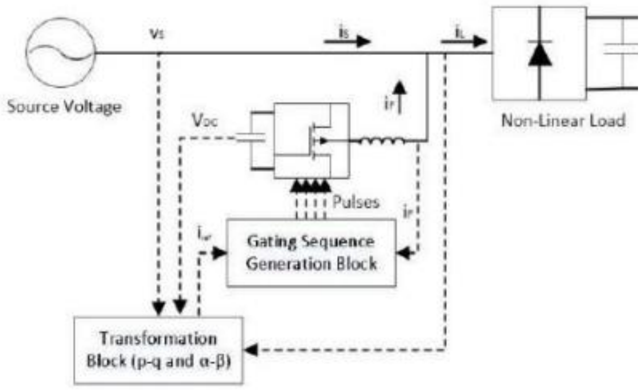

Figure 2. Schematic of SAPF

3. THE INSTANTANEOUS POWER THEORY / P-Q THEORY

The p-q theory uses the Clarke Transformation, often known as the - transformation, to cope with reactive and power components [10], [11].

A. Alpha–Beta Transformation

Vα, Iα, Vβ, Iβ, Vo, and Io are obtained by mapping three-phase instantaneous currents (ia, ib, and ic) and voltages (Va, Vb, Vc) onto the - frame using the Clarke Transformation. 0. [11] is a matrix representation of the Clarke Transformation of three-phase voltages and currents:

$$\begin{bmatrix} V_o \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & \sqrt{3/2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & \sqrt{3/2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

The - transformation has the advantage of separating the zero-sequence component of load current, which simplifies equations for further calculations. In this example, the real and imaginary power components are:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

The SAPF should provide or adjust all other power components, including harmonic and reactive, and the only component of power demand by load should be the average value of the instantaneous real power Pavg from the source. We shall continue as follows to find current compensation in the - coordinate: [12], [13]:

$$p_{reg} = k_p(V_{ref} - V_{dc}) \quad (4)$$

The value of px, which defines the compensable power, is given in [14].

$$p_x = (p - p_{avg}) - p_{reg} \quad (5)$$

$$q_x = q \quad (6)$$

The following expression can be us ed to retrieve the compensation current in the 0-coordinate using load currents:

$$\begin{bmatrix} i_{ref_\alpha} \\ i_{ref_\beta} \end{bmatrix} = \frac{1}{V_\alpha{}^2 + V_\beta{}^2} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p_x \\ q_x \end{bmatrix} \quad (7)$$

$$i_{ref_0} = i_{L_0} = \frac{1}{\sqrt{3}}(i_a + i_b + i_c) \quad (8)$$

The reference currents in the three-phase system (Irefa, Irefb, and Irefc) are recalculated in the - coordinate system using the inverse Clarke Transformation. [15]

$$\begin{bmatrix} i_{ref_a} \\ i_{ref_b} \\ i_{ref_c} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3/2} \\ 1/\sqrt{2} & -1/2 & -\sqrt{3/2} \end{bmatrix} \begin{bmatrix} i_{ref_0} \\ i_{ref_\alpha} \\ i_{ref_\beta} \end{bmatrix} \quad (9)$$

B. Reference Current Generation Block

The estimation of reference current is the most essential phase when load currents and source voltages are measured and Clark Transformation is used. On a two-axis coordinate system, these values are shown. The actual and reactive powers are calculated using the same formulas as before. A low-pass filter is then used to separate the harmonic and reactive components of the power. The SAPF only takes into account the power components that cause harmonics and power loss at the inverter, not the actual power demand of the associated non-linear load. [5]

C. Hysteresis Band Current Controller

Hysteresis current control is a useful way to control an inverter's output. It helps keep the output current waveform near to the reference current waveform by comparing and minimising errors. The comparators control flags to reduce the source current and keep it within the defined band when the value of the actual current Icomp exceeds the value of the reference current Iref. The HBCC generates the VSI switch gating sequence using the error. [16], [17] The SAPF will output current that is sinusoidal and adjusts for harmonic current components. When the current falls below the lower set limit of the hysteresis band, the same thing happens.

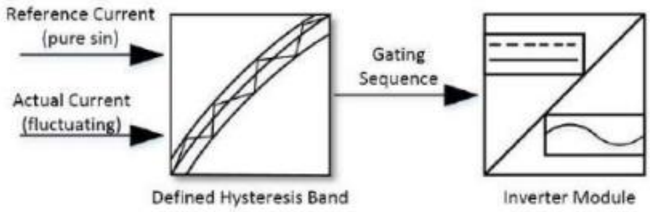

Figure. 3. Block Diagram Hysteresis Current Control

The hysteresis band current control approach is preferred because it is simple and inexpensive to apply, and its dynamic response is outstanding. However, expecting to fix the commutation frequency with this control strategy is ludicrous.

This inconvenience is negligible in our case. The current controllers based on this method are now considered standard in most modern control systems [18].

D. P-Loss Calculation Block

To maintain Vcap constant, the difference between the voltage across the DC-Link Capacitor Vcap and Vref is sent to a PI-controller. During transients, the DC-link capacitor serves as an energy storage component by providing the real power difference between the load and the source. The real power computed to account for inverter switching losses is known as Ploss [5]

4. SYSTEM PARAMETERS

Non-linear load, DC-link Capacitor, MOSFET based Inverter, and other circuit parameters and components will be discussed in this section. [19]

A. Non-Linear Load

We used a bridge rectifier with an RL branch in parallel, a 1k Ohm resistance capable of retaining 100W of power, and a 100mH inductor to create non-sinusoidal current components (harmonics) in the power line.

B. Circuit Parameters

Table I lists the values of the components used in the power and control circuits:

Table 1

System & Component parameters

Phase to Phase RMS Voltage	400 V
Fundamental Frequency	50 Hz
Resistance of Coupling Inductor	50 m
Inductance of Coupling Inductor	5 mH
DC-Link Capacitor (each)	470 µF
Resistance of Non-Linear Load	1k Ohm
Inductance of Non-Linear Load	100 mH

Design of active filter

Design a non-inverting active low pass filter circuit that has a gain of ten at low frequencies, a high frequency cut-off or corner frequency of 159hz and an input impedance of 10KΩ

The voltage gain of a non-inverting operational amplifier is given as:

$$A_F = 1 + \frac{R_2}{R_1} = 10$$

Assume a value for resistor R1 of 1kω rearranging the formula above gives a value for R2 of:

$$R_2 = (10 - 1)\ x\ R_1 = 9\ x\ 1k\Omega = 9k\Omega$$

R1 = 1k and R2 = 9k for a voltage gain of 10. Because a 9k resistor isn't available, the next best value of 9k1 is used instead. When you convert this voltage gain to a decibel db number, you get

$$Gain\ in\ dB = 20\log A = 20\log 10 = 20dB$$

With an input impedance of 10k, the cut-off or corner frequency (c) is given as 159hz. The formula for determining the cut off frequency is:

$$fc = \frac{1}{2\pi RC}\ Hz$$

We can find the value of the filter capacitor c by rearranging the conventional formula as follows:

$$C = \frac{1}{2\pi\, fc\, R} = \frac{1}{2\pi\ x\ 159\ x\ 10k\Omega} = 100nF$$

As a result, the frequency response of the final low pass filter circuit is as follows:

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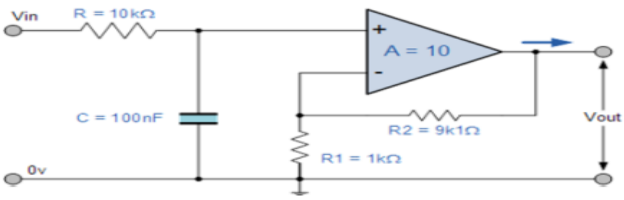

5. SIMULATION RESULTS OF THREE-PHASE SAPF

The "Reference Current Generation Block" is the most significant block in this approach. To construct the gathering sequence that is sent to the "3-Phase Inverter," the reference current generated by this block is compared to the compensating current generated by the "Hysteresis Band Current Controller" block. Figure 4 shows that the Simulink model of three phases without shunt active power filter. The three-phase voltage source is connected to non linear load. In this Simulink diagram it consists of two nonlinear loads one load is directly connected to the source and another load is connected through circuit breaker. When non-linear load is connected harmonic distortions more we are observed the waveform (fig 6) and the circuit breaker is operated at a 0.5 second after 0.5 seconds another non-linear load is connected. Then harmonic distortion is more we observe waveform 6 before compensation device.

As the number of harmonic distortion is more, the reduction of this connecting shunt active power filter is shown in figure 5. Shunt active power filter is connected in between 3 phase measurement block & load bus. Shunt active power filter reject high-frequency signal it allows only low-frequency signal so the number of harmonic distortion is less we can observe wave from form 7

figure 9 shows that FFT analysis of current in construct load current is reduced to 1.86 percentage utilization of shunt active power filter.

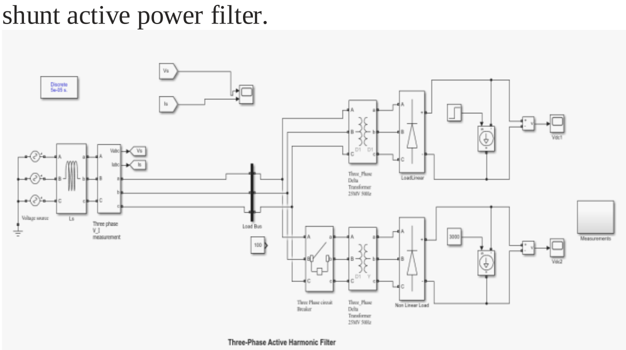

Fig. 4. Simulink Model of Three-Phase without SAPF

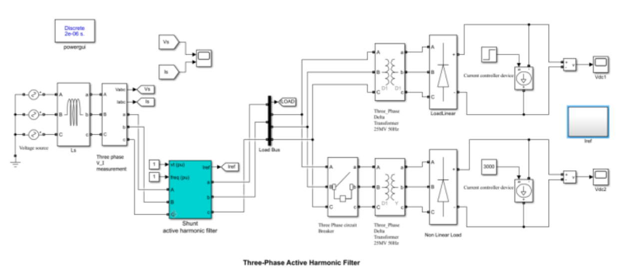

Fig. 5. Simulink Model of Three-Phase with SAPF

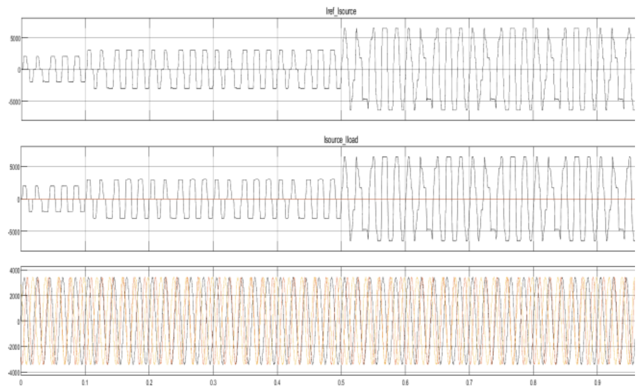

Figure.6. Source Voltage, Source Current, Compensating Current, Load current respectively without filter

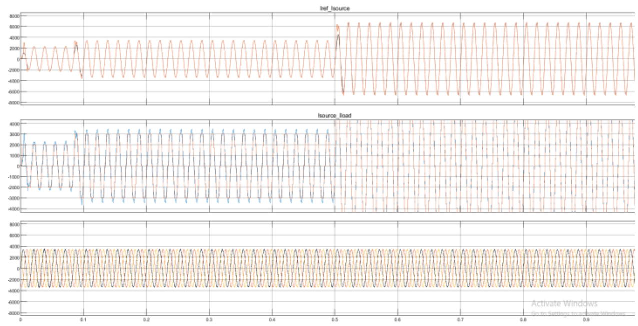

Figure. 7. Source Voltage, Source current, Compensating Current, Load current respectively With filter

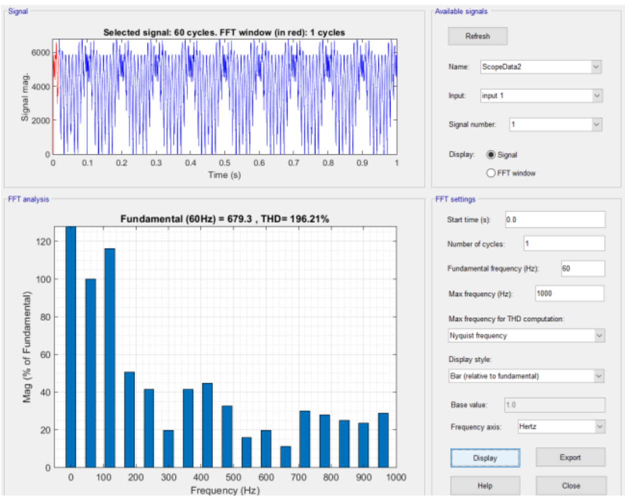

Figure. 8. FFT-Analysis of Load Current without filter

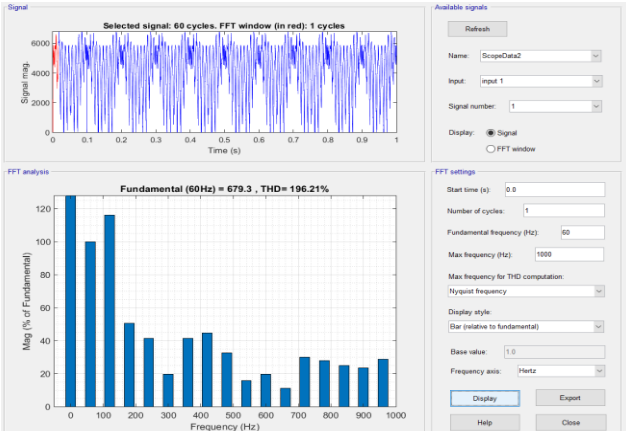

Figure. 8. FFT-Analysis of Load Current without filter

CONCLUSION

We used Simulink to simulate a three-phase SAPF and were able to improve THD percentage by a significant amount. THD percentage should be kept below 5%, according to the IEEE 519 standard. Performing a comparative FFT-analysis of load and source currents shows that the magnitude of the harmonic current components is considerably reduced. These technologies improve not just THD but also Pf by compensating for reactive power. The simulated system is adaptive, with a dynamic reaction that changes as the load and power requirements change Finally, boosting THD % and Pf with SAPF is a great way for minimizing harmonics in power systems.

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