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Design and Simulation of a Shunt Active Power Filter for Harmonic Mitigation

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Research Article

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Abstract

The aim of this paper is to present the design process of a shunt active filter (SAF) in power systems and to highlight its importance in mitigating harmonics. The huge widespread of non-linear loads is rendering the source currents non-sinusoidal and thus producing harmful harmonics. In order to appreciate the effect of SAFs in power systems, a problem is adopted in which a non-linear load is present. The system is then modelled, and MATLAB Simulink simulations are carried on to highlight the undesirable presence of harmonics without the filter being installed and to showcase the power of the SAF in reducing the harmonic distortion of the system remarkably.

Key words: Active Filters, Harmonic Filters, Harmonic Distortion, Power Quality, Diodes, Current.

I. INTRODUCTION

Power quality is becoming a very serious and profound issue in the world of electrical engineering. Due to the huge spread of non-linear loads across all power grids, the non-linear current is forcing a non-linear supply voltage to be created which causes immense power quality problems ranging from dips and sags to harmonics and fluctuations. As the concern about power quality grows, electric utilities are always trying to find a way to provide pure power to the consumer, especially if the latter has equipment and processes that are sensitive to power fluctuations.

Harmonics are one of the main issues caused by non-linear loads. Harmonics can be very dangerous sometimes, as they may lead to the overheating of equipment, misfiring in variable speed drives, and motor torque pulsations. Efforts have been made to reduce harmonics via active filters, passive filters, hybrid filters, or custom power devices. Nevertheless, research on designing such filters has been relentless during the past few years, where a shift towards active filters connected in shunt can be recognized, mainly because they are less costly than the passive ones, have less size and weight and can be easily tuned and adjusted. Moreover, the filtering characteristic of the passive filter is strongly affected by the system impedance that may create series or parallel resonance, causing amplification of harmonic voltage or current at a specific frequency.

On the other hand, a shunt active power filter is a group of power electronic circuits consisting of power switching devices and passive energy storage elements such as capacitors and inductors. The power switching devices are driven with a specific control strategy to produce a current that can compensate for harmonic and poor power factor load.

Previous papers present several approaches on how to design the SAF in accordance with the IEEE requirements that should be found in an electrical system. For instance,

Hussein and Abidin adopt a time-domain approach in designing the controller of their filter, whereas George Adam adopts Akagi’s method of reactive power control for the design of his SAF.

In this paper, a problem with a non-linear load comprising of a diode rectifier will be presented. The problem will be assumed as three-phase, operating at a nominal frequency of 50 Hz. A preliminary simulation will be carried on without the SAF, and the results will be presented. The choice of the components of the SAF will then be made and designed accordingly, and the full

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system will then be simulated in the presence of the SAF, and results will be compared with the primary simulation in order to appreciate the role of the filter. The focus will be mainly laid on the source current and how to minimize the harmonic content in that signal.

II. POWER QUALITY MEASUREMENTS

The electrical equivalent of the system studied is shown in Figure 1. The system is made up of a three-phase source operating at 415 V, with a specific line impedance and negligible source resistance. The load consists of the diode rectifier which is the main cause of the non-linearity present. The diode rectifier is also three-phase and consists of a load on the DC side equivalent to a current source of 40 A. It should be noted that the scope of this paper does not cover the unbalanced part, thus all three phases are assumed to be balanced and the simulations were carried on accordingly.

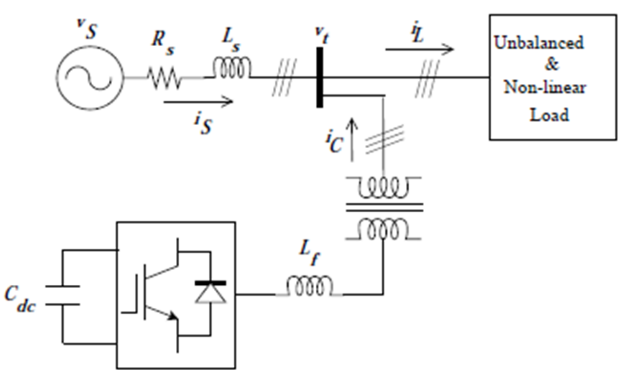

Figure 1: Circuit Diagram

At the point of common coupling (PCC), the shunt active filter is set to inject harmonic content that will cancel out the ones present in the source current, thus rendering it sinusoidal. But prior to the full operation, a first simulation is carried on with only the load present, and the following results were analyzed.

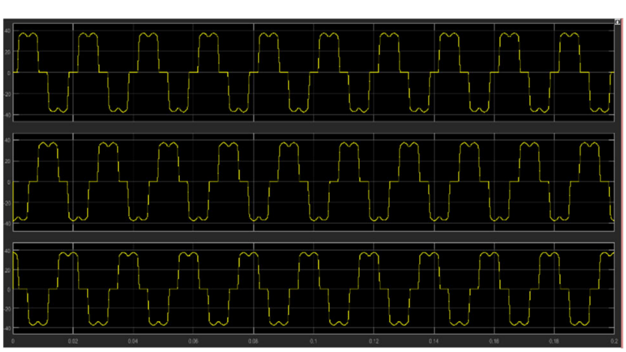

Figure 2: Source currents before compensation

As it can be readily seen from Figure 2, the source current is definitely non-sinusoidal and has harmonic content present within the signal. The power gui block in Simulink has the feature of Fast Fourier Transform (FFT) analysis which allows the specific analysis of the harmonic orders present in a distorted signal. Figure 3 clearly shows that the 5th and 7th harmonics are quite dominant, and are causing the signal to have a Total harmonic distortion (THD) of 26.25%, which is unacceptable based on IEEE standards. The THD basically cannot exceed 5% since a higher value will cause system overheating and equipment damage, in addition to other power quality problems.

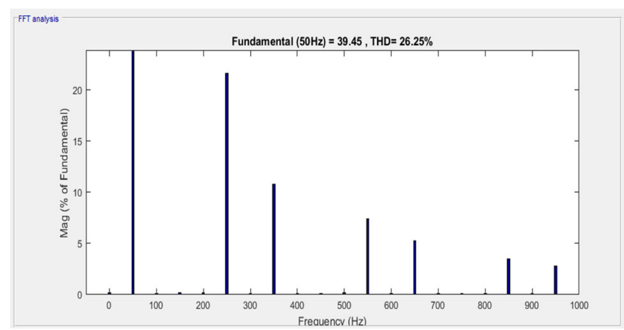

Figure 3: THD of the current signal

III. CHOICE OF COMPENSATION

A shunt active power filter is mainly comprised of the following components:

- Sensors and transformers, which are used to detect signals and inject waveforms.
- A distortion identifier, that generates a reference waveform.
- An inverter, which is used to reproduce the reference waveform.
- Synchronizers, which make sure that the injected waveforms are synchronized with system voltages and currents.
- DC bus to provide the needed power to the inverter.

The main steps that an active filter needs to achieve are to be able to produce a reference signal, inject it into the system, and make sure it is controlled and synchronized with the system voltages and currents. The choice to be made here is on the method of generating a reference signal.

The traditional way occurs in the time domain, where the distorted signal is passed through a filter (either low-pass or high-pass) and the fundamental component is isolated to obtain only the harmonics. Another method is to use the same approach but in the frequency domain in order to avoid any delays (time lags) that may happen in real-time.

This paper will adopt the power control method based on the p-q theory which was first proposed by Akagi et al., back in 1983. This method is based on the algebraic transformation of the current and voltage of the system from the abc system to αβ0 system using the Clarke transformation presented in the following equations:

$$\begin{bmatrix} i\alpha \\ i\beta \\ i0 \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix} \begin{bmatrix} iLa \\ iLb \\ iLc \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v\alpha \\ v\beta \\ v0 \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix} \begin{bmatrix} vLa \\ vLb \\ vLc \end{bmatrix} \quad (2)$$

where i_{La}, i_{Lb}, and i_{Lc} are the load currents and v_{La}, v_{Lb}, and
v_{Lc} are the load voltages.
According to the p-q theory, the active, reactive, and zero-sequence powers are defined in the following equations:

$$p = v\alpha\ i\alpha + v\beta\ i\beta \quad (3)$$

$$q = v\alpha\ i\beta - v\beta\ i\alpha \quad (4)$$

$$p0 = v0i0 \quad (5)$$

A low-pass filter is then used as a buffer to eliminate the AC component of the current signal in the P-Q domain, noting that the filter could have been installed at the level of the alpha-beta domain before computing the P and Q values. After obtaining the reference current, a new transformation is applied to get back to the abc domain.

In addition to obtaining a reference waveform, a PI controller is implemented in order to make sure that the reproduced waveform actually tracks the generated reference. So, at every time step, a check is performed to see whether the generated signal is adequate.

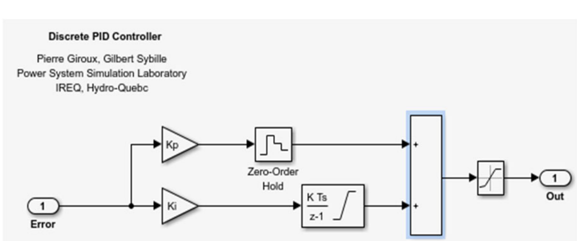

Figure 4: PID controller

The final step in designing the filter control process is the synchronizer. There are multiple ways to ensure synchronization of the signal. One can either use a PWM generator, a PLL (phase-locked loop) or the hysteresis method. The hysteresis current controller is used in the paper for its simplicity, easy implementation and fast response current loop. Along with these, it has the added advantage that there is no need for knowledge of load parameters.

The next page shows an image of the full model of the shunt active filter:

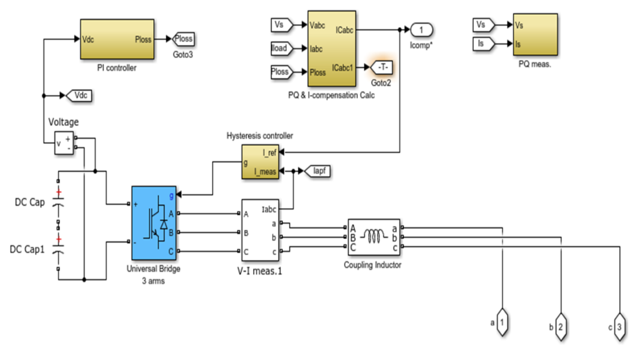

Figure 5: Simulink model of the filter

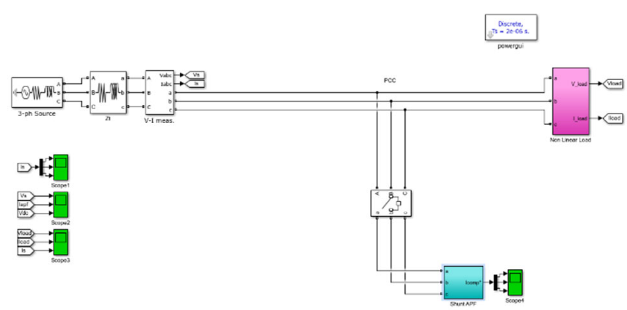

Figure 6: Full Simulink model

IV. Simulation and Results

The system is simulated with the following parameters:

- Source voltage of 415 V at 50 Hz
- Source resistance of 1 mΩ
- Line resistance of 1.5 Ω and negligible inductance
- A switch that connects the SAF at PCC after 0.05 s
- Diode rectifier load, where the diodes have a 0.7 V on-state voltage.
- 40 µF capacitors.
- Diode Insulated-gate bipolar transistors (IGBT) to control the switching.
- The DC side of the load rectifier has 12.5 Ω resistance.

- The system is discretized in a step of 2 μs and the simulation is run for 0.2 s, which equals 10 million time steps.

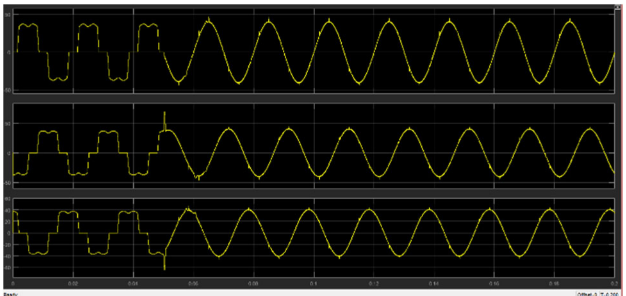

Figure 7: Source current, before, and after compensation

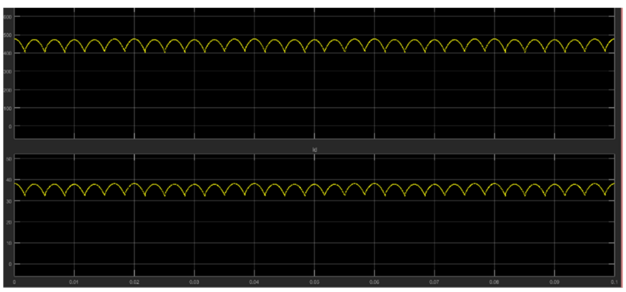

Figure 8: Load voltage and current

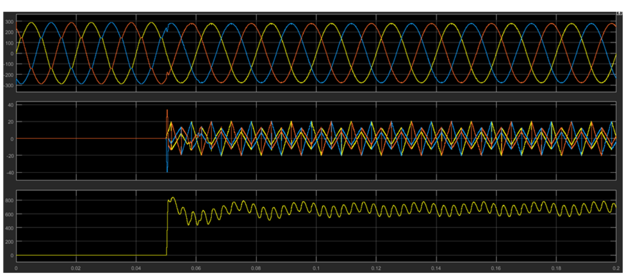

Figure 9: Source voltage, injected waveforms, and DC bus voltage

It can be readily noted that the filter is working almost to absolute perfection. At t=0.05 s, when the switch is invoked, the current shift from non-linear to sinusoidal, as can be seen in Figure 7. It can be also seen how the filter is producing the distortions needed to cancel out any harmonic content. The load is also perfectly rectified.

To further appreciate the effect of the filter, and to make sure that it is doing its job, THD must be investigated. The following table summarizes and shows how THD is significantly reduced:

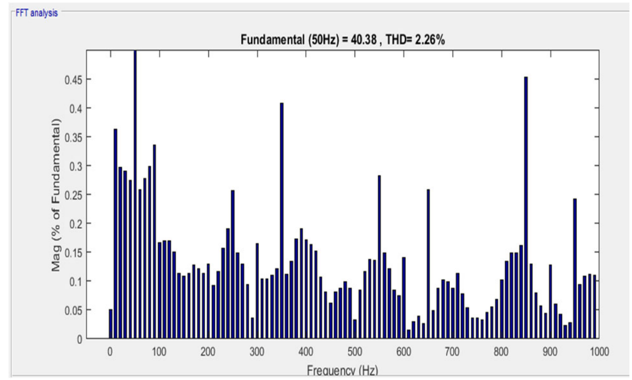

Figure 10: THD after compensation

150 Hz	(h3):	0.11%	245.1°
160 Hz		0.11%	243.5°
170 Hz		0.13%	226.7°
180 Hz		0.12%	204.1°
190 Hz		0.11%	168.2°
200 Hz	(h4):	0.13%	95.8°
210 Hz		0.09%	50.7°
220 Hz		0.12%	10.9°
230 Hz		0.16%	-26.1°
240 Hz		0.19%	-64.1°
250 Hz	(h5):	0.26%	177.2°
260 Hz		0.15%	239.7°
270 Hz		0.13%	215.8°
280 Hz		0.09%	194.3°
290 Hz		0.04%	208.4°
300 Hz	(h6):	0.16%	250.1°
310 Hz		0.10%	202.1°
320 Hz		0.10%	181.2°
330 Hz		0.11%	158.3°
340 Hz		0.12%	112.9°
350 Hz	(h7):	0.41%	40.9°
360 Hz		0.11%	10.4°
370 Hz		0.13%	-28.1°
380 Hz		0.17%	-63.3°

Figure 11: 5th and 7th harmonics

The results clearly show that the dominant harmonics (5th and 7th) have been reduced significantly, and comprise now only 0.26% and 0.41% of the fundamental. The THD is reduced from 26% down to 2.25%, which is less than 5% and is acceptable by IEEE standards.

V. Conclusion

This paper presented the design and analysis of a shunt active power filter used to mitigate harmonics in electric circuits. The filter worked perfectly in injecting harmonic content and rendering the source current perfectly sinusoidal. The control technique was based on the p-q theory, in addition to a PI controller. The simulation results clearly showed that the harmonic content was greatly reduced, as the THD went down from an unacceptable 26.25% to an astounding 2.25%.

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A more detailed image of the drive is presen.