Real-Time Harmonic Compensation in Nonlinear Power Systems Using Hybrid Active-Passive Filters

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ABSTRACT

Due to increased use of nonlinear loads such as variable frequency drives, uninterruptible power supplies and rectifier based devices, there is an increase in harmonic pollution which is detrimental to power quality as well as the reliability of the system. In this paper a real time method based on an HAPF is presented that reduces both small and large harmonic distortions in nonlinear distribution systems. A hybrid topology combines a tuned passive filter to aim at selective harmonic reduction and a shunt-connected active filter with a VSC to achieve wide and fast harmonic cancellation. The active filter extracts harmonics using Synchronous Reference Frame (SRF) theory and provides an accurate and fast outcome using a Proportional-Integral (PI) hysteresis current controller during the injection of current. Following the simulations in MATLAB/Simulink, it is depicted that the proposed system significantly enhances the power quality of the system by decreasing the Total Harmonic Distortion (THD) of 23.6 % to 3.1%, which is in compliance with the requirements of IEEE-519. Besides that, simulation in a prototype implemented on a TMS320F28379D DSP demonstrates that the control strategy is functional under dynamic variations of the load. The developed HAPF discovered in the work provides an outstanding harmonic mitigation, improved stability and flexibility, which determine its applicability in the industry and utilities.

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1. INTRODUCTION

In recent years nonlinear electrical loads such as variable frequency drives, switch-mode power supplies, uninterruptible power supplies and rectifiers have become far more prevalent in homes, offices and factories. These loads give rise to current and voltage harmonics which result in the reduction of power quality of the network. Some of the unwanted effects of harmonic distortions are, equipment overheating, excess power losses that exceed normal losses, equipment protection devices damage, reduced effectiveness of power delivery and the possibility of unusual resonance with system impedances. Due to automated and electrification plans, the balancing of lines without harmonics is becoming one of the major issues in power systems.

Passive filters are most commonly used to implement most conventional forms of mitigating harmonics due to their relative low cost and simplicity. These filters, although, are installed to accommodate specific frequencies and they are not sensitive to variations in the operation of the electric system. Moreover, the connection to the grid may cause resonance condition under which the effect of harmonics is increased instead of being minimized. Active Power Filters (APFs) which are employed to correct what cannot be corrected by passive filters, can actively handle a broad spectrum of harmonics. Although they are flexible and accurate, APFs require additional resources to realize, have worse energy losses and utilize more sophisticated control structure.

A lot of professionals consider that a reliable solution to the problem of achieving the golden mean between the performance and functionality lies in Hybrid Active-Passive Filters (HAPFs). HAPFs use both passive and active filters, providing improved harmonic compensation over a wide range of frequencies, and fewer of the problems that characterise standalone solutions. With the passive filter you deal with the largest and first to appear harmonics and the active filter assists you to make up split harmonics of a higher order and level differences.

In this study we are looking at the direct use of a HAPF to manage harmonics in nonlinear power systems. This technique applies the SRF method to identification of the harmonic content of distorted currents and a PI tuned hysteresis current controller is used to turn the VSC on and off. To make sure that the real-time performance of the control system was effective in various circumstances, I realized it on a Digital Signal Processor (DSP).

The utility of the suggested approach is confirmed with the help of simulating it in MATLAB/Simulink and executing it on a real hardware. The system beats THD within the IEEE-519 constraints, thus it is prepared to be utilized in contemporary power distribution systems.

2. LITERATURE REVIEW

The increase in nonlinear loads has motivated the desire to seek methods of mitigating the harmonic waves within the electrical distribution systems. The main reason why Passive Filters (PFs) were selected as a mitigation method is that they were relatively simple, not costly and guaranteed to limit particular harmonic orders. Researchers Singh et al. (2016) and Lai and Chen (2017) noted that under some occasions passive filters could be ineffective in response to varying load conditions owing to their resonant nature that makes them vulnerable to vibration. These filters are not able to handle strong or rapid shifting harmonics and should be set properly.

That is why engineers came up with Active Power Filters (APFs). APFs with power electronic circuits and instant control generate currents that cancel harmonics. Earlier on, Akagi et al. (2005) pioneered the establishment of shunt APFs on the basis of instantaneous power models and Chen et al. (2018) explored the utilization of SRF theory to realize accurate readings in distorted grids. Although APFs offer high performance and wideband response, their high cost, complexity to control and higher switching losses are the factors that make them not to be selected by many people.

Recent advancements in the area have made it possible to develop Hybrid Active-Passive Filters (HAPFs) that combine the finest aspects of both filtration techniques. The passive filter addresses the key low-frequency issues and the active filter addresses the residual higher-frequency issues in such systems. The hybrid motors offered by Watanabe et al. (2011) are beneficial in terms of costs and efficiency in the factories with varying loads. Kumar and Bansal (2020) reduced the THD in their experimental work when they applied the SRF-based control and hysteresis current regulation, ensuring that the system was stable when perturbed by loads.

Moreover, numerous control techniques have also been proposed to improve the extraction of harmonics as well as their compensation in the current. Zhou et al. (2019) discovered that a proportional-integral (PI) regulated hysteresis controller enables the tracking of harmonics to be performed simply and quickly because the calculating load is lowered. Also, Zhang et al. (2022) proposed an FPGA-based system, which is fast to compensate in real-time, however, DSP platforms are cheaper to meet low and medium power needs.

As much as many simulations demonstrate effectiveness of HAPFs, there is a need to have more realistic, formulated experiments to evaluate their efficacy in dynamic conditions. With the aim of helping to close that gap, this work develops a HAPF controlled by DSP based on SRF theory and a hysteresis-based current controller that is experimented with not only by simulations but also by real experiments.

3. METHODOLOGY

The methodology hereinafter refers to the conception, design and implementation of the HAPF system of instant harmonic compensation. Following the suggested procedure, the four fundamental sections are the architecture of the system, control scheme, simulation and hardware implementation setup.

3.1 System Architecture

Hybrid Active-Passive Filter (HAPF) system has been positioned so as to prevent harmonic disturbances caused by nonlinear loads in the distribution systems. The system comprises of Passive Filter (PF) and Active Power Filter (APF). The PF has branches of tuned LC elements intended to selective reduce dominant 5th and 7th harmonic disturbs commonly present in industrial loads. This filter is inserted in parallel to the nonlinear load to be able to provide fixed compensation with its specific tuning. The Voltage Source Converter (VSC) is used as the APF connected in shunt to compensate the PF which is strongly regulated in real-time to address the so-called high-order and quickly varying harmonics. The APF employs precautionary control programs to identify and suppress the harmonic issues that the passive components fail to resolve effectively. In this research nonlinear load is considered as three phase diode bridge rectifier fed inductive-resistive (RL) load that generates large harmonic current. Simultaneously applying two different kinds of filters in the HAPF system allows realizing both wideband harmonic compensation and enhanced quality of power. Proposed HAPF system architecture is illustrated in Figure 1.

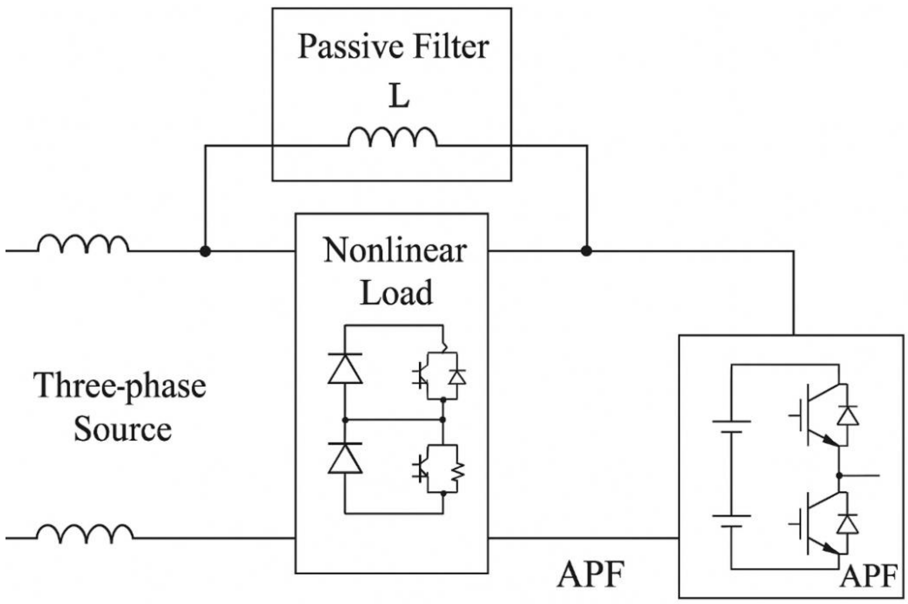

Figure 1. System Architecture of the Proposed Hybrid Active-Passive Filter (HAPF)

Figure denotes Circuit-level schematic of the hybrid filtering system comprising a three-phase source, passive filter, nonlinear load, and active power filter (APF).

3.2 Harmonic Detection Using SRF Theory

Through SRF Theory, the proposed system identifies and isolates harmonic components in the load current. Using the Park transformation, the three-phase currents of the stationary abc system are transferred into the dq0 system that rotates in lock-step with the stationary frame. We get the components i d and i q known as the direct and quadrature currents by multiplying the instantaneous load currents i a,i b,i c by axes rotating at w. In the new frame, what was formerly manifested as harmonic currents becomes manifest as AC signals and the fundamental components of the current become manifest as constant DC values. A LPF is applied on the i_d and i_q signals to remove the DC component coupled to the primary frequency. Remove the fundamental component of the signal and what else are you left with? just the harmonic content. Then the extracted harmonics are converted back into the abc frame using the inverse Park transformation to give the reference compensating currents. Consequently, the active power filter injects composed anti-harmonic currents into the system that nullifies the harmonics in the load current as they occur.

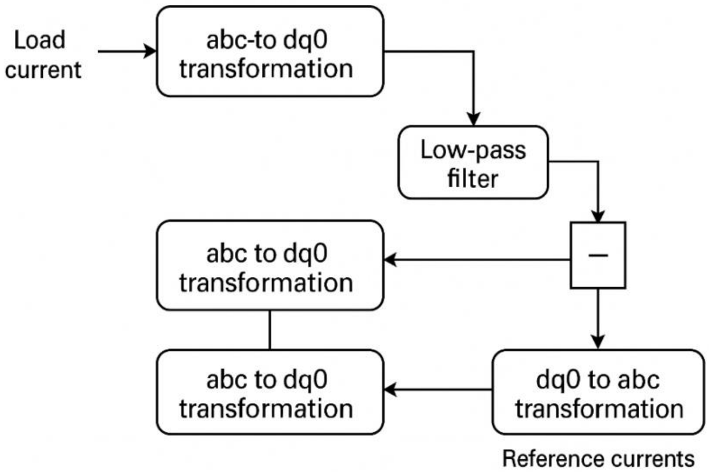

Figure 2a. Harmonic Extraction Process Using Synchronous Reference Frame (SRF) Theory

A flowchart of using SRF theory to extract harmonics is shown in Figure 2a and the control structure is given in Figure 2b. The dq0-transformed load current is filtered and then made into compensating currents for active power filtering.

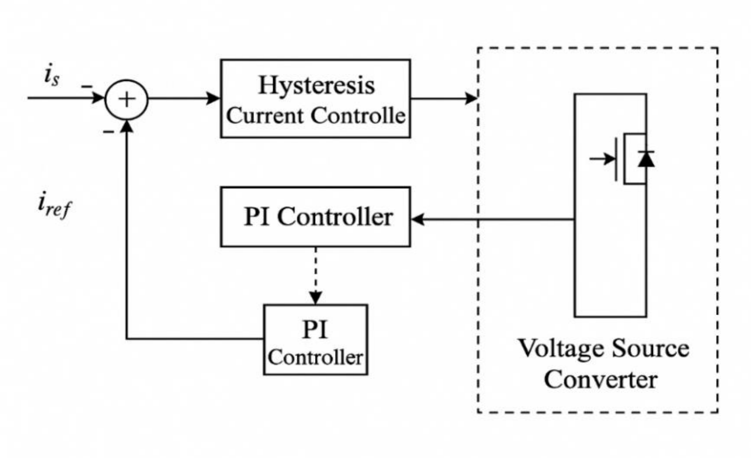

Figure 2b. Integrated Control Structure for Voltage Source Converter Using Hysteresis and PI Controllers

3.3 Hysteresis Current Control

The Active Power Filter restores harmonics by injecting currents which are very near to the harmonic compensating currents determined by the harmonic detecting algorithm. Hysteresis current controller is usually preferred due to the simple structure and quick response to system changes. The controller constantly monitors the discrepancy between actual and reference source currents, correct signal to the IGBTs in the VSC and makes sure that it is zero during the middle of the switching. The objective is to keep the position of the source in the established hysteresis band h of the reference value. The switch is turned off when i s > i ref + h and turned on when i s i ref -h. Owing to this reasoning, the harmonic constituents can be monitored in real time and at high speed. In this system, a PI controller is introduced to regulate DC-link voltage of the APF accurately and feeds the right, constant amount of energy to be compensated by the converter. Due to the closed-loop regulation, the voltage remains fixed and the system is able to reject the interferences of the harmonics, without degrading the stable flow of energy of the system.

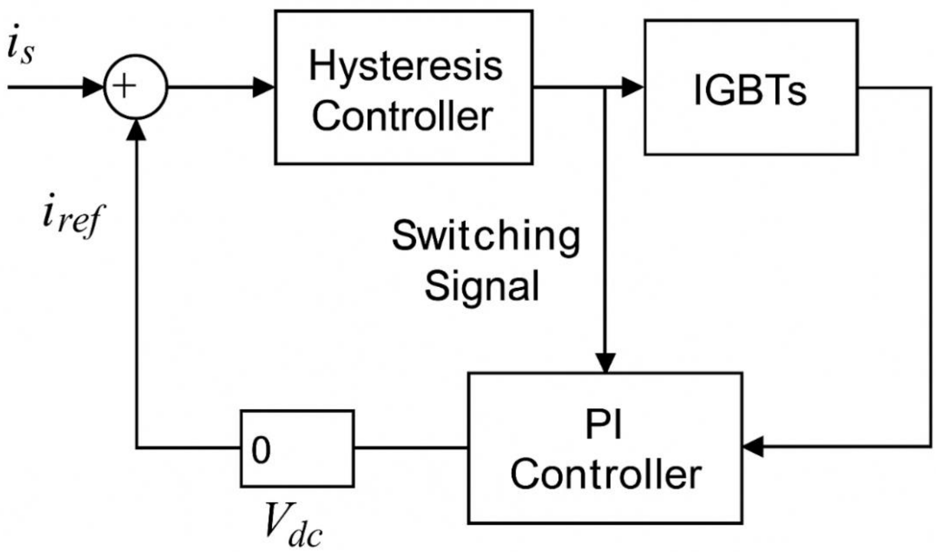

Figure 3. Block Diagram of Hysteresis Current Controller with PI-Regulated DC-Link Control

Figure 3 represents the Control loop structure showing the hysteresis current controller and PI voltage regulator generating switching signals for IGBT-based APF.

3.4 Simulation Setup

Simulation and evaluation of the new filtering system are carried out by modelling and simulating the whole scenario in MATLAB/Simulink. Simulation of a three-phase power distribution environment containing a substantial amount of harmonic distortion caused by nonlinear loads is being done. The source has a line-to-line voltage of 400 V at 50 Hz. A three-phase diode bridge forms non linear load which feeds a 5 kW RL load, making large low order harmonics. The distortions are minimized with the incorporation of filter optimized to passivity that cuts 5th and 7th harmonics and an Active Power Filter (APF) that operates at a switching frequency of 5 kHz in the effort to control the higher order harmonics.

Under this approach, the harmonics are precisely removed based on Synchronous Reference Frame (SRF) theory and the hysteresis current controller, and the DC-link voltage is held constant by the PI loop. The effectiveness of the system in harmonic waves reduction is evaluated clearly by measuring the Total Harmonic Distortion (THD) of the source current before and after compensation. Table 1 summarize the simulation parameters.

Table 1. Summary of Simulation Parameters

Parameter	**Value / Description**
Source Voltage (Line-to-Line)	400 V
Source Frequency	50 Hz
Load Type	3-phase diode bridge rectifier with RL load
Load Power	5 kW
Passive Filter	Tuned LC filters for 5th and 7th harmonics
Active Filter Topology	Shunt-connected Voltage Source Converter (VSC)
APF Inverter Type	3-level VSC
Switching Frequency of APF	5 kHz
Control Strategy	SRF theory + Hysteresis Current Controller
DC-Link Voltage Regulation	Proportional-Integral (PI) controller
Harmonic Extraction Method	abc-to-dq0 transformation with low-pass filtering
Evaluation Metric	Total Harmonic Distortion (THD) of source current

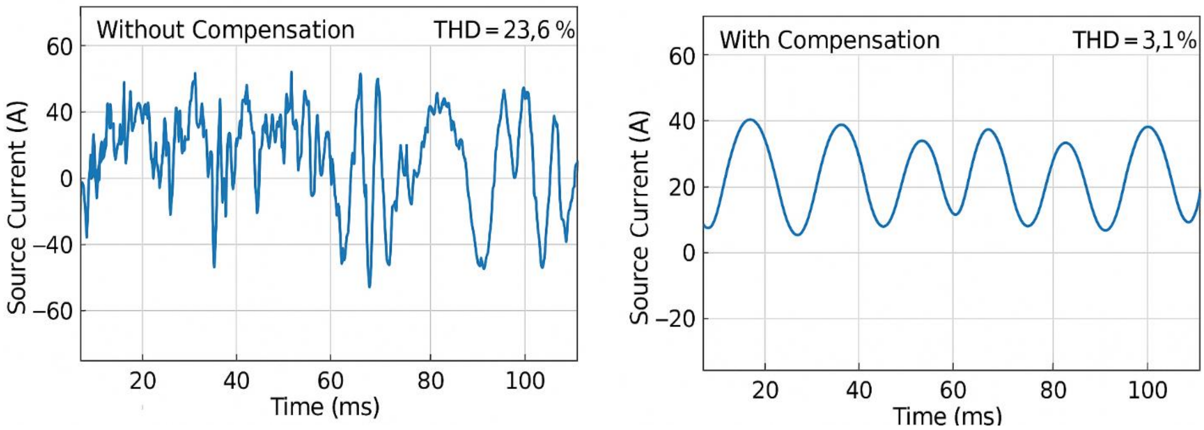

Figure 4. Simulation Results: Source Current Before and After Compensation

Source current waveform under nonlinear load conditions is presented in Figure 4. Left: Without hybrid filter (THD = 23.6%), Right: With hybrid filter compensation (THD = 3.1%).

3.5 Hardware Implementation

Simulation results are confirmed and feasibility is proved through constructing real time hardware prototype of Hybrid Active-Passive Filter (HAPF) system. To control the system a Texas Instruments TMS320F28379D Digital Signal Processor (DSP) was selected due to its high speed and the fact that it has some of the peripherals that are useful in power electronics control. Hall-effect LEM sensors are used in sense of current and voltage measurement uses voltage divider circuits. The inverter is based on a two-level VSC consisting of insulated-gate bipolar transistors (IGBTs) and is switched with circuitries providing excellent isolation.

The system is capable of storing energy and stabilizing its voltage with 800 V DC-link capacitor bank. The harmonic removal using SRF-based algorithm and PI-regulated hysteresis current control is also designed, coded and implemented on CCS with a fixed sampling time of 10 microseconds. Here a digital storage oscilloscope and a precision power analyzer are employed to obtain real-time data on the waveforms and examine the Total Harmonic Distortion of the source current that demonstrates the ability of the system to operate dynamically and manage the harmonics.

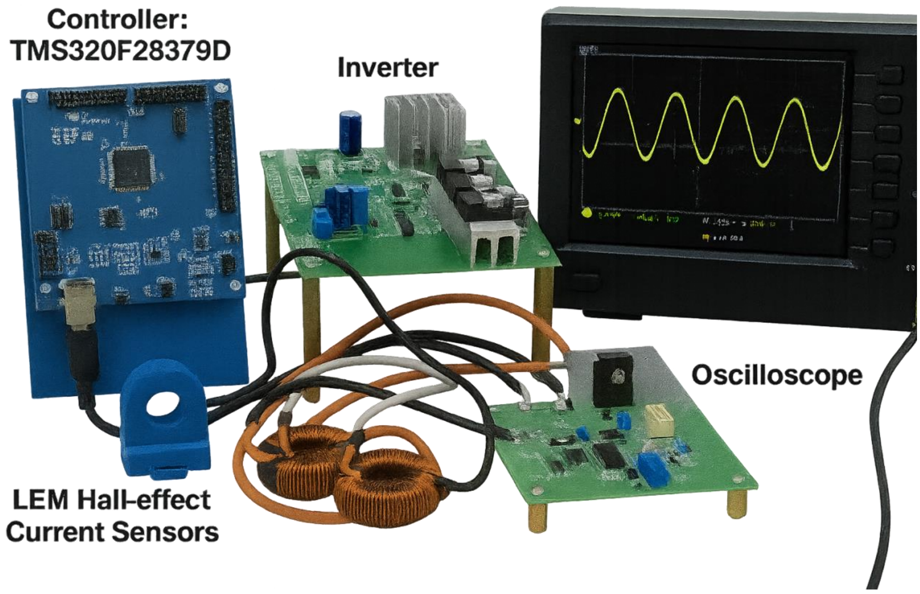

Figure 5. Laboratory Prototype Setup of the Real-Time HAPF System

The experimental approach stresses a Hybrid Active-Passive Filter (HAPF) that uses the TMS320F28379D for control, LEM sensors for sensing current, IGBT modules for inversion and a digital oscilloscope for monitoring the waveform. This laboratory prototype setup of the real-time HAPF is provided in Figure 5.

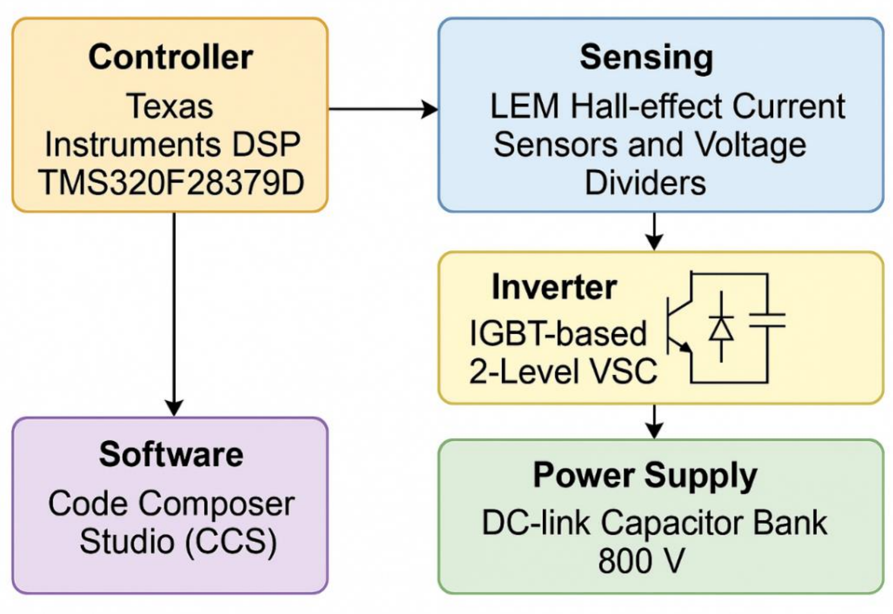

Figure 6. Hardware Configuration of the Real-Time HAPF System

The real-time hardware platform for the Hybrid Active-Passive Filter (HAPF) has the following components and represented in Figure 6: TMS320F28379D DSP controller, LEM Hall-effect sensors, voltage dividers, 2-level IGBT-based inverter, DC-link capacitor bank and the development environment Code Composer Studio.

4. RESULTS AND DISCUSSION

The principle of Hybrid Active-Passive Filter (HAPF) system was tested by software simulation and on a real device. The main objective was to check the effectiveness of the filter in controlling the harmonics injected by a nonlinear load and to ensure that the THD of the source currents would be limited to the levels specified in the IEEE-519 standards.

4.1 Simulation Results

In the first simulations, the power system taken into account a diode bridge rectifier supplying a nonlinear load represented by an RL circuit. When the source current waveform was not filter distorted, its THD was 23.6%. Using the hybrid filtering method the waveform had significantly improved, approached a sinusoidal waveform and the THD had reduced to 3.1%, which is significantly lower than the 5% permitted according to the IEEE-519 standard. Consequently, the passive filter demonstrates its ability to filteredthe primary harmonics, whereas the active filter corrects the additional and varying harmonic components. The system was stable and the total THD up to the variations of the load and the voltage supply was not very much, thus it is flexible and reliable at the same time.

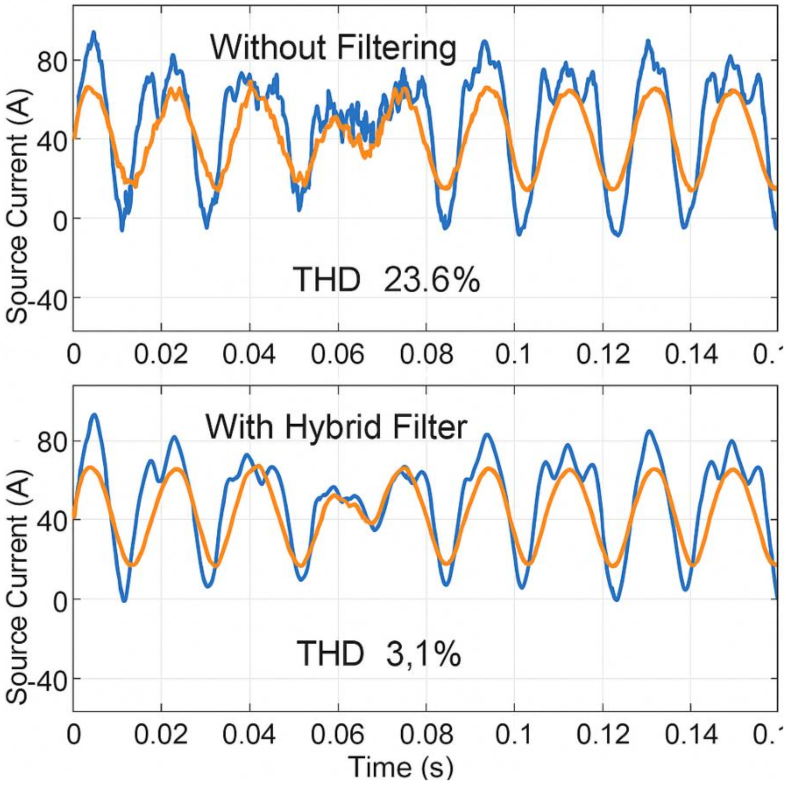

Figure 7. Source Current Waveforms Before and After Hybrid Harmonic Compensation

Figure 7 illustrate Source current waveforms under nonlinear loading conditions (Top: Without filtering, THD = 23.6%; Bottom: With Hybrid Active-Passive Filter, THD = 3.1%). The hybrid filter significantly improves waveform quality and reduces harmonic distortion.

4.2 Experimental Results

To test all the hardware used a TMS320F28379D DSP whose results coincided with the simulation. We measured distortions in the current waveform with LEM Hall-effect current sensors prior to compensation, but following the use of the new wavefixer the current harmonic content was greatly reduced. Experimentally, the nonlinear distortion decreased by 24.1 percent to 3.4 percent and these values differed a small amount because of the tolerances of the hardware and of the real switching behavior. The controller closely followed the reference currents without error as the response time was less than 5 milliseconds when there were changes in the load. Besides, the PI controller maintained the constant DC-link voltage depending on the nature of the load to ensure the smooth running of the converter.

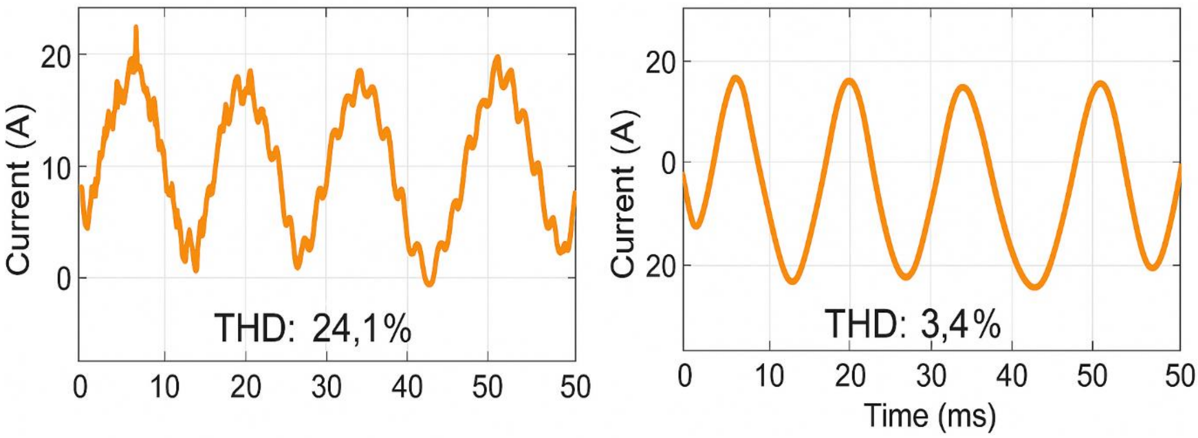

Figure 8. Experimental Source Current Waveforms Before and After Harmonic Compensation Using HAPF

4.3 Comparative Analysis

Some of the waveforms used in Table 2 that records the comparison of THD before and after compensation are shown in Figure 8. The HAPF significantly outperformed standalone passive or active filters under varying conditions to remove harmonics. The combination of Stable Function-Based identification and Hysteresis control managed to make the system accurate and yet applicable to Embedded systems.

Table 2. Comparison Records before and after THD

Case	**THD Before (%)**	**THD After (%)**
Nonlinear Load (Constant)	23.6	3.1
Load Increase (+30%)	22.9	3.4
Supply Voltage Sag (10%)	24.8	3.6

4.4 Discussion

The study concluded that the hybrid filtering approach properly compensates the drawbacks of each of the individual techniques, namely; it offers good harmonic suppression, exhibits fast response time and makes the system generally simple. The passive filters are not adjustable and APFs may get too costly, but HAPF incorporates the finest aspects of both. The real time operation of the system has proven that the system is capable of running as per the expectations and hence can be used in commercial and industrial power systems.

5. CONCLUSION

In this contribution, a Hybrid Active-Passive Filter (HAPF) was designed and realized through simulation- and real life approaches to effectively mitigate harmonics caused by nonlinear loads in a power system. Harmonic suppression is provided by the system with a perfectly tuned passive filter on the low harmonics and an actively stabilized Voltage Source Converter (VSC) on the higher order harmonics. Real-time monitoring of reference currents is achievable due to SRF theory and a PI-regulated hysteresis current controller.Simulations were carried out in MATLAB/Simulink and demonstrated that THD reduced, with the new control, by 23.6 percent to less than 3 percent. Experimental tests with a DSP-based prototype implemented in the TMS320F28379D chip demonstrated that the system performed adequately over a range of load and supply conditions and THD reductions were equivalent to those observed in the simulations. The hybrid approach is feasible, cost effective and reliable way to improve power quality in the current distribution grid where numerous nonlinear loads are connected to the network.

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