Compensate for Loading Effects on Power Lines with a DSP-Controlled Active Shunt Filter

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INTRODUCTION

Systems with passive LC elements, such as capacity compensators, resonant passive filters of higher harmonics, or filters with structures and parameters determined by optimization methods have been traditionally used to compensate for power factor and other loading effects imposed by electricity users on the power network. However, widespread use of loads that involve power-electronic systems can cause major distortion of voltage and (especially) current waveforms, and even cause substantial dc currents to flow in power transformer secondaries. For these types of loads, the kinds of compensation systems mentioned above often prove to be unsatisfactory. Nowadays, power-system engineers are more likely to consider using other types of compensators, especially active power filters or hybrid systems (power filters with passive L-C elements such as those described in References 2, 3, 6, 7, 8, 9, 11) to increase system efficiency.

Recent approaches to development of compensation methods aim to develop compensators of a type that would be able to realize dynamic compensation (in real time) and would also be more resistant to interference caused by the power network or electricity users. Their objectives include optimization of the loads as seen by power sources (power network). According to Fryze's suggestion [5] and subsequent developments [4, 10, 12, 13], to achieve such compensation it is necessary to eliminate a differential current (between a distorted load current and an ideal form of current (i.e., in-phase sine wave)) flowing through the power source. In concept, this can be done by generating and injecting a current equal to and in opposite phase to the differential current. In practice, obtaining such a source is difficult; what is really called for is an active system with parametric elements or controlled-current power sources.

STRUCTURE OF AN ACTIVE FILTER

In this article we consider a proposal to employ a power-electronic current source controlled through the use of digital-signal-processing computer technology to achieve an *active shunt filter* (alternative names are: *differential current compensation system* or *compensator*), to approach a realization of optimal compensation. The assumed aim is dynamic compensation of differential current, which is the difference between load current i_L (t) and reference current i_{REF} (t). The reference current is the optimal active current calculated with the method suggested in article [10]. Figure 1 shows the block diagram of the system.

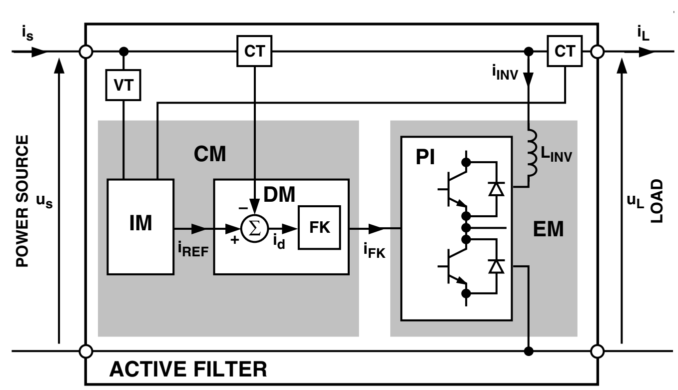


Figure 1. Block diagram of the active filter.

The active filter consists of the following modules and elements:

- Control Module (CM), based on a microcomputer system with digital signal processing (DSP),
- Execution Module (EM) in form of a power-electronic current source,
- Voltage (VT) and current (CT) transducers [Types LA55-P and LV25 (LEM®)].

The active filter control process occurs in two phases:

- Determining the reference current $i_{REF}(t)$,
- Dynamic shaping of desired compensator current in the form

$$i_{INV}(t) = i_L(t) - i_{REF}(t)$$

The quality and dynamic properties of the compensation process depend mostly on the method used for calculating the reference-current parameters. Akagi *et al*'s theory of instantaneous reactive power [1] is commonly used to control power active filters. The authors believe that this theory does not fulfill the requirements of optimization of work in an energy source/receiver system. The general aim of optimization is to minimize the out-of-phase component of source current, reduce distortion of sinusoidal waveforms, and minimize active power losses in transmission of energy from source to receiver. To determine a current which would have such properties, we applied the variational methods of [10]. As a result, we obtained an expression describing an optimal source current (the target *reference current*) in the following analytical form:

$$i_{REF}(t) = {}_a i(t) = {}_e k(t)\ {}_e G(t)\ e(t) = A_{REF}(t)\, e(t)$$

Where: $e(t)$ is the voltage source, ${}_eG(t)$ the equivalent conductance in form: ${}_eG(t) = {}_aP(t)/E^2(t)$, where: ${}_aP(t)$ and $E(t)$ are instantaneous values of active power and rms voltage source [10]. The frequency and phase of the reference signal correspond to suitable values of the first harmonic of the voltage source, $e(t)$.

To effectively realize the whole control process, CM was divided into two sub-modules:

- the Identification Module (IM), which calculates frequency, w_{REF}, phase, φ_{REF}, and amplitude, A_{REF}, of reference current, $i_{REF}(t)$,
- the Decision Module (DM), which performs these tasks:
  - shaping magnitude and phase characteristics of the active filter to obtain wideband transfer and high open-loop gain in the feedback loop. This is necessary to ensure a high degree of compensation of non-linear current and to work stably under conditions of a wide variety of load parameters,

- eliminating parasitic products of pulse-width modulation (PWM), used in generating i_{REF}, from the feedback signal.

THE HARDWARE AND SOFTWARE

The prototype model of the compensator uses the Analog Devices ADDS-2106x-EZ-KIT microcomputer system, with the ADSP-21061 SHARC® floating-point digital signal processor. This high-performance system was needed because of the high calculating power required both by algorithms implemented within the Identification Module (IM) and in suitably shaping frequency transfer characteristics of the active filter. It is essential to assure the stability margin of all systems working in feedback closed loop under conditions of a wide range of load-parameter changes.

The evaluation system was developed with the addition of a universal analog and digital input/output module type ALS100, which had been designed by P.E.P. ALFINE as an extension of the ADDS-2106x-EZ-KIT. This module (Figure 2), designed for power-electronics applications, includes A/D and D/A converters, as well as PWM generators and a System Console (LCD & KBD). Communication with the host PC is established via an RS-232 port under control of a DSPHOST program.

Figure 2 shows the hardware and software structure of the Control Module. The main module of the control program was written in C language (ADDS-21000-SW-PC ver. 3.3), and time-critical procedures are written in Assembler.

The Control Module consist of:

- measuring resistors (R), in collaboration with transducers,
- an AD7864 four-channel, simultaneous-sampling A/D converter.
- A PWM generator that uses the ADMC201 motion coprocessor,
- System Console (SC),
- the Software Identification Module of reference current parameters (SIM),
- the Software Decision Module (SDM) collaborating with the Adder (Σ), which calculates current value of the error signal; i.e., the difference of reference and compensator current.

The SIM (Figure 3), consists of three independent blocks: *software-frequency-identifier* of the reference (SFI), *software-amplitude-identifier* of the reference (SAI) and *software synchronizer* of suitable values of the reference (SSYNC).

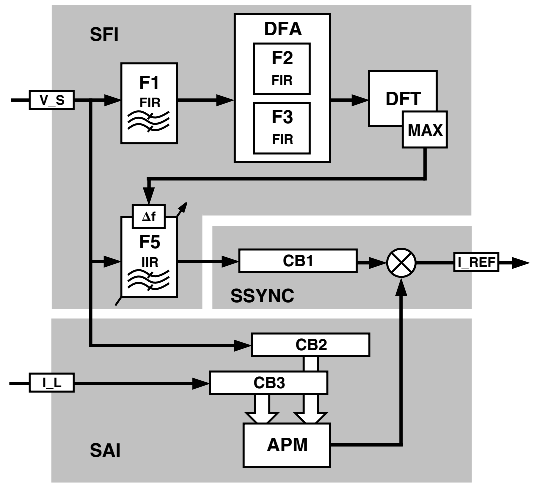


Figure 3. Software structure of Software Identification Module (SIM)

The SFI uses a mains-supply-voltage pre-filtration method, with the aid of a bandpass FIR filter (F1), to eliminate higher harmonics and increase noise immunity of the identification algorithm [14]. Next the signal is subjected to a Hilbert transformation to obtain its analytical form (complex signal in the time domain). It permits elimination of frequency products on the negative part of the frequency axis and decreases the identification time to under 12 ms. This is a short time in relation to the 20-ms (50-Hz) mains-voltage period of the present design, and would also be considerably shorter than the 16.7-ms period of 60-Hz systems [14]. The complex signal is subjected to a digital Fourier transform (DFT) to calculate its basic frequency. This is realized by the DFT and MAX blocks. Calculated in this way, the value of basic frequency serves next to control the tuned filter (F5), a high-Q, IIR-type filter. The F5 filter is in fact the reference current generator; its output signal frequency is equal to the mains-voltage frequency $u_S(t)$.

The amplitude of reference current is calculated within the SAI block, which is based on both load-voltage and load-current samples, stored within circular buffers CB2 and CB3.

A synchronization block, SSYNC, eliminates effects of different delay times, involved in calculations within the SFI and SAI blocks. Finally, the SSYNC connects suitable values of frequency and magnitude of reference current. The total time of identification and synchronization of the reference current generator (in this design) is about 18 ms.

The Decision Module is realized in the form of a 2nd order FIR filter with constant coefficients; its frequency transmittance model is given by following equation:

$$\left|T_{FK}(\Omega)\right| = \frac{1 + \cos(\Omega)}{2}$$

The basic condition of proper operation of the filter is that the system sample frequency is twice the PWM carrier frequency (in this system: 30 and 15 kHz).

The Execution Module is a power-electronics controlled current

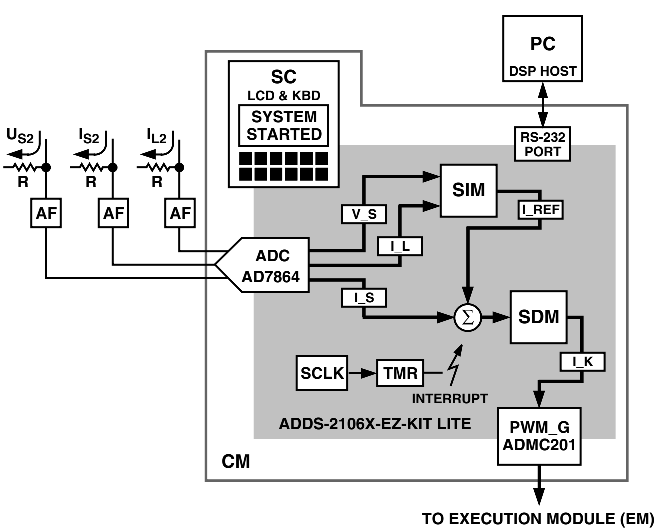


Figure 2. The hardware and software structure of Control Module (CM)

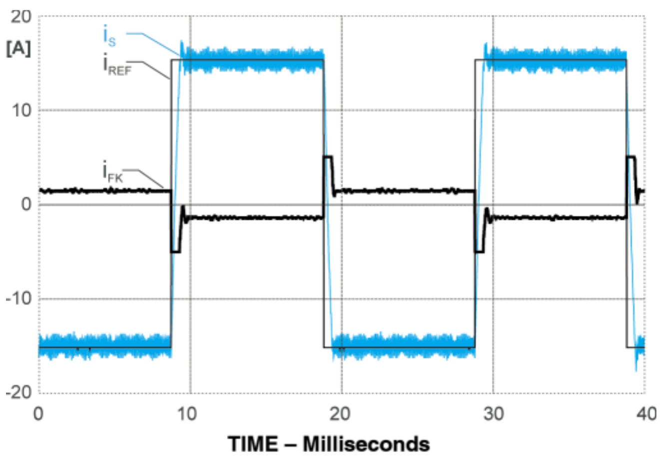
source, which uses a highly integrated Intelligent Power Module (IPM) type PM50RSA120 (Mitsubishi) and inductance coil, L_{INV}. This coil also limits parasitic products of the PWM.

The general source of energy for the current source is a capacitor within the dc circuit of the inverter (IPM). The inverter is coupled with the Control Module with the aid of fast photocouplers.

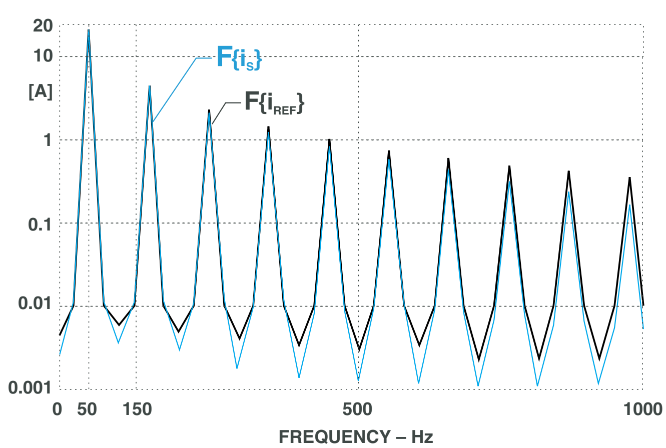
PERFORMANCE OF THE PROTOTYPE SYSTEM

Experimental tests of the above-mentioned prototype models of the power-electronic current source and single-phase active compensation system were carried out for different types of load and supply conditions. Here is a small selection of the results of the tests.

The waveforms of Figure 4 show the rectangular shape of reference signal $i_{REF}(t)$, output current of current source $i_S(t)$ and feedback signal $i_{FK}(t)$ (Figure 4a), and results of spectrum analysis of these quantities (Figure 4b). The bandwidth (–3 dB) of the current source was equal to 3.2 kHz with non-uniform amplitude characteristic 0.4 dB. The total harmonic distortion (THD) of output current within this band was 0.7%—and 0.2% within the 0.5-kHz bandwidth.



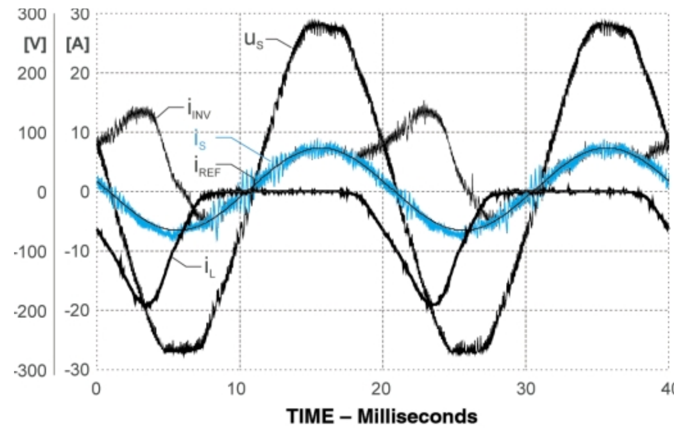
a) Waveforms of selected quantities.



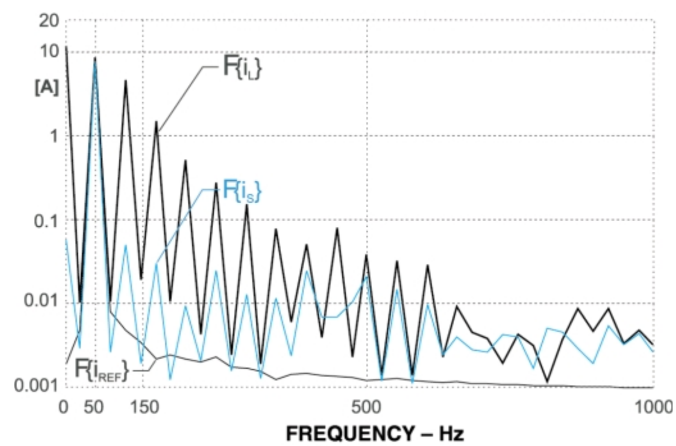
b) Spectrum analysis.

Figure 4. Investigation results of current source prototype system for the case of rectangular shape of reference signal.

Figures 5 and 6 illustrate the workings of the complete active filter. The source of the distorted current (Figure 5) is a simple single-diode rectifier with an R-L-type load (resistor and inductor in series). It is a particularly unfavorable case, because it simultaneously generates a strongly distorted current with a dc component and reactive power. The waveforms of source voltage, u_S, and currents of load, i_L, power network, i_S, active filter, i_{INV} and reference signal i_{REF}, are shown in Figure 5a—and also results of spectrum analysis of selected quantities (Figure 5b). Figure 6 shows similar quantities for an RC-loaded 4-diode-bridge, the typical configuration of most consumer-electronics power packs.

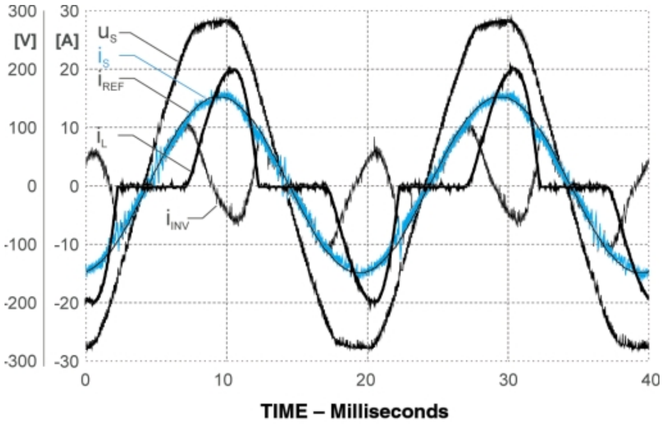


a) Waveforms of selected voltage and current quantities.

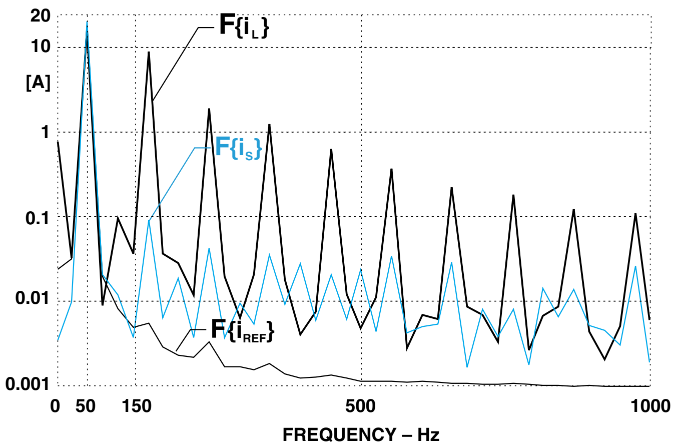


b) Spectrum analysis.

Figure 5. Investigation results of the active-filter prototype model with a strongly nonlinear passive receiver—a single-diode rectifier with an R-L (resistance and inductance in series) load.



a) Waveforms of selected voltage and current quantities.



b) Spectrum analysis.

Figure 6. Investigation results of the active-filter prototype model with an RC-loaded 4-diode bridge.

As in the case of a current source, the active compensation's system of differential current provides good mapping of the reference signal, $i_{REF}(t)$, which is calculated in the Identification Module. The power network current is in the same phase as the waveform of power network voltage (because of compensation of so-called reactive power), and its higher harmonics values are considerably reduced. The THD value of active filter input current, $i_S(t)$, was under 1%.

CONCLUSION

We have shown here a system capable of achieving optimal compensation in real time by elimination of differential current, employing an applied power-electronic controlled current source using PWM. Included are a functional block diagram and a description of the working principle of the system, which is controlled by a digital signal processor. The measured results of tests carried out on the system for a variety of loads showed that the compensator was highly effective. It greatly reduced both the nonlinear distortion of the input current (THD<1%) and the requirement for reactive power from the power source. The delay in identifying reference-signal parameters was about 12 ms (substantially less than one period of power-source frequency), with total frequency identification error of 0.1%. In general all investigations results of the prototype model show very good mapping of the reference signal by the compensator system and considerable reduction of higher harmonics of source current.

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