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Hardware in Loop Testing of Energy Measurement Integrated Circuits

Vladimir B. Ćuk[1], Aleksandar B. Nikolić, Aleksandar D. Žigić

Abstract - Hardware in loop testing of integrated circuit used for power and energy measurements is presented in the paper. System is based on a DSP board, data acquisition card (DAQ) and PC computer with a real-time mathematical model. The aim of the paper is to provide measurement accuracy verification in the laboratory conditions and to simulate different disturbances (nonlinearity, high-order harmonics, phase unbalance, voltage sag, etc.) using modeled load.
Keywords - Power quality, Measurement, Integrated circuits, Real-time, Simulation.

I. INTRODUCTION

In modern electrical networks, voltages and especially currents are often nonsinusoidal. The number of components capable of producing considerable harmonic distortion is very high and is increasing rapidly. It is very likely that the waveform distortion will continue to grow in the years to come.

Power quality problems that cause those irregularities affect power and energy measurement sometimes as well. Not all power and energy meters can measure correctly in these conditions, although they have a specified measurement precision [1], [2].

Some studies about power measurement accuracy in nonsinusoidal conditions have been done earlier [3]-[5]. The results were acceptable in most cases for commercial devices, but errors in measurement were found when the input signals had variable frequency, high crest factor or high harmonic content with quickly altering values.

That was the reason for developing the system proposed in the paper. The main requirement for this system was the ability to simulate various irregular network conditions with the "phantom load" technique: nonlinearities, high-order harmonics, phase unbalance, voltage sags, etc., which are difficult to provide in the laboratory and require very expensive equipment. The biggest advantage of the proposed system is its relatively low price. Generated signals have low levels (in this case -0.5÷0.5V, but they can easily be shifted to -5÷5V range) so they can be applied to the measurement IC directly. Current signals are simulated as voltage signals, for the same reason. Because of this, the system can't be used for calibrating whole measurement systems, but it can test the accuracy of their core (the power measurement IC).

II. BASIC EXPERIMENTAL SETUP

Initial experimental setup is formed based on a proven energy measurement IC. These chips are today very cheap, but on the other side they give a lot of possibilities for developing sophisticated measurement systems and have enough precision for billing applications. During development phase, an experiment is performed in which the Analog Devices ADE 7754 energy measurement IC is tested [6]. The same apparatus can later be used for testing similar IC's, with possible changes of signal levels and communication between the DSP board and IC.

A. *Hardware used in the model*

The whole experiment is schematically shown in Fig. 1. DSP board used for this development system is Texas Instruments TMS320F2812 eZdsp. This particular DSP board is used because of the existence of a targeted toolbox in Matlab for this board [7] and the necessary SPI communication that is needed to access the observed integrated circuit.

The DSP board generates simulated signals, acquires measurement data from the IC (by SPI communication) and sends measurement data to the host PC (by RTDX communication).

Voltage and current signals are outputted from the DSP board thru digital outputs (30 GPO's), and sent to D/A converters. Two Burr-Brown DAC 7624, 12-bit, 4 channel D/A converters are used to generate analog signals. Each of the A/D converters uses 3 of their channels. One of them is used to generate voltage signals, and the other one generates current signals.

Signals from the D/A converters are then sent to LP filters (passive, RC filters are used), and proceeded to the current and voltage inputs of the measurement IC. In this case, the ADE 7754 energy measurement IC is used, but in the future, some other power and energy measurement IC's are planed as well.

[1] Electrical engineering institute "Nikola Tesla",
Koste Glavinića 8a, 11000 Belgrade, Serbia,
e-mail: vcuk@ieent.org, anikolic@ieent.org, azigic@ieent.org

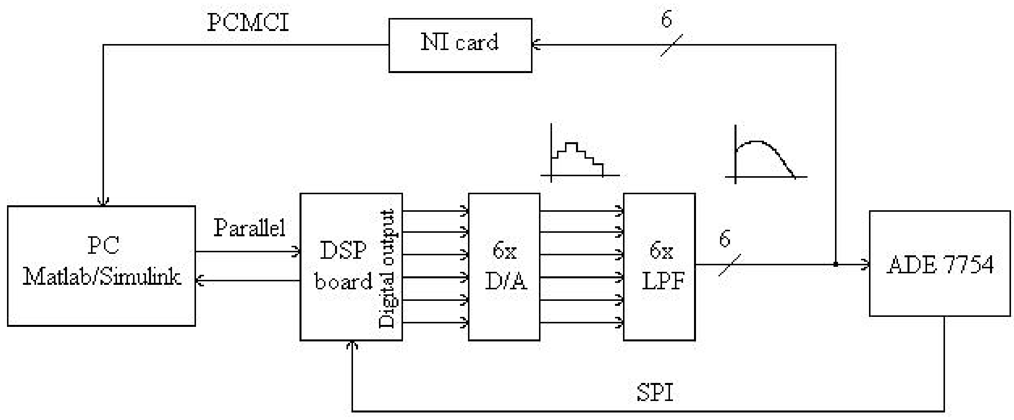

Fig. 1. Block diagram of the experimental setup

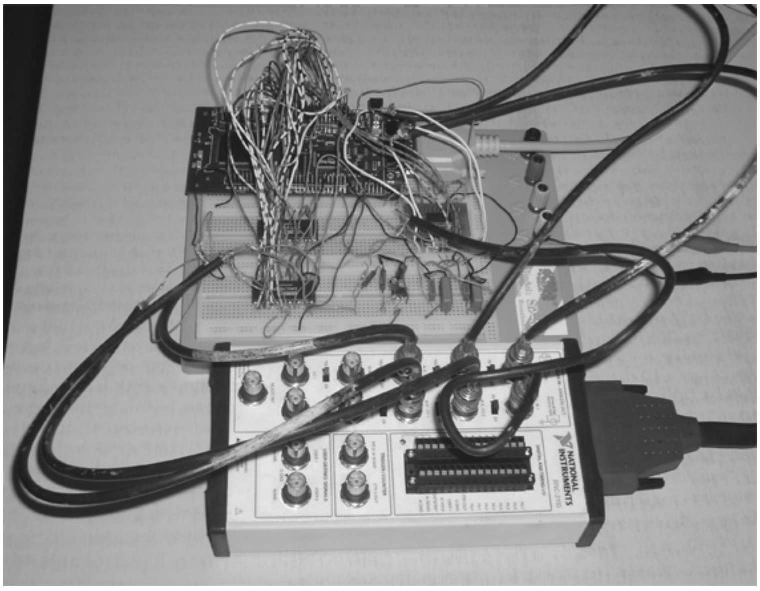

Fig. 2. Hardware for the development system

Simulated signals are not as big as the ones in real networks, but they are sent to the IC without conditioning, so they are in the same range as conditioned signals measured by a real measurement system.

The DAQ board used is National Instruments DAQ 6062E. This board measures voltage and current signals from the LP filters and sends them to the computer. Host PC calculates reference powers from these signals. The host PC is also used to program the DSP board (thru parallel port).

Fig. 2. is a photography of the whole system.

B. *Software used for the development system*

One part of a desired electrical network is simulated with developed Matlab/Simulink real-time model [7], that has adjustable parameters such as RMS values of various harmonics of voltages and currents and their phase stands. In such a way nonlinearities could be simulated. All of these parameters can be time dependent, so all of the expected disturbances in a network could be simulated, too.

From the model, voltage and current signals are forwarded to the Texas Instruments F2812 DSP board that can be accessed directly from Matlab/Simulink with a corresponding toolbox [8].

The code for this experiment is divided into three parts. The first program – the host side of the model, executes on the PC, and its job is to acquire data from the DSP board and the data acquisition (DAQ) board and to calculate the measurement error.

Active and reactive powers are not read from the IC directly. ADE 7754 stores these values in a 54-bit nonreadable register, so they have to be calculated from active and apparent energy. The DSP board reads values of active and apparent energy in turns from the IC and sends them to the host PC by RTDX communication. The host program accepts these values from RTDX and calculates rates of active and reactive energy flow, which represent active and reactive power measured by the IC.

On the other hand, the same program acquires instantaneous values of voltages and currents measured by the DAQ board and calculates active and reactive powers. Algorithms for power calculation found in SimPowerSystems toolbox are used for power calculation.

The error signals for active and reactive power are then calculated by subtracting reference powers (powers calculated with DAQ board measurements) from the powers measured with the IC.

The second program – the target side of the model, executes on the DSP board. This programs job is to generate simulated signals, send them to D/A converters by general-purpose outputs (GPO's), calibrate the IC, acquire data from the IC and send it to the host by the RTDX channel.

A part of this program used for signal generation works as an arbitrary waveform generator because generating 6 complicated and independent functions at once would use too much processing power.

Pre-generated waveform signals are loaded into memory and loop continuously (they can be sent once as well). They are converted into 16-bit unsigned integer numbers because the GPO uses this format. After that, they are scaled down to numbers that use only 12 bits (12 bit D/A converters are used) and sent to 12 GPO's. At the same time, one counter with 4 different states is used to determine which channel is loaded (D/A converters have 4 channels, of which 3 are used on each), the channels address, and weather latching or sending data is happening. This takes 3 additional GPO's per channel, and overall 30 GPO's are used for all 6 signals.

The SPI communication supported by the target toolbox in Simulink isn't suitable for reading ADE 7754 registers. Simulink's algorithm for SPI communication doesn't have much programmability, and on the other hand the ADE 7754 requires at least 4 μs between read and write operations with the chip select (CS) signal on the low level. This gap couldn't be filled using just Simulink. Because of that, the SPI communication part of the program had to be changed in Code Composer Studio (CCS), after the code was generated in Matlab. A part of the program that writes data in some ADE 7754 registers was also added in CCS (configuring and calibrating the IC).

Configuration of the IC's measurement is done by setting the OPMODE (Operational Mode), MMODE (Measurement Mode), WATMODE (Active Power Calculation Formula) and VAMODE (Apparent Power Calculation Formula) registers, according to [6]. These registers are responsible for setting the IC in normal mode (with all of the A/D converters, LP filters and HP filters activated), choosing the line for period measurement, and choosing formulas for active and apparent power calculation (the last two settings are made corresponding to a 4 wire star (Y) meter form.

Calibration and configuring of the chip is needed after every reset. Calibration parameters are derived from an experiment with pure sinusoidal voltage and current signals and without phase unbalance or time changes, according to [9]. Two sets of undistorted signals were used, with different power factors. In the first set, the power factor was 1, and in the second set, the power factor was 0.5.

Values of these undistorted signals applied to the IC's inputs are measured by the DAQ board as well, and readings of measurement registers are used to calculate the values of the calibration registers. The ADE 7754 has several calibration registers: GAIN (used for current and voltage gain setting), AWG, BWG and CWG (used for setting active power gain in each of the phases), AVAG, BVAG and CVAG (used for setting apparent power gain in each of the phases), APHCAL, BPHCAL and CPHCAL (used for phase calibration), AAPOS, BAPOS and CAPOS (used for power offset calibration), WDIV (sets the active energy divider) and VADIV (sets the apparent energy divider).

After the calibration, the program starts reading two registers in turns. The first of these two registers is RAENERGY. Active power is accumulated over time and stored in this 24-bit register (and some other registers as well). After a read operation, this register is reset to 0. Because of that, the average active power between two reads is equal to the contents of the RAENERGY register divided by the time between two consecutive reads. The second register being read continuously is RVAENERGY. This register is very similar to the RAENERGY. The only difference between these two registers is that the RVAENERGY accumulates apparent power over time instead of active power. The average apparent power between two register reads is calculated the same way as the average active power.

The third program needed to conduct this experiment is not executed in real time. This program is a Simulink model used to generate voltage and current waveforms loaded in the arbitrary waveform generators (in the target side program). Simulink offers a wide range of simulation models. Waveforms can be generated using mathematical functions, with all of their parameters configured. Another way to generate signals is to make a real world model using the SimPowerSystems toolbox. This toolbox has pre built models of power system elements, power electronic devices and electrical drives. This is very convenient for simulating real world situations expected in every system. Further development of this system will include these pre built models for signal generation.

III. RESULTS AND DISCUSSION

One set of generated voltage and current signals is presented in Fig. 3 and Fig. 4, respectively. They are generated as sums of harmonic components, and recorded by the DAQ board. Harmonic distortions of current signals are bigger than voltage distortions. Also, the current signals form an unbalanced system. THD factors and phase stands of first order harmonics for all 6 signals are presented in Table 1.

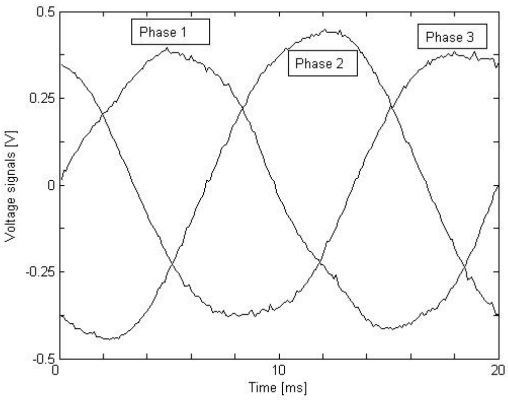

Fig. 3. Generated voltage signals

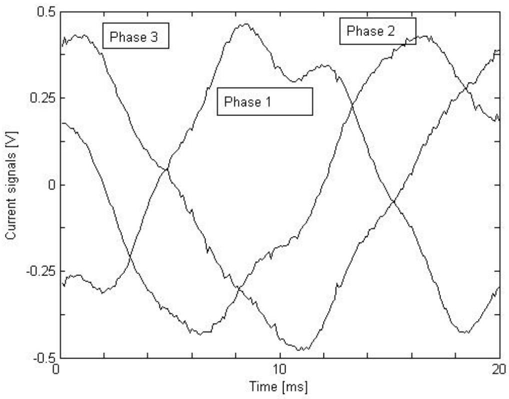

Fig. 4. Generated current signals

Table 1

Signal name	THD [%]	Phase stand, first order harmonic [°]
Voltage 1	6.2	0
Voltage 2	6.4	120
Voltage 3	3.8	240
Current 1	18.1	44
Current 2	13.3	161
Current 3	15.3	285

Fig. 5 presents active and reactive power measured by Simulink (from waveforms recorded by the DAQ board).

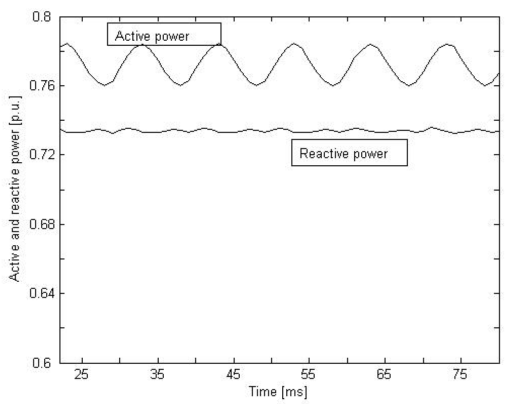

Fig. 5. Power measured by the DAQ board

Fig. 6 presents active and reactive power measured by the ADE 7754.

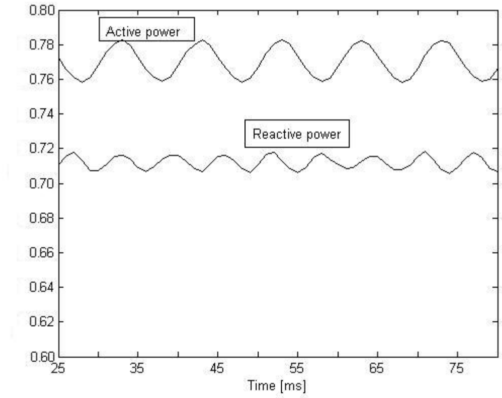

Fig. 6. Power measured by the ADE 7754 board

As mentioned earlier, those are actually powers calculated in Simulink from the active and apparent energy measured by the ADE 7754, and time.
As expected, the active power measurements had less differences then reactive power measurements. According to [6] and [7], Simulink and ADE 7754 use the same technique to calculate total active power.
On the other hand, reactive power calculation differed in these two cases. ADE 7754 is meant to be used for active and apparent power calculated, and reactive power measurement is left as an estimation option. That is way this IC can estimate reactive power only with the formula:

$$Q = sign(Q) \cdot \left(S^2 - P^2\right)^{1/2} \qquad (1)$$

Formula (1) calculates reactive power accurately only if no higher order harmonics are present in the network. In this case, the average error in reactive power measurement was 3.67%, while the average error in active power measurement was 0.2% (measurements were not conducted with full scale signals).

IV. CONCLUSIONS

The only final conclusion in the analysis of this IC's measurement is that it measures active power correctly in the presence of high order harmonics.
Errors from reactive power measurement were large, but this IC is not meant to be used for reactive power measurement anyway, as it is clearly indicated in [6]. Its reactive power estimation is meant only as an option.
The final goal of the project presented in the paper is developing of a universal apparatus for testing power and energy measurement integrated circuits. This device should have more lines of communication (for different types of IC`s). To realize complex and different situations that could be occurred in a real power network, a mathematical model with an adjustable measurement input is developed. This model

is simulated using real-time simulation with data acquisition card and DSP board as a part of simulation model (Hardware-in-Loop simulation). Such approach gives opportunity to test different power measurement circuits under circumstances that could not be achieved in laboratory or could be very expensive if performed in a real world.

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