Design of a Bidirectional Electrical Energy Measurement System for Applications in Distributed Generation

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***Abstract*—This work focuses on the development of a bi-directional electrical energy measurement system under a distributed generation (DG) scheme. The measurement system consists of an IC ADE9000 for the measurement of high-precision multi-phase electrical energy, circuits and sensors for voltage and current conditioning, an Arduino Due as a control unit and an Ethernet module ENC28j60 for IP connection. The measurement system includes a data management scheme based on a web platform contained in a server where measurement queries can be performed as well as user administration through a database.**

***Index Terms*—distributed generation, smart metering, hardware development**

I. Introduction

One of the main challenges facing the energy sector is to meet the demand for energy by ensuring continuity in its supply due to the strong growth in recent years. Based on this, the energy policy has a strategic vision to meet the energy needs of the population and all productive sectors so that for this scenario the implementation of other forms of renewable energy represents an alternative with extensive potential to reduce total dependence on hydroelectric sources. The growing share of electricity from photovoltaic and wind sources has led to greater interest in them [1], [4].

Currently the way energy is produced and consumed is not sustainable The generation sources with the greatest weight in the matrices are fossil fuels (oil, coal and gas), the main sources of energy are contributors to climate change. In view of this situation, the incorporation of new clean and renewable energy sources arises [5].

There is a new approach to the generation and distribution of electrical energy that contemplates the use of small units of energy conversion, which produce electricity from renewable sources and operate connected to the distribution network, called Distributed Generation (DG) [5], [6]. This new DG approach gives rise to a new concept called net balance, which allows users to import the energy produced by their autogeneration system into the electricity grid. In this scheme the smart metering system is an essential component because it allows the measurement of the energy exported and imported into the network, the calculation of its net value and remote access to data to manage energy consumption. [7].

In the present work, a data manager is in charge of supervising the monitoring of an electrical network based on distributed generation, it is estimated that intelligent meters are becoming great industry standards, and implementations are growing exponentially all over the world.

The smart meters have an encrypted data technology that makes it more robust , in addition to standing out in other areas such as speed, control, and security of data obtained.

II. Distributed Generation Issues

A. Generation and Distribution of Electrical Energy

The monitoring system includes all means and elements for the generation, transport and distribution of electricity, as well as control, safety and protection mechanisms, as can be seen in the Fig. 1. The energy sources for them are typically combustion (petroleum, coal or natural), nuclear or hydraulic. Generally centralized stations are located in areas far away from the load centers which implies transmission over long distances causing inefficiency and energy losses.

DG also known as decentralized generation is an approach that employs technology with small electrical power conversion units close to end users that can operate independently or connected to the electrical distribution system [6]. DG technologies often consist of modular generators, and offer a number of potential benefits such as providing low-cost

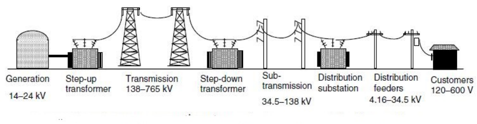

Fig. 1. Transmission and Distribution of Electrical Energy

electricity, high reliability and safety with fewer environmental consequences than traditional power generators [3].

Unlike centralized generation stations as seen in Fig. 2, located in areas distant from load centres, the approach used in the GD system is based on small plants and can provide energy with little dependence on the distribution and transmission network, considerably reducing energy losses. [8].

B. Net Balance

The Net Balance (NB) or Net Electricity measurement is a general utility scheme for the use and payment of the resource in which a customer who generates his own electricity can compensate the energy balances instantaneously or deferred, allowing consumers the individual production of energy for their own consumption, making their production curve compatible with their demand curve.

In the Fig. 3 indicates a residential customer who owns a photovoltaic generator, and allows the excess produced by the self-consumption system to be imported into the electricity grid in order to be able to make use of that excess at another time. In this way, the electricity company provides electricity when the demand is higher than the production of the self-consumption system, discounting the consumption of the network from the bill, the excesses poured into it.

C. Types of Electric Meters

- **Electromechanical-based meter:** The most common type of energy meter is the electromechanical induction

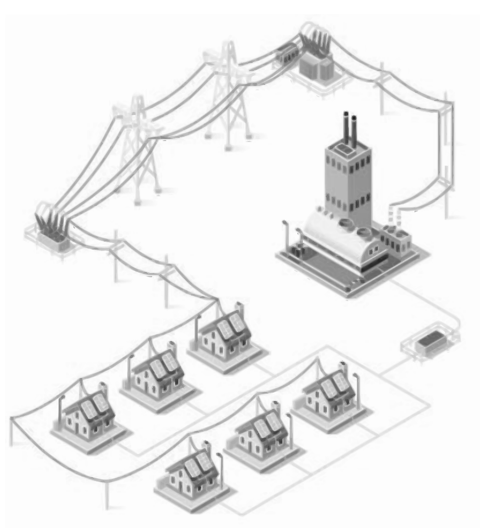

Fig. 2. Decentralized Generation System

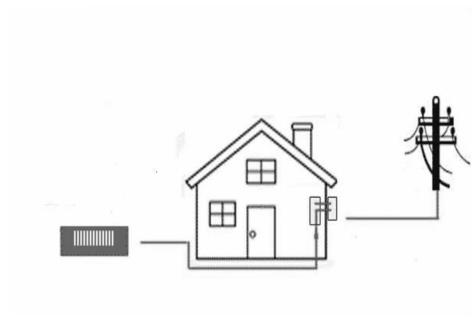

Fig. 3. Net Electricity Measurement System

watt-hour meter. This meter operates by counting the revolutions of a non-magnetic but electrically conductive disk, which is made to spin at a speed proportional to the power passing through the meter. The number of revolutions is therefore proportional to the energy used where the disk is driven by two coils. One coil is connected in such a way that it produces a magnetic flux proportional to the voltage and the other produces a flux that is proportional to the current. This produces a Foucault current in the disk and the effect is such that the force exerted on the disk is proportional to the product of the voltage, the current and the angle between them [9].
- **Electronic-based meter:** Electronic meters use solid state components to carry out power and energy measurement. They digitize the voltage and current signals and use them to calculate the magnitudes to be measured. They display the energy consumed on an LCD or LED display, and some can also transmit the readings to remote locations. In addition to measuring the energy consumed, electronic meters can also record other load and source parameters such as the users' instantaneous and maximum demand rate, voltage, power factor and reactive power used, etc. They can also support billing according to time of day. For example, recording the energy consumed during peak and non-peak hours [9].
- **Smart Meter:** An intelligent metering device, like the one seen in Fig. 4, is a type of advanced meter (electric, water or gas meter) that calculates consumption in a more detailed way than conventional meters. These devices also offer the possibility of communicating this information through some communication network to a control center of the local utility company, which can use the data for billing or tracking purposes. Also some have the ability to interrupt supply in the event that payment for the service has not been made [10].

  An intelligent meter works by communicating directly with your energy provider, so the company will always have an accurate meter reading without having to go to the site to obtain the state of consumption including the use of mobile type wireless technology to send data.

Fig. 4. Intelligent Metering Device

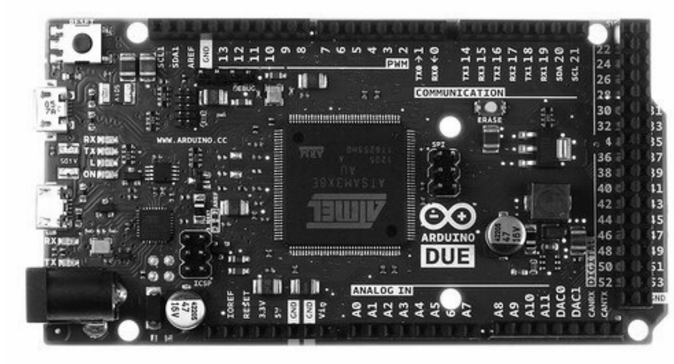

Fig. 6. Microcontrolador Arduino DUE

These types of meters offer many advantages over others such as more accurate billing, better monitoring and management of energy consumption with a real-time database and the ability to use the information collected for network planning and fraud control [11].

III. Proposed Smart Meter: Hardware design

The prototype design was divided into functional work blocks. Initially, the appropriate integrated circuit for the measurement of electrical energy is defined.

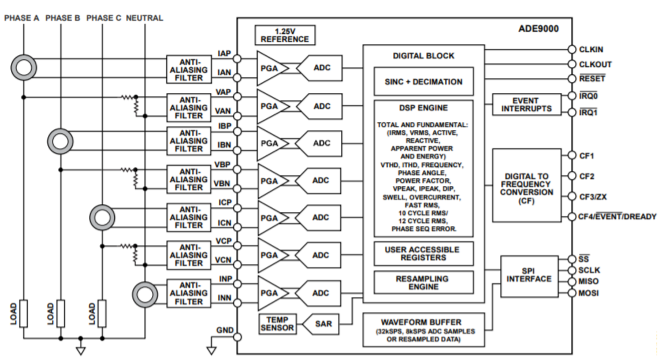

Fig. 5. Block Diagrams, CI ADE9000

The ADE9000 is an Integrated Circuit (IC) for high-precision multi-phase electrical energy measurement with a serial interface and pulse output. The ADE9000 incorporates a second order Analog-to-Digital Coverter (ADC) sigma delta, reference circuit, temperature sensor, and all the signal processing required to perform the measurement of active, reactive, apparent, harmonic distortion, power factor, and rms value calculation. Fig. 5 shows the block diagram of the CI - ADE9000.

Once the integrated circuit has been determined, the appropriate microcontroller is defined for the control unit and the Ethernet connection module for communication via the IP protocol.

The Arduino DUE [12] is an electronic board based on the Atmel SAM3X8E ARM Cortex-M3 CPU. It is the first Arduino board based on a 32-bit ARM core microcontroller. It has 54 digital input/output pins (of which 12 can be used as PWM outputs), 12 analog inputs, 4 UARTs (hardware serial ports), an 84 MHz clock, a USB OTG compatible connection, 2 DAC (digital to analog), 2 TWI, a power connector, an SPI header, a JTAG header, and a reset button.

The module Ethernet ENC28J60 [13]allows the Arduino to be connected to an Ethernet network at a speed of 50 Mbps. It is assembled with long DIP headers. The module is based on the ENC28J60 Ethernet chip which provides a network (IP) stack capable of supporting TCP and UDP.

Finally, the voltage conditioning sensors and circuits are defined as current required. For the voltage channels was selected a circuit that was suitable to have a full scale output of ± 1 V, as it provides total isolation between the high voltage circuit and the digital components of the power meter. Fig. 7 shows the block diagram of the signal conditioning circuit.

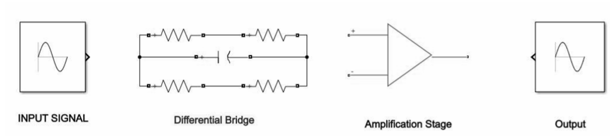

Fig. 7. Block Diagram of Signal Conditioning Circuit.

For the current channels a Current Transformer (CT) has been selected as the input sensor, because the ADE9000 has current channels with differential input, which means that very elaborate signal conditioning circuits are not necessary for the connection of the transformer.In addition the CTs have a wide dynamic range, which allows a linear excursion between full scale and 10% of the full scale of the transformer.

A. Hardware diagram

The system is represented by a diagram consisting of four main blocks, the sensors and conditioning circuits, the ADE9000 circuit, the data processor and the display and connection circuit, which indicate the various modules developed. As shown in the Fig. 8.

- **Sensors and Conditioning Circuits (Signal Conditioning Plate):** The modular plate containing the conditioning circuits for the voltage and current channels mentioned above, as well as the power supply for the system. The conditioned signals as well as the power supply are transmitted via a 17x2-pin multi-filament flat cable to the ADE9000 measurement board or circuit.
- **ADE9000 circuit (Measuring plate):**The measuring plate containing the ADE9000 receives the conditioned signals for the voltage and current channels as its supply from the signal conditioning plate. The voltage and current signals from the signal conditioning board are filtered using the anti-aliasing filter mounted on the board before being presented to the analog inputs of the ADE9000. The ADE9000 has several registers that it uses for calibration and data storage. These registers can be accessed thanks to the SPI serial port.
- **Data Processing (Control Unit):** The Control Unit of the meter is made up of the Arduino DUE development board, which is in charge of obtaining data from the ADE9000 through the SPI port, processing it and making it available for viewing. [14]. In addition, the microcontroller is in charge of handling requests that enter the Ethernet port of the ENC28j60 module, which is in turn controlled through the SPI port and the execution of the HTTP client in such a way that it is possible to upload data to the web server.
- **Display circuit and Ethernet connection:** The circuit contains the Ethernet module ENC28j60 which provides connection via IP protocol and a 16x2 LCD monitor, used for displaying measurements locally. You can see the prototype made in the **Fig. 9**.

IV. Software Design

The prototype consists of two distinct areas. The first area is Management, which is responsible for capturing data, storing them and providing a multi-user monitoring interface. The second is the Measurement area (MEASUREMENT), in charge of making the measurements, processing them and transmitting them to the management block by means of an Ethernet protocol.

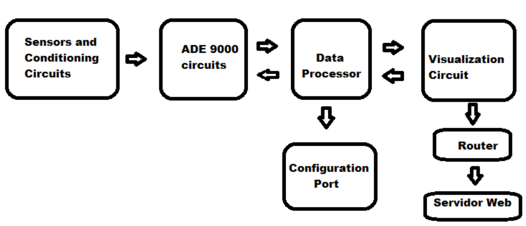

Fig. 8. Hardware Block Diagram

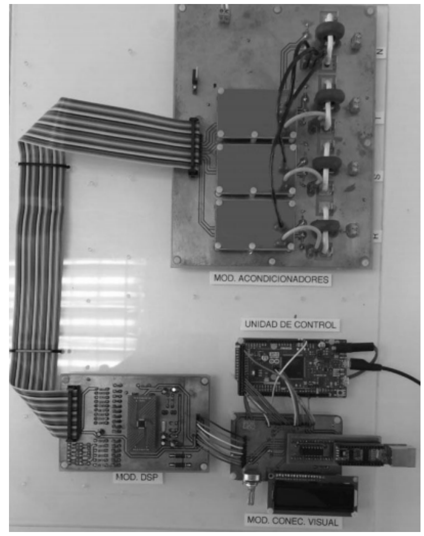

Fig. 9. Prototype Implemented.

A. *Measuring area software (MEASUREMENT)*

The Measurement area software, specifically the control unit, was developed using the Arduino IDE software. [12] with a modular scheme for each of the tasks. The control unit program consists of three distinct blocks; the Metering block, the HTTP Client block and the Local Interface block. Each of these blocks is described below.

- **Local interface:** The most important component of the Local Interface block is an existing display window in the Arduino IDE software, which allows the user to interact with the meter locally via serial communication using the USB port. The network configuration data can be displayed first, then the various measurement values and finally if the HTTP client frame has been sent correctly.
- **Measuring block:** The functions of the Measurement Block are to access the configuration registers of the ADE9000 in order to carry out the configuration before each reading, to write previously calculated values in the configuration registers and to read the obtained measurements.
- **HTTP Client:** This is the program block that allows the development board to establish a remote connection through an IP network. It is based on the HTTP protocol (Hypertext Transfer Protocol), which is a protocol of the application layer of the TCP/IP network stack. The development card, Arduino Due, is able to connect to the Internet and function as a client or server of a wide variety of protocols using the Ethernet module ENC28j60 described above, through the UIPEthernet library. For this specific case, the meter will be an HTTP Client, which will be in charge of transmitting from an http request of the GET type that contains the measurements to the local server, which will later translate it and load the

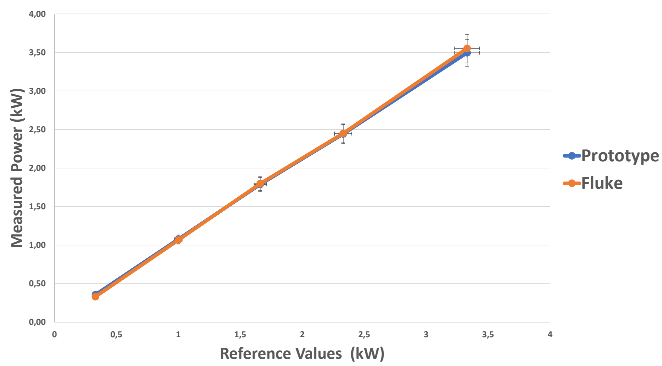

Fig. 10. Measurement result with resistive load for the active power.

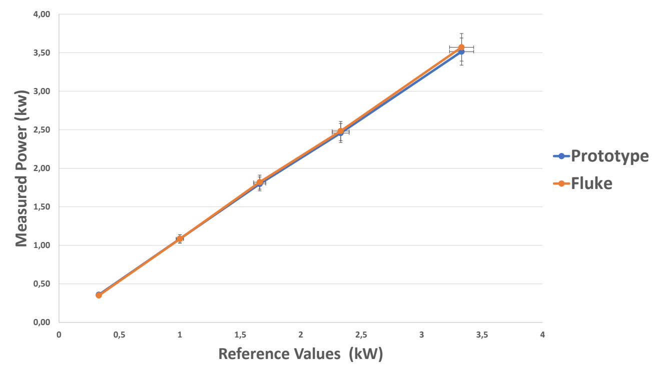

Fig. 11. Measurement result with resistive load for apparent power.

data to the Database.

B. Management area software

The software of the Management area that will manage the local server was developed using the languages MySQL, HTML, JavaScript, CSS3 and PHP. As local server was used the software WAMPSERVER, which contains: MySQL or MariaDB, PHP and Apache.

V. Experimental Results

The efficiency analysis of the meter consisted in taking samples for different power values for two types of load; resistive and inductive. These values were then subjected to statistical analysis to find their dispersion, grouping and relative error using as a reference the values measured with the power quality meter *Fluke* 435. The simulation of the resistive load was achieved through a variable load bank designed specifically for this purpose, and the inductive load through a three-phase motor of 0.6 HP.

A. Performance analysis with a resistive load

In the Fig. 10 and 11 the results obtained in the measurements with the resistive load are shown, for the active and apparent power respectively. In the graphs it is seen how the curves corresponding to the active and apparent powers, obtained with the prototype, are superimposed with the reference curves measured with the meter *Fluke*.

The results of the measurements with resistive load for the power factor are shown in the Fig. 12 with values ranging from 0.98 to 1.00.

In the Fig. 13 you have the variations of the relative error for each variable measured with respect to the meter*Fluke*.

If the maximum error for class II instruments is taken into account, it can be concluded that relative errors not exceeding 3 % were obtained with the resistive load, which complies with the requirements of the standard. This may be due to the characteristics of the equipment used to simulate the resistive load and the nature of the load, which presents fixed magnitudes in a stable state and a low generation of harmonics.

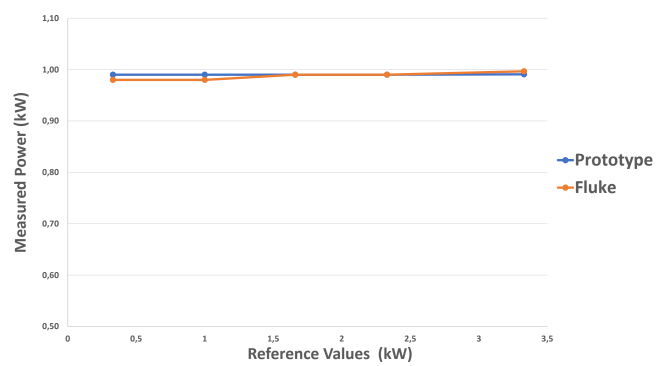

Fig. 12. Measurement result with resistive load for the power factor.

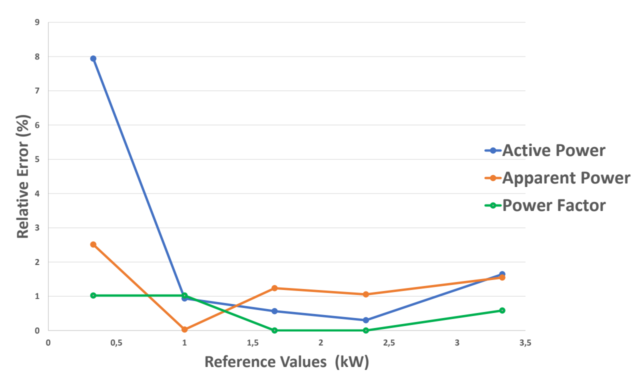

Fig. 13. Proportionate values obtained for the relative error.

B. Performance analysis with inductive load

In the Fig. 14 the results are observed for the active, reactive, apparent and power factor powers obtained with the inductive load. It is possible to appreciate the low active power developed by the load.

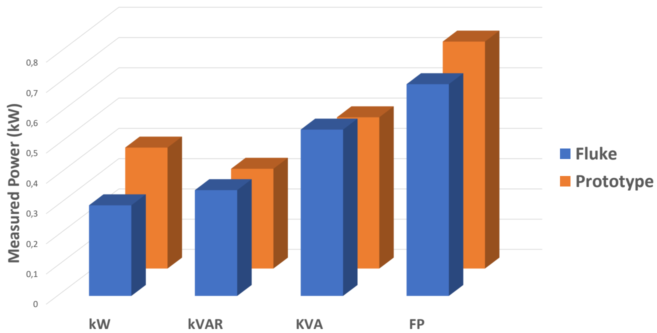

Fig. 14. Measurement results with inductive load for active, reactive, apparent and power factor.

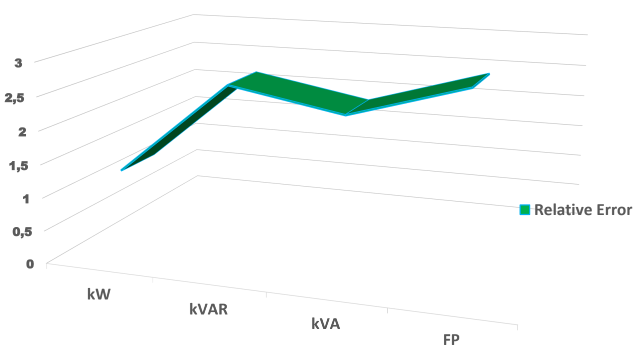

Fig. 15. Measurement results with inductive load for relative errors.

The values of the relative error for the measured variables are shown in the Fig. 15.

Inductive load measurements were performed without applying mechanical load to the motor that was used to simulate the load. If we take into account the maximum error for class II instruments, it can be concluded that with the inductive load results were obtained with relative errors not exceeding 3 %, which meets the requirements of the standard.

VI. Conclusion

A prototype of a bi-directional electric power measurement system for distributed generation applications was developed with the appropriate hardware and software, allowing access to measurement data locally and remotely through a user interface and administrators contained in a server. In addition to implementing a database containing user data and magnitudes obtained, with results approved from NTC 2288 and 2148 for class II instruments.

It is recommended as future research work to increase the performance of the prototype by acquiring a device for wireless transmission of higher generation and lower latency.

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