REAL-TIME EVALUATION PERFORMANCE OF SOLAR POWER GRID-TIE INVERTERS

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ABSTRACT

Recently photovoltaic (PV) applications, as a source of electrical energy, have progressively increased in terms of generation capacity and in the sense of its spread over large areas around the world. In Mexico, the Electrical Research Institute has developed a 1 kW capacity single-phase inverter. These types of power electronic devices require continuous monitoring of their performance. This work presents a control and measurement digital system to evaluate the solar power grid-tie inverter performance. A software application, based on virtual instrumentation, was developed to monitor the main input and output electrical variables of the inverter in real time. These variables are processed to obtain: DC power input, AC power output, power factor and line harmonics; as well as peak efficiency, peak power tracking voltage, total electrical energy delivered and maximum nocturnal current consumption. The main functions of the system are: electrical signals acquisition, electrical variable calculation, tendency graphical displaying and signals and variable calculations recording in files. This system is able to connect to internet using the TCP / IP protocol, which displays information into a web page. The user can have access from Smartphones and/or personal computers from anywhere in the world.

Keywords: data acquisition, grid connection, inverters performance, PV inverters

EVALUACIÓN EN TIEMPO-REAL DEL DESEMPEÑO DE INVERSORES FOTOVOLTAICOS INTERCONECTADOS A LA RED ELÉCTRICA

RESUMEN

Recientemente las aplicaciones fotovoltaicas, como fuente de energía eléctrica, han incrementado progresivamente en términos de capacidad de generación y de su propagación en grandes áreas de todo el mundo. En México, el Instituto de Investigaciones Eléctricas ha desarrollado un inversor monofásico de 1 kW de capacidad. Estos tipos de equipos de electrónica de potencia requieren de monitoreo continuo de su desempeño. Este trabajo presenta un sistema digital de medición y control para evaluar el desempeño de inversores fotovoltaicos conectados a la red eléctrica. Se desarrolló una aplicación de software basada en instrumentación virtual para monitorear en tiempo real las principales variables eléctricas de entrada y salida del inversor. Estas variables son procesadas para obtener: potencia de entrada en CD, potencia de salida en CA, factor de potencia y contenido armónico; así como la eficiencia máxima, voltaje de operación, energía total entregada y corriente máxima de consumo en las noches. Las funciones principales del sistema son: adquisición de señales eléctricas, cálculo de variables eléctricas, despliegue gráfico de tendencias, almacenamiento de señales y variables calculadas. Este sistema es capaz de conectarse a internet usando el protocolo TCP/IP, el cual despliega información en una página web. El usuario puede acceder desde su dispositivo móvil y/o computadora personal desde cualquier lugar en el mundo.

Palabras clave: adquisición de datos, conexión a red, desempeño de inversores, inversores fotovoltaicos

INTRODUCTION

PV technology today has become a major actor in the electricity sector globally (IEA 2013). The most common applications of photovoltaic power generation are: small isolated systems based on PV panels in combination with the use of backup storage batteries, and grid-connected PV systems that use the available energy from the sun to deliver it to the grid. All energy captured by the panels is converted from DC voltage to AC voltage at the grid frequency. This energy is consumed by the user and the surplus is used by other users connected to the grid of the local electrical utility.

This new energy source is environmentally clean and has been demonstrated that meets required standards for the traditional generation based on non-renewable sources. Additionally, it allows delivering electrical power to big range of applications, geographical localizations and weather.

Preliminary market data reported shows a roughly stable PV market in 2012, compared to 2011. At least 28.4 GW of PV systems have been installed in the world last year. In America, preliminary data for Canada shows the installation of 268 MW while the appetite for PV in Latin and Central America hasn't transformed into a real market yet. Several GW of PV plants have been validated in Chile, but except in Peru with some 50 MW and Mexico with 15 MW, the real PV development of grid-connected PV plants hasn't started yet in the region IEA (2013).

Photovoltaic inverter that is in charge of electric power conversion is a critical component used in solar photovoltaic power systems. Many concerns are focused on the operation of photovoltaic inverter due to the wrong designing which may cause terrible consequences on safety, performance and grid interconnection characteristics of solar photovoltaic power systems (YU-JEN LIU *et al.*, 2014)

Grid-connected PV systems are a challenge in maintaining correct operability due to the power conversion complexity from DC to AC, variations of solar radiation along the day, electrical grid voltage, frequency variations and the autonomous operation requirements for the power inverter to synchronize it with the grid tracking the PV maximum power point in accordance with the solar radiation. Additionally it is required to deliver the energy at maximum efficiency and low harmonic distortion (BOWER *et al.*, 2004)

Inverter interfacing PV module(s) with the grid involves two major tasks. One is to ensure that the PV module(s) is operated at the maximum power point (MPP). The other is to inject a sinusoidal current into the grid (KJAER *et al.*, 2005). The quantification of the real energy delivered to the grid is left to the electrical company that utilizes the power-metering infrastructure installed at the users' homes.

This paper presents a digital system for data acquisition and evaluation of photovoltaic inverters. An application based on virtual instrumentation in LabView® was developed to measure the input and output of electrical variables. The application measures the DC voltage and current from the photovoltaic panels array and the AC voltage and current at the inverter output. Additionally, measurements are performed to complement the test, such as short circuit current of photovoltaic panel to calibrate the solar radiation measurement, ambient temperature and inverter temperature. The electrical variables are processed to obtain: DC power input, AC power output, power factor, line harmonics and conversion efficiency. The functions that measurement system performs in real time are graphical display, data logging, the RMS average calculation for voltages and currents. The data logging function allows configuring trigger events, capturing and recording voltage dips, grid disconnections, solar panels disconnections and overvoltage. The communication protocol based on TCP/IP allows an online remote monitoring via web.

MONITORING SYSTEM ARCHITECTURE

The system configuration is based on a) a real time data acquisition module of National Instruments company (NI) and b) the monitoring software that contains the processing functions and displays information for the users.

a) Data acquisition module. This module is integrated by a real time controller (Compact-RIO 9024) with 800 Mhz processor, 512Mb memory RAM and capability storage of 4 Gb; a chassis FPGA (Field Programmable Gate Array) of 4 slots with five millions of reprogrammable gates (NI-9018), two analog inputs cards (NI-9215) with 4 input channels and a read temperature card (NI-9211) with 4 channels. The software can be monitoring 5 analog channels simultaneously with 50,000 samples per second and with 16 bits of resolution from analog-digital converter. The analog channels operate in range of ± 10 V. Commercial sensors have been used to acquire voltage and current signals, with a 10:1 V gain for the voltage signals (to 1000V) and 100 mV:1 A gain for current signals (to 10 A). The sampling frequency for the temperature is 1 ms and has been used thermocouples sensors with operation range from -50º to 250 ºC.

b) Monitoring software. It is the system graphical interface, through which the user can monitor the photovoltaic inverter tendency. The monitoring software was developed in the LABVIEW 2010 programming language and has been installed into Real-Time operative system into compact-RIO controller. The software allows the electrical signal acquisition, variables calculation, tendency graphical display, file storage for all signals, as well as variables to be calculated. It also allows the trigger configuration for event capture such as voltage dips, grid disconnection, solar panels disconnection, overvoltage or low voltage. The communication protocol used is the TCP/IP. This protocol allows displaying information into web page, which can be accessed locally or from anywhere in the world.

The block diagram of the measurement system is shown in figure 1. The point connection for voltage and current signals from the solar panels and the photovoltaic inverter are shown. In addition, it has two access modes to human machine interface (HMI) system; local and remote mode. Local mode is made through point-to-point connection between system acquisition and a computer. In remote access mode it is necessary to configure an IP direction to the acquisition system for allowing access from the computer through internet network using an internet browser. In both modes, local and remote, the functionality of the system is the same.

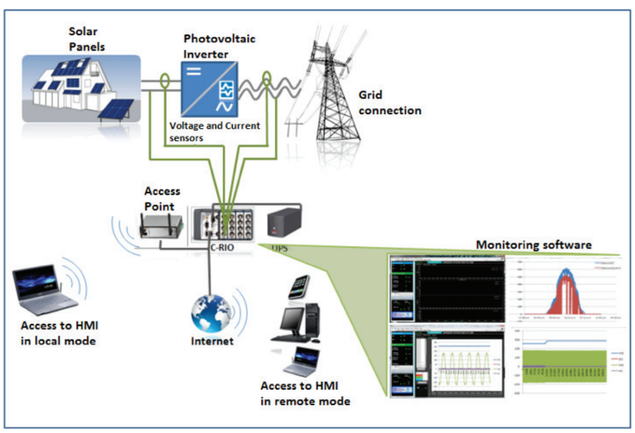

Figure 1. *Block diagram of the measurement system to PV inverters*

PROGRAMMING ARCHITECTURE

The software programming was made utilizing functions or virtual instrument (VI) of the programming language. The program was made in two hardware levels: a) Real-Time controller and b) field-programmable gate array FPGA.

a) Real time software program. The program into real time controller is based on programming architecture called producer-consumer and parallel execution cycles. This programming level is made by the program opening into FPGA, the reading of the statics memory known as "FIFO's", the setting of samples per second, electrical variable calculation, graphical display of voltages and currents, individual display of RMS values and calculated, data conversion of temperature in Celsius grades, file storage of RMS values and calculated per second, detection and file storage of trigger condition that was made by the user, harmonic noise calculation and values update for display into HTML page.

b) FPGA software program. The program in the FPGA consists of a main execution cycle. In this cycle the sampling frequency is controlled and the analog values of the electrical signals are digitized. These values are written sequentially in a FIFO memory called "canales" that stores 100,000 data and adds a header value to identify the channels correctly.

The communication architecture of the data acquisition module is shown in figure 2. The scheme contains two communication types between real time module and data acquisition cards. The first communication type is the "FPGA" mode, which is exploited to the maximum frequency sampling of each card and data transfer acquired through the FIFO's memory blocks. The second type of communication is the mode "scan interface", in this mode the maximum frequency sampling is 1 ms and the information transfer is done via shared variables (NI 2009). In this development the communication mode FPGA was used, for a needed sampling frequency above 20 kHz.

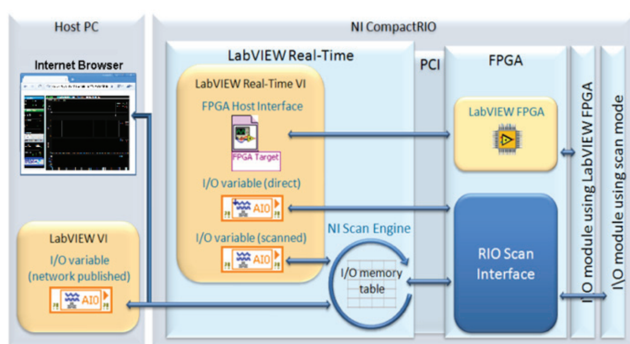

Figure 2. *Communication architecture of the data acquisition module*

The graphical interface of the monitoring system is shown in figure 3 which displays in numeric form the electrical variables calculation. Into HMI the power of DC and AC is shown in graphical form, the waveforms of voltage and current in AC; and the voltage and current in DC.

To calculate electrical variables such as RMS, DC values, AC values, harmonic distortion, and others, the standard functions were used included in the programming software. The signals processing is made sample by sample.

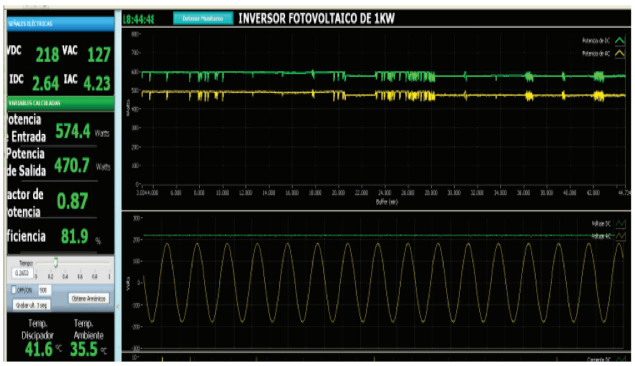

Figure 3. *Graphical interface of the monitoring system*

EVALUATION PERFORMANCE OF 1 KW PV INVERTER

This section describes the use of the monitoring system for photovoltaic inverters. The system was used to characterize the operation of 1 kW grid-tie PV inverter prototype developed by the Electrical Research Institute (IIE). In the monitoring software it was established a sampling frequency of 24 kHz which is equal to 400 samples per cycle of a sine wave of 60 Hz.

The experimental setup comprises: a real-time data acquisition and control system, two voltage sensors, three current sensors, two thermocouple sensors, three breakers, an access point, a laptop, monitoring software, a PV array and a single phase photovoltaic inverter.

The real-time data acquisition and control system are used to perform the test procedure and timing, and to measure and record values of the temperature, currents and test voltages. The voltage sensors are used to measure the utility AC voltage and DC voltage from the PV array, the current sensors are used to measure the AC current inverter, DC current from PV array and DC current from one PV panel in short circuit.

It is recognized that a small percentage difference in the efficiency of a photovoltaic (PV) inverters causes a substantial variation in their cost. This is understandable because a PV inverter is expected to be in service for a good number of years (as long as the PV modules) and therefore the total energy yield that can be extracted using the inverter needs to be considered in the initial investment calculation (SALAM *et al.*, 2014).

Some performance measures can be difficult to interpret because of multiple simultaneous interactions. For example, inverter efficiency changes as the array operating voltage changes, thus the effect of MPPT inaccuracy which changes the array operating voltage may be compounded or partially offset. For example, if one day is cloudy and the other day is sunny the efficiency value can be inaccurate due to voltage variations from solar panels. This system identifies the same operating conditions for several days and then calculates the mean of those values (SCHIMPF *et al.*, 2008).

There are also thermocouple sensors which are used to measure the environment air temperature and inverter temperature at the inverter's heat sink. The breakers are used to emulate several failure events such as a power failure on the grid (islanding), PV array disconnection and activation (turn-on) or deactivation (turn-off) of the power inverter, an access point is used to communicate with a laptop in order to display data using the monitoring software, PV solar panels connected in series configuration and finally a 1 kW single phase photovoltaic inverter was used to evaluate the whole system.

The test procedures were developed with the assumption that the primary user of the information generated would be a knowledgeable system designer. However, sophisticated end-users will find the basic information of value, and the data let them to be massaged into broader measures of performance. This procedure suggests calculations for several consumer comparison factors, such as weighted efficiency (SCHIMPF *et al.*, 2008).

To determine the power inverter performance developed by the IIE, it was used a 14 in-series 75W SIEMENS® solar panel array, with 17.5 V in open-circuit and 4.8 A short-circuit capacity. The table 1 shows the acquired signals during the monitoring and the range values.

Table 1. Monitoring signals list of IIE photovoltaic inverter

No.	ID	Description	Range
1	VCD	Panels Voltage	0 – 300 V
2	ICD	Panels Current	0 – 4.4 A
3	VCA	Inverter output voltage	0 – 130 V
4	ICA	Inverter output current	0-8 A
5	ICC	Short circuit current	0 – 4.8 A
6	E.T	Environmental Temperature	10 – 35 ºC
7	T. Dis	Dissipaters temperature	10 – 70 ºC

The solar panels and physical installation to do all tests to the power inverter prototype developed by the IIE were shown in figure 4. The figure shows the interrupters that allow the connection/disconnection of the AC/DC signals. The photovoltaic inverter is at the top, the transformer is below and the monitoring system at the bottom with voltage, current and temperature sensors, and the network cable connected to network LAN, which allows the remote access to HMI.

The system was tested during 3 months and the results were not good enough as it was expected and was very useful to determine a plan to improve the power inverter. The tests results helped improve the power inverter because there were losses in the energy conversion process affecting the power efficiency. The inverter power consumption detected at night was too much, around 500 mA. Both aspects are very important in a power inverter because an inverter with a lot of energy losses impacts directly in cost-benefit of the product and becomes in a non-profitable system, taking a long recovery period. Data was recorded in files with the photovoltaic inverter response during these three months to events such as solar panels disconnection, grid failure, the presence of high cloud cover and moderate rainfall.

Figure 4. Electrical installation of the inverter and monitoring system

Table 2 presents one day of typical power inverter operation. Taking one typical operation day of the power inverter as an example, in the next table is shown the hours while the inverter was working, the input power from the panels and the output power delivered into the grid.

Table 2. Power inverter performance

Hours at day	Input (Wh)	Output (Wh)	Efficiency (%)	Standby consumption (Wh)	Real Power delivered (Wh)
1 to 5	0	0	0.0	60	-300
6	2	0	0.0	60	-60
7	25	1.1	4.4	60	-58.9
8	91.5	43.5	47.5	60	-16.5
9	212	136	64.2	60	76
10	287	203	70.7	60	143
11	465	372	80.0	60	312
12	535	440	82.2	60	380
13	541	447	82.6	60	387
14	533	438	82.2	60	378
15	369	284	77.0	60	224
16	246	170	69.1	60	110
17	45.7	9.4	20.6	60	-50.6
18	21.6	0	0.0	60	-60
19 to 24	0	0	0.0	60	-420

The real power delivered into the grid is the output power inverter minus the inverter power consumption. The real power delivered into the grid with negative sign means that the inverter is consuming power.

The common time the power inverter is in standby mode is more than the time it is delivering power into the grid, so if the inverter is not efficient enough the inverter is not a good solution as an energy plant resource. This inverter during the day delivered around 2,010 W and at night its consumption was 966. So, an actual power of 1,044 W has been delivered to the grid.

Seven days of typical power inverter operation measured by the control and measurement system showing the power inverter performance were presented in figure 5. This graph represents the input (photovoltaic power plan available) and output (power delivered into the grid) and is very clear that the power available from the photovoltaic plant is not exploited as it has to because the power inverter has a very low efficiency.

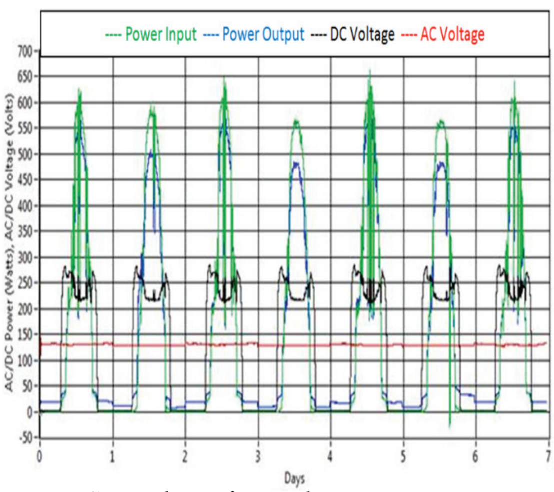

Figure 5. *Seven days of typical power inverter operation*

After the photovoltaic inverter developed by the IIE was evaluated by the control and measurement system, it was scheduled to improve it and after six months another photovoltaic power inverter was ready. The researchers focused on improving the power inverter consumption and on the power inverter efficiency. Both power inverters were tested with the same electrical conditions at the same time to compare their performance and to know if this new prototype was much better. The performance of the Alfa inverter was very similar to the control and measurement system was recorded in the first test. After measured both inverters for 3 months, one day of typical operation was taken to compare both inverters.

The system showed that the beta power inverter development was very adequate because the power consumption in sleep mode decreased to 20 W (≈166 mA) and the efficiency in the conversion process was enhanced. The control and measurement system was capable to compare both photovoltaic installations systems and determine that the installation with the beta inverter was more efficient. To make this more representative, one typical day of operation of both inverters compared with the available power from the photovoltaic plant is shown in figure 6.

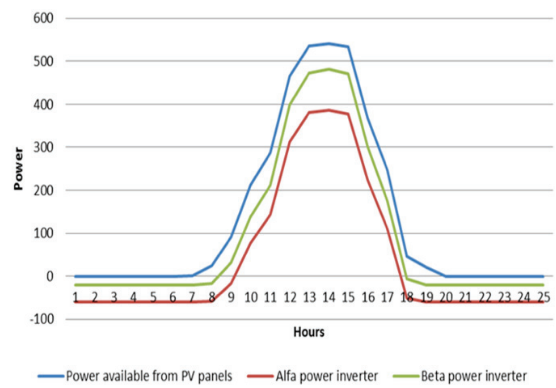

Figure 6. *Seven days of typical power inverter operation*

All negative values represent the power consumption of the inverter in sleep mode. Negative values of both inverters are shown but the beta power inverter has less consumption than the Alfa power inverter, meaning that the beta prototype has a better electronic design.

A graph of one typical day of both inverters operation is shown in figure 7. This graph represents the input (photovoltaic power plan available) and output (power delivered into the grid) and is very clear the performance difference between both power inverters.

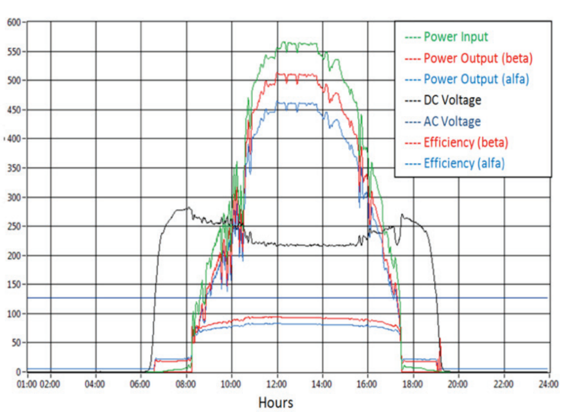

Figure 7. *Power, voltage and efficiency curves of inverters alfa and beta*

The technical data obtained of the beta power inverter are presented in table 3 and the efficiency curve is show in figure 8.

Table 3. Power inverter performance

	Variable	Value	Unit
1	Start-up and shutdown voltage	203	V
2	DC Panels voltage	0 - 290	V
3	Maximum DC current panels	3	A
4	AC grid voltage	128	V
5	Maximum AC current delivered	4.44	A
6	Power factor	0.95	
7	Inverter efficiency	92.4	%
8	Maximum dissipater temperature	45	°C
9	Average ambient temperature	30	°C
10	Output AC frequency	59.9-60.2	Hz
12	Maximum consumption current	166	mA
13	Harmonic distortion THD.	< 5	%
14	Maximum power input measured	623	W
15	Maximum power delivered measured	575	W

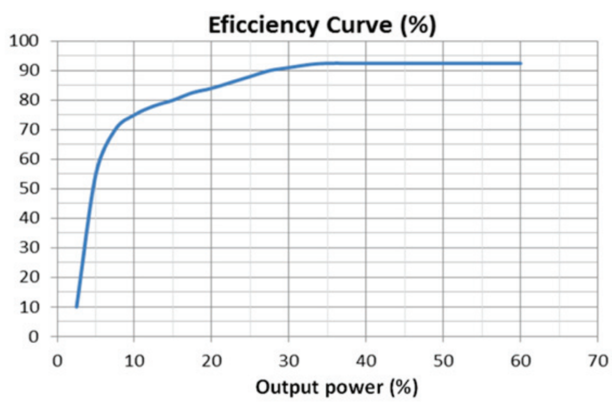

Figure 8. *Efficiency curve of IIE grid-tie inverter*

CONCLUSIONS

Due to the increase of photovoltaic capacity in the world and the PV inverters installation that requires continuous monitoring of its performance, a measurement and control system is developed to evaluate the solar power grid-tie inverter performance. Through this system, two photovoltaic inverters were characterized. The measurement system allows to see tendency graphs of values such as: DC power input from the panels, AC power output delivered to the grid, power factor and line harmonics; inverter efficiency, waveform of voltage and current, and balance of energy consumed vs injected. The recorded files allow to identify operating conditions such as start-up, shutdown, voltage drop, grid synchronization and restart. Those operating conditions can be captured with triggers or user controlled. Most of the tests were performed remotely; in this test the measurement system is configured to access from internet.

This system helped to enhance electronic design of inverter in order to increase efficiency and decrease energy consumption. Finally, both technical data and efficiency curve of IIE grid tie inverter are presented in the test report generated by the system. The data showed an efficiency of 92.4%.

This system has shown a first-rate solution to characterize solar power grid-tie inverters in the field in order to know their performance working in true scenarios. Moreover, it is a useful tool for developers and for solar energy system's integrators.

As shown in this paper it is very important to know the performance of your PV plant installation but the most important part is the power inverter because it depends on the real energy exploited which is delivered into the grid. At the end, this energy will save money on your electric bills. Regardless your status as a client, a consumer or a provider, it is very important to measure the PV power inverter performance to do your investment more profitable.

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