Protection, Control, Automation, and Integration for Off-Grid Solar-Powered Microgrids in Mexico

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***Abstract*—Comisión Federal de Electricidad (CFE), the national Mexican electric utility, launched the White Flag Program (Programa Bandera Blanca) with the objective of providing electricity to rural communities with more than 100 inhabitants. In 2012, CFE launched two projects to provide electric service to two communities belonging to the Huichol indigenous group, Guásimas del Metate and Tierra Blanca del Picacho, which are both located in the mountains near Tepic, Nayarit, Mexico. Each microgrid consists of a photovoltaic power plant, a step-up transformer bank, and a radial medium-voltage distribution network. This paper describes the solar-powered microgrids; their protection, control, and monitoring systems; and the operational experience accumulated thus far.**

I. INTRODUCTION

In 2012, Comisión Federal de Electricidad (CFE), the national Mexican electric utility, provided electric service to 98.11 percent of the country [1]. However, rural communities in Mexico (mainly isolated indigenous communities) still lack electric service. Conventional electrification is neither practical nor affordable for these communities that are isolated and located far away from the electric grid. CFE launched the White Flag Program (Programa Bandera Blanca) with the objective of using renewable energy systems to provide electric service to these communities. This program is focused on providing electricity to communities with more than 100 inhabitants [2]. The levels of solar radiation at different locations were measured to determine communities suitable for the installation of photovoltaic systems. Based on these results, in 2012, the CFE White Flag Program launched two projects to provide electric service to two communities belonging to the Huichol indigenous group, Guásimas del Metate and Tierra Blanca del Picacho, both located in the mountains near Tepic, Nayarit, Mexico.

Greenergy, a Mexican company that designs and builds photovoltaic power plants, was responsible for the design and construction of these two solar-powered microgrids that had to comply with CFE special requirements. Both systems are currently in operation.

The microgrids consist of a photovoltaic system, a step-up 0.22/13.8 kV transformer bank, and a radial 13.8 kV distribution network. Each microgrid includes an integrated protection, control, and monitoring (PCM) system. The system collects and processes data from the microgrid substations and sends the data to the supervisory control and data acquisition (SCADA) master of two remote CFE control centers. The system includes local and remote controls to operate the microgrid breaker.

CFE is studying the possibility of interconnecting neighboring microgrids in the future to improve service availability. The specific requirements, solutions, and operational experiences from these pioneering projects serve as a guideline for future solar-powered microgrid projects in Mexico.

This paper describes the solar-powered microgrids, their PCM systems, and the operational experience accumulated thus far.

II. MICROGRID SYSTEM DESCRIPTION

The microgrids of Guásimas del Metate and Tierra Blanca del Picacho are identical and feed a load composed of approximately 52 households. They operate as off-grid systems with battery storage. Fig. 1 shows an aerial view of the Guásimas del Metate community.

Fig. 1. Aerial view of the Guásimas del Metate community. The solar farm is on the left side. (Photo courtesy of Greenergy.)

Fig. 2 shows the general diagram of the microgrid systems, which include the following:

- A photovoltaic system generating power at 220 V.
- A grounded wye-grounded wye step-up 75 kVA, 0.22/13.8 kV transformer bank.
- A radial 13.8 kV distribution network.
- An integrated PCM system.

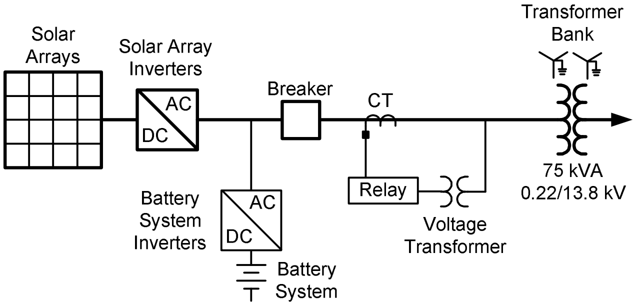


Fig. 2. General diagram showing the main elements of the microgrid systems.

The photovoltaic systems include photovoltaic arrays (formed by multiple solar modules), a racking system that supports the solar modules, a battery system, and dc-to-ac power converters (inverters).

The microgrids also include a separate photovoltaic system that feeds the substation auxiliaries. This system produces 39 kWh per day. This system is outside the scope of this paper.

The integrated PCM systems collect and process data from the microgrid intelligent electronic devices (IEDs) and send the data to the SCADA masters of two CFE control centers via satellite communication. The systems include local and remote controls to operate the substation breakers.

A. Solar Modules

The solar modules, or panels, consist of an array of 60 polycrystalline photovoltaic cells (see Fig. 3). Each solar panel generates up to 255 W, with a maximum dc voltage of 37.9 V at open-circuit conditions and a maximum current of 8.38 A. The panel efficiency is 15.7 percent. The short-circuit current is limited to 8.75 A by the electronic inverter control systems.

Fig. 3. Solar panels installed at the Guásimas del Metate solar farm. (Photo courtesy of Greenergy.)

The total installed power of the photovoltaic power plant is 45.9 kW. To ensure the required performance of 180 kWh per day throughout the entire year, the solar panels are oriented to face south with a tilt equal to the local latitude (22.03 degrees).

B. Electronic Inverters

As shown in Fig. 2, the photovoltaic systems include inverters that convert the dc power generated by the solar arrays (solar array inverters) and the dc energy stored in the battery banks (battery system inverters) into ac power.

1) Solar Array Inverters

The solar array inverters are on-grid inverters, which require a connection to an ac source in order to inject the converted power into the ac grid. The battery system inverters (see the following subsection) serve as the external ac source. The solar array inverters have 8 kW of nominal power and produce 220 V, 60 Hz three-phase voltage, with a 97 percent maximum efficiency. These inverters receive 512 Vdc in an open circuit or 428 Vdc at full-load operation.

The inverter control system performs the following functions:

- Provides ac voltage and frequency control.
- Shuts the inverter down for dc or ac circuit faults (by changing the gate turn-off thyristor [GTO] firing angle). The inverter time to shutdown is approximately 5 milliseconds. The protection algorithm responds to the voltage sag created by the fault or any other system condition.
- Starts the inverters upon detection of ac voltage provided by the battery system inverters.

Fig. 4 shows the solar array inverters installed in the inverter room of the Tierra Blanca del Picacho solar farm. Six inverters convert the solar array dc power to supply ac power to the microgrid.

Fig. 4. Solar array inverters installed in the inverter room of the Tierra Blanca del Picacho solar farm. (Photo courtesy of Greenergy.)

2) Battery System Inverters

The battery system inverters (see Fig. 5) are off-grid inverters capable of feeding an ac power distribution system without needing to be connected to another ac source. These inverters are connected directly to the battery banks operating at 48 Vdc. These inverters operate in a master-slave regime, where three inverters create a 220 V three-phase system. The inverter control system performs the same functions as those of the solar array inverter control system and also the following functions:

- Controls the division of load between both types of inverters.
- Restarts the inverters after a shutdown.
- Controls the battery bank charge and discharge processes.

Fig. 5. Battery system inverters installed in the inverter room of the Guásimas del Metate solar farm. (Photo courtesy of Greenergy.)

C. Battery System

1) Battery Banks

The battery banks are composed of open-type lead-acid batteries with a positive tubular plate (OPzS) and a liquid electrolyte [3]. This type of battery was selected to ensure the best performance in this photovoltaic application.

CFE specifications required 48 V battery banks, and 2 V batteries with a capacity of 1,850 Ah at 20ºC were selected. The battery banks consist of two parallel-connected rows of 24 series-connected batteries each. To facilitate battery bank maintenance, the design includes three independent battery banks with three inverters per bank.

Fig. 6 shows the battery room inside the control enclosure of the Guásimas del Metate solar farm.

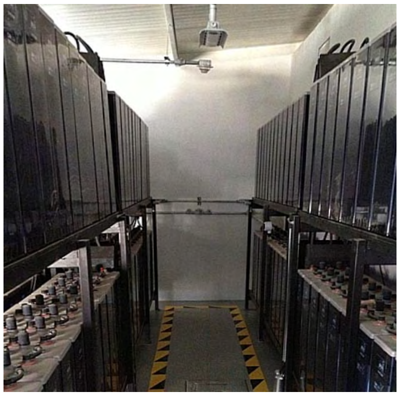


Fig. 6. Battery room of the Guásimas del Metate solar farm. (Photo courtesy of Greenergy.)

2) Battery Charge System

The battery system inverters also serve as battery chargers and control the charging process. During daytime, if the solar arrays generate more than enough energy to satisfy the load demand, the battery system inverters convert the excess ac energy back into dc and store it in the battery banks.

The battery system inverter control estimates the battery charge (state-of-charge parameter) by constantly monitoring the amount of ampere-hours delivered to or extracted from the battery banks. The estimation includes the charge losses caused by battery gasification and the autodischarge defects. The control system also calculates the battery health state, which is a measure of the actual usable capacity of the battery expressed as a percentage of the nominal capacity.

Temperature sensors provide the inverter controls with information on the battery temperature. The battery system inverters automatically shut down the battery charging process when the battery temperature reaches a value equal to 5°C below the maximum allowed temperature. This protection extends the battery life.

III. SYSTEM REQUIREMENTS AND DESIGN SCOPE

A. System Requirements

The system specifications provided by CFE are the following:

- Each microgrid must have two photovoltaic systems, one to feed the microgrid and charge the batteries and another to feed the substation auxiliaries. The main photovoltaic systems must have an installed power of 40 kVA, with a capacity of 180 kWh per day. The systems must ensure autonomous energy supply for two days in case of extended cloud cover.
- The microgrids must include a 13.8 kV distribution system fed by a 0.22/13.8 kV transformer bank. The solar array and battery system inverters must feed the transformer at 220 V.
- The microgrid design must consider the following:
  - The systems are isolated (it takes at least 8 hours for CFE personnel to reach the communities); hence, a robust PCM system must be provided for CFE to remotely monitor the system and respond to contingencies in a timely fashion.
  - The systems are part of a pilot project on the use of solar energy to serve isolated communities in Mexico. The lessons learned will lead to an understanding of the system behavior and the establishment of best practices to apply in future projects.

To improve and obtain the best performance for this system, Greenergy complied with the CFE specifications. To add value, they set the system with the following system parameters:

- The maximum discharge level allowed for the battery banks is 50 percent.
- The design considers a probability of energy supply loss of 3.5 percent (equivalent to 13 days a year) and an excess of solar generation of 4,969 kWh during the summer.

B. *System Design Scope*

The system design is made up of the following:

- Lighting system based on light-emitting diode (LED) technology for each community.
- Control enclosure with rooms for inverters, battery banks, and protection, control, and communications equipment.
- Redundant power supply for protection and control equipment (48 Vdc and 127 Vac).
- Microgrid backup protection system using microprocessor-based relays.
- Revenue and power quality metering at the transformer low- and high-voltage sides.
- Data acquisition from substation IEDs via DNP3.
- Local and remote control of the microgrid breaker.
- Local and remote monitoring of the state and parameters of the solar farm.
- Control and monitoring of the battery bank temperature.
- Control and monitoring of the battery bank hydrogen extractors.
- SCADA reporting to two CFE control centers in DNP3.
- Historical data storage in Structured Query Language (SQL) format.
- Satellite communication to provide photovoltaic system remote control and monitoring.
- Time synchronization via Global Positioning System (GPS) clocks.
- Closed-circuit television.
- Control enclosure intrusion sensors.

IV. MICROGRID DIGITAL SIMULATION

A. *Microgrid Modeling*

We performed computer simulations using PSCAD Version 4.2 software to investigate the microgrid transient behavior and to decide on the protection functions to apply. We simulated faults on the dc circuit, the 220 V network, and the 13.8 kV network. We analyzed three-phase, phase-to-phase, phase-to-phase-to-ground, and single-phase-to-ground faults. We also studied the behavior of the frequency for faults and for failures of the inverter control system.

Fig. 7 shows a part of the PSCAD model that includes the inverters and their control system. The control logic is based on the inverter manufacturer manual.

The simulation was performed for a load condition of 35 kW and 5 kVAR, which is typical for these communities, where load is mainly composed of lighting and some motors. The signals obtained in the simulation for steady-state conditions very closely match the signals measured during normal microgrid operation, which partially validates the PSCAD model. No fault has occurred in the microgrids since their commissioning.

B. *Faults on the DC Circuit*

As mentioned in Section II, Subsection B, the control systems of the solar array and battery bank inverters include an undervoltage protection algorithm that detects dc and ac circuit faults and automatically shuts down the inverter in approximately 5 milliseconds.

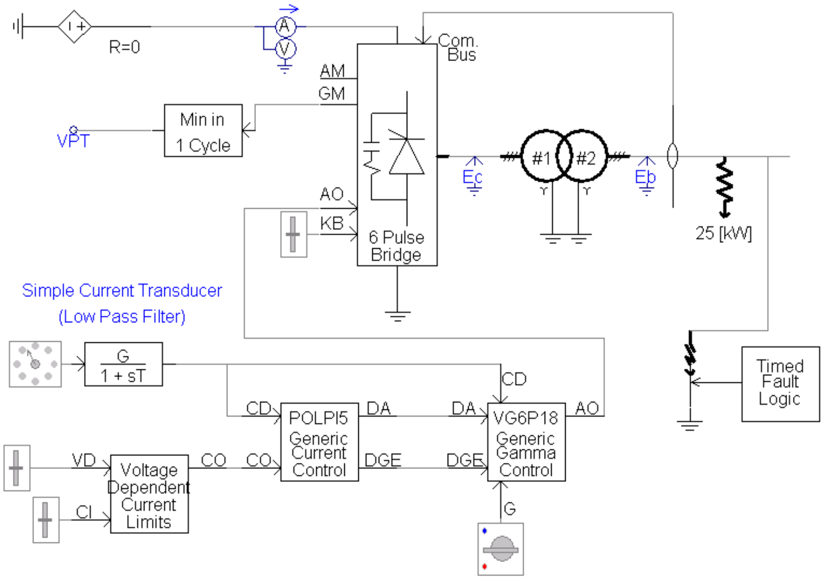


Fig. 7. Part of the PSCAD model used for the microgrid system transient behavior analysis.

Fig. 8 shows the current for a fault on the dc circuit. The simulation time is 1 second: the fault was applied at 500 milliseconds with a duration of 100 milliseconds. We assumed no operation of the control system protection algorithm in order to fully visualize the current signal. We did consider the effect of the current control algorithm, which only allows the slight current rise shown in Fig. 8 upon fault inception.

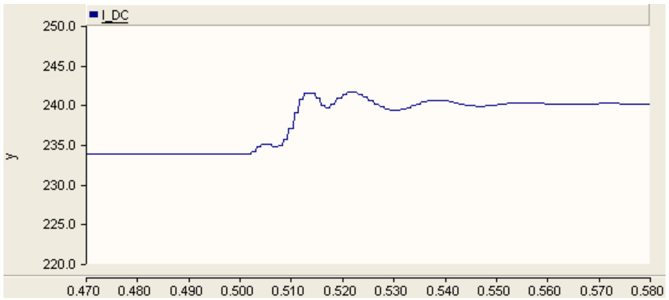


Fig. 8. DC current signal for a dc circuit fault (the x-axis is in seconds, and the y-axis is in amperes).

C. *Faults on the 220 V Network*

Fig. 9 and Fig. 10 show the currents and voltages during a bolted three-phase fault on the 220 V network. The simulation time is 1 second, and the fault was applied at 500 milliseconds with a duration of 8 milliseconds. Fig. 9 shows that the current slightly increases at fault inception and goes to 0 in less than 1 cycle when the protection algorithm of the inverter control system shuts down the inverter. An overcurrent element cannot respond to this small current increase. However, the voltage collapses during the fault (see Fig. 10), so an undervoltage element can provide sensitive fault detection.

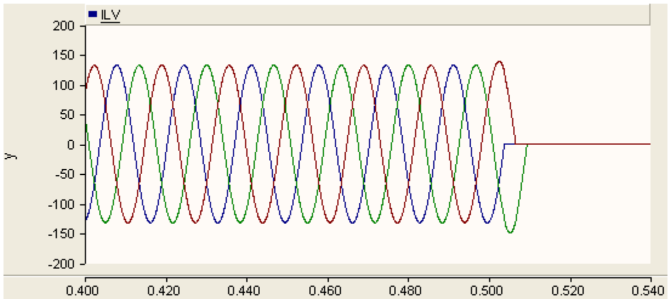


Fig. 9. Current waveform for a bolted three-phase fault on the 220 V network (the x-axis is in seconds, and the y-axis is in amperes).

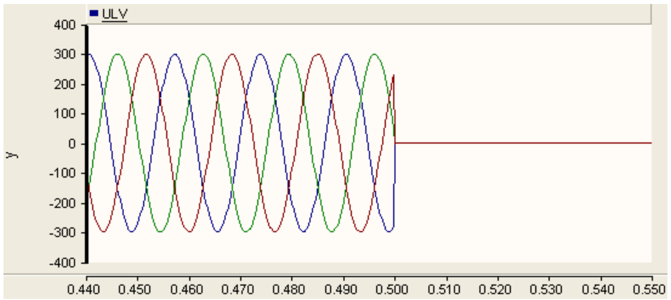


Fig. 10. Voltage waveform for a bolted three-phase fault on the 220 V network (the x-axis is in seconds, and the y-axis is in volts).

D. *Faults on the 13.8 kV Network*

Fig. 11 and Fig. 12 show the currents and voltages for a bolted three-phase fault on the 13.8 kV network. Their waveshapes are very similar to those for a fault on the 220 V network.

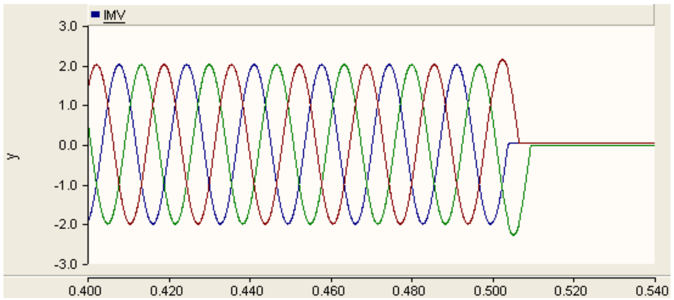


Fig. 11. Current waveform for a bolted three-phase fault on the 13.8 kV network (the x-axis is in seconds and the y-axis is in amperes).

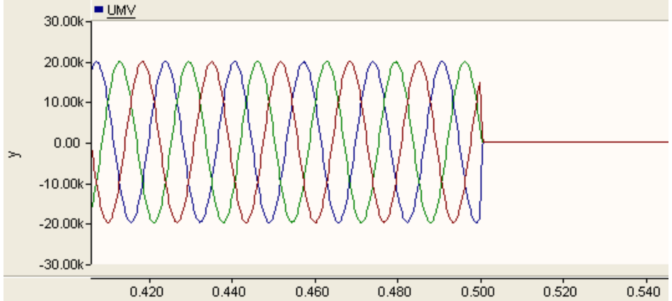


Fig. 12. Voltage waveform for a bolted three-phase fault on the 13.8 kV network (the x-axis is in seconds, and the y-axis is in kilovolts).

E. *Frequency Dynamic Behavior*

Our simulation results show that frequency remains stable during faults. However, frequency experiences significant variations for failures of the inverter control systems. For example, Fig. 13 shows frequency oscillations with a maximum amplitude of 0.02 pu (1.2 Hz) and a more than 1-second duration for a failure of one inverter control system. These frequency variations can be used to detect inverter control system failures.

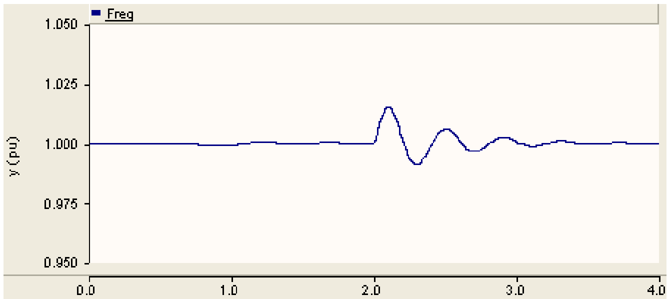


Fig. 13. Behavior of the frequency on the 220 V network for a failure in one of the inverter control systems (the x-axis is in seconds, and the y-axis is in pu).

V. MICROGRID PROTECTION SYSTEM

The undervoltage protection algorithm for the inverter control systems provides primary protection for faults in the dc and ac circuits.

The backup protection functions required to address inverter control system failures are provided by a microprocessor-based multifunction relay installed in the 220 V network, as shown in Fig. 2. This relay trips the transformer low-voltage side breaker.

To determine the protection functions to enable in the backup multifunction relay, we included different protection algorithms in the PSCAD model. We modeled the instrument transformers, the analog and digital filters, the phasor calculation process, and the following protection elements: phase overcurrent (50/51), ground overcurrent (51N), undervoltage (27), voltage unbalance (60), and volts-hertz (24). We studied the behavior of the 50/51, 51N, 27, and 60 elements during faults. We also evaluated the 24 element performance for inverter control system failures.

Table I summarizes the protection element response to different fault types on the 13.8 kV network. We obtained the same results for faults on the 220 V network.

TABLE I
PROTECTION ELEMENT RESPONSE TO FAULTS ON THE 13.8 KV NETWORK

Protection Element	**Fault Types**			
	Single Phase	**Phase to Phase**	**Phase to Phase to Ground**	**Three Phase**
50/51	Does not operate	Does not operate	Does not operate	Does not operate
51N	Sometimes operates	Does not operate	Does not operate	Does not operate
27	Operates	Operates	Operates	Operates
60	Operates	Operates	Operates	Does not operate

The simulation results summarized in Table I show that the 27 element responds to all fault types and the 60 element responds to all unbalanced faults. We decided to enable these two elements for fault backup protection and also the 24 element to provide redundant backup protection for inverter control system failures.

VI. INTEGRATED IED NETWORK

Given the remote location of the indigenous communities, remote control and monitoring of the microgrids are very important to maintain service continuity and monitor load growth. In addition, these CFE pilot projects to provide electric service to isolated communities using solar energy provide information on the real-world operation of photovoltaic systems, their life span, and the level of maintenance required. Continuous monitoring provides us with the information needed to evaluate system performance.

The integrated network collects data from different IEDs located inside and outside the control enclosure. The following devices are integrated in the network:

- Six solar array inverters.
- Nine battery system inverters.
- Two battery system inverters for substation auxiliaries.
- A solar array inverter for substation auxiliaries.
- A meteorological station.
- A data logger.
- An automation platform.
- A programmable logic controller (PLC).
- A protective relay.
- Two revenue meters.

The original project specifications required the use of DNP3 in the local-area network (LAN) and for communication with the remote SCADA masters. However, the solar array inverters, battery system inverters, and meteorological station devices are able to publish data only in their native SMA Net protocol. In addition, the PLC publishes data in Modbus® RTU. CFE approved the use of Modbus to integrate devices without a native DNP3 protocol.

Fig. 14 shows the integrated IED network architecture. This LAN performs data processing and protocol conversion and communicates with the remote CFE control centers.

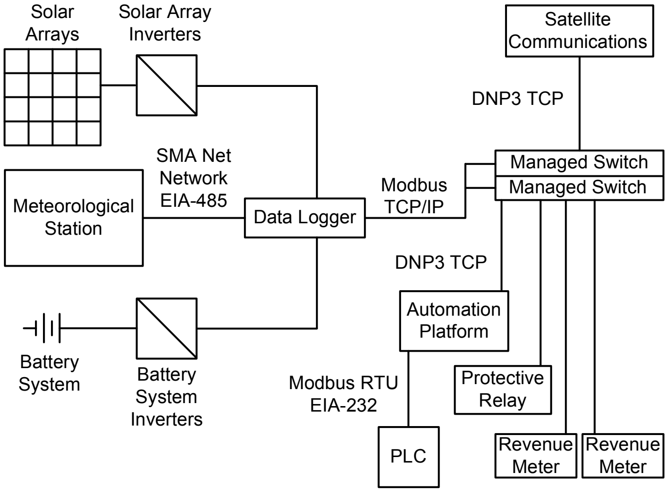


Fig. 14. Communications architecture of the microgrid integrated system.

The solar array and battery system inverters, the meteorological station, and the data logger are connected in a EIA-485 bus network topology. As explained in Section II, Subsection B, the battery system inverters operate in a master-slave regime. Three inverters form an array to create a three-phase system. One of the inverter controls in the array serves as the master, regulating frequency, voltage, and current and providing configuration settings to the other two inverter controls. This master control also concentrates the data published by the other two inverter controls so that the data of the three inverters in the array are available in a single device. The data logger concentrates the data in SMA Net protocol and converts the data to Modbus TCP/IP. The data configuration of the battery system inverter model used in these projects was not compatible with that of the data logger. Based on the importance of these projects, the inverter manufacturer developed a special firmware version that restructures the internal data configuration to ensure compatibility with the data logger.

The data logger serves as a gateway between the devices in the SMA Net network and the automation platform, as shown in Fig. 14. A managed switch provides the link between the data logger (Modbus TCP/IP) and the devices with native DNP3 protocol (the automation platform, relay, and meters).

Once the data logger discovers the devices in the SMA Net network, it places them in an assignment table. Table II is an example of the assignment table, where each row corresponds to one device in the SMA Net network. Internally, the data logger associates the data contained in each SMA Net network device with a device in the table. This arrangement allows every device in the SMA Net network to act as a Modbus slave unit that can be polled from a Modbus master. The assignment table includes the manufacturer device identification (ID) number, the device serial number, and the unit ID number. Table II shows the device designation number with the corresponding Modbus slave address registers in parentheses. The unit ID number is the Modbus slave address that the automation platform interrogates. When the first autodiscovery process is performed, the data logger automatically assigns a unit ID to each discovered device, from 3 up to 247.

TABLE II
EXAMPLE OF THE DATA LOGGER ASSIGNMENT TABLE.

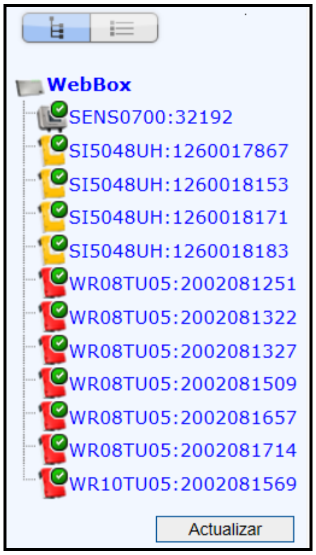
Device	**Device Designation (Modbus Address Register)**		
	Device ID	**Serial Number**	**Unit ID**
1	156 (42109)	1003 (42110)	4 (42112)
2	157 (42113)	1004 (42114)	5 (42116)
3	158 (42117)	1006 (42118)	255 (41120)

Fig. 15 is a screen capture of the data logger web-based interface showing the devices included in the SMA Net network.

The integrated IED network uses an automation platform to poll data from the data logger via Modbus TCP/IP, from the PLC via Modbus RTU, and from the protective relay and the two revenue meters via DNP3 TCP (see Fig. 14). This automation platform has the following functions:

- Serves as the data concentrator for the data coming from the different devices.
- Performs protocol conversion from Modbus to DNP3.
- Performs the human-machine interface (HMI) function.
- Functions as a SCADA server, sending data to the remote SCADA masters in DNP3.
- Functions as a programmable automation controller executing control and automation logic.
- Performs database storage in an SQL format.

The automation platform concentrates the microgrid data and sends the data to the remote SCADA masters (see Fig. 14). A dedicated satellite communications channel provides the link between the integrated IED network and the SCADA masters. This satellite link operates in the Ku band (from 11.2 to 12.0 GHz), with a bandwidth of 512 kbps symmetrical (512 kbps uplink and downlink). A very small aperture terminal (VSAT) network was used to create a virtual private network (VPN) between the LAN and the CFE corporate network.



WebBox
- SENS0700:32192
- SI5048UH:1260017867
- SI5048UH:1260018153
- SI5048UH:1260018171
- SI5048UH:1260018183
- WR08TU05:2002081251
- WR08TU05:2002081322
- WR08TU05:2002081327
- WR08TU05:2002081509
- WR08TU05:2002081657
- WR08TU05:2002081714
- WR10TU05:2002081569

Fig. 15. Screen capture of the web-based data logger interface showing the devices included in the SMA Net network (courtesy of Greenergy).

VII. CONTROL AND MONITORING SYSTEM

A. Local Control and Monitoring

The automation platform includes an HMI as one of its multiple functions. This local HMI is accessible with an Internet browser running on a desktop computer located in the control enclosure. The browser points to the automation platform Internet Protocol (IP) address to access the HMI.

The local HMI allows for manually opening and closing the microgrid breaker. The panel designed for the automation platform, the protective relay, two meters, the satellite clock, and two managed switches includes a set of emergency operation pushbuttons. These pushbuttons allow manual opening and closing of the microgrid breaker to provide control backup when local HMI or remote SCADA access is not available.

The HMI displays the following monitoring information:

- Inverter dc and ac voltage and current measurements.
- Active energy and power and reactive power delivered to the microgrid by the solar array and battery system inverters.
- Frequency.
- Revenue metering data from the meters at both sides of the transformer.
- Power quality data from the meters at both sides of the transformer.
- Inverter operation time.
- Inverter status and alarms.
- Battery charge status and health.
- Battery temperature.
- Status of the battery room exhaust fans.

- Communications device and link status.
- Control enclosure temperature.
- Control enclosure alarms: intrusion, smoke and/or fire, high hydrogen concentration, and air conditioning failures.
- Historical data on analog measurements and alarms.
- Meteorological station data.

Fig. 16 depicts the main local HMI screen. This screen shows voltage and current measurements for the six solar array inverters (red) and the three arrays of battery system inverters (yellow). The screen also displays power, frequency, voltage, and current measurements from both sides of the transformer.

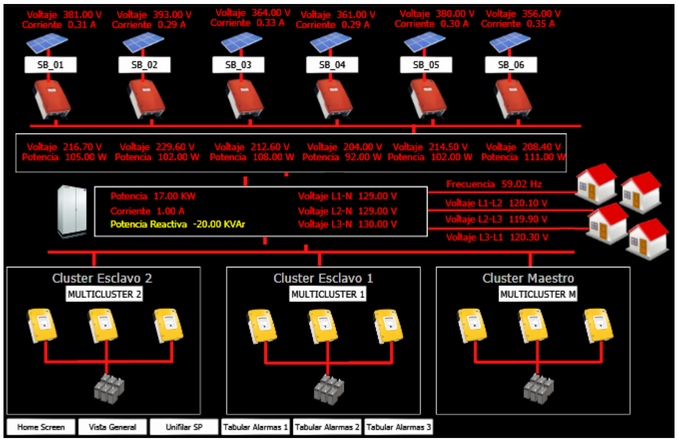


Fig. 16. Main local HMI screen (courtesy of Greenergy).

B. Remote Control and Monitoring

An HMI available at each control center allows remote opening and closing of the microgrid breaker.

To avoid overloading the satellite link bandwidth and to ensure fast data transmission, CFE engineers selected the data to include in the DNP3 map sent to the SCADA masters. Reducing the amount of transmitted data also saves bandwidth for streaming the video surveillance data. The control center personnel can also access the local HMI with an Internet browser, which allows them to monitor in real time the information they do not receive.

The control center HMIs display the following monitoring information:

- Inverter dc and ac voltage and current measurements.
- Active and reactive power delivered to the microgrid.
- Frequency.
- Revenue metering data.
- Power quality data.
- Inverter status and alarms.
- Battery charge status and health.
- Battery temperature.
- Status of the battery room exhaust fans.
- Communications device and link status.
- Control enclosure temperature.
- Control enclosure alarms.
- Meteorological station data.

C. Automation

1) Automatic Reclosing (79)

When a fault occurs, the inverter control systems shut down the inverters and the relay protection functions responding to voltage also operate to trip the breaker.

For temporary faults, the inverters start on their own and energize the 220 V network. To restore service in the 13.8 kV network, we programmed a two-shot automatic reclosing (79) function in the protective relay. The reclosing dead times are 15 seconds and 30 seconds, respectively.

2) Preparing the Breaker for Reclosing Operations

The microgrid breaker has a closing coil, an opening coil, and a trip coil. The breaker operates as follows:

- A closing operation closes the breaker contacts.
- An opening operation opens the breaker contacts. The breaker remains ready for a subsequent closing operation.
- A trip operation opens the breaker contacts and locks the breaker out. To close the breaker, it is necessary to perform an opening operation first.

Opening commands from the local and remote HMIs and from the panel pushbuttons energize the breaker opening coil, so the breaker remains ready for a subsequent closing operation. However, a protective relay operation energizes the breaker trip coil, so an opening operation is necessary before reclosing the breaker.

Using the protective relay programming abilities, we developed logic that performs the breaker opening operation after a trip to allow the 79 element to reclose the breaker. The logic issues a breaker opening signal 1 second after detecting the closure of the relay output trip contact.

3) Automatic Breaker Tripping for Inverter Failures

The Greenergy design ensures the continuous supply of the 180 kWh per day required by CFE. The battery system inverters were chosen to serve the load demand continuously after the loss of one inverter array or for a limited time after the loss of two arrays. For this overload condition, the inverter control systems shut down the inverters to avoid damage. In addition, the battery bank charge level cannot reach a programmed minimum value. We programmed logic in the automation platform to preserve the inverter and battery life. This logic trips the breaker with a time delay when two battery system inverter arrays fail. To avoid long service interruptions, the inverter control systems attempt the automatic restart of the failed inverters after a time.

VIII. SYSTEM TESTING AND OPERATION

The PCM system tests included panel operational and functional tests in the factory and integrated system tests in the field during commissioning. In addition, the microgrid system was tested as a whole.

A. PCM System Testing

The objective of the panel operational tests was to verify the panel circuits. This test included the following activities:

- Visual inspection. A check of the physical condition of the panel and cabinet and a verification of the physical equipment layout with the corresponding general layout diagrams were performed.
- Continuity tests. Point-to-point wiring continuity checks for the panel circuits were performed. The terminal types, the quality of terminal crimping, and the wire sizes, colors, and labeling were checked.
- DC circuit tests. The dc panel circuit was energized. Proper IED startup, the polarity and independence of dc circuits, and the continuity of the positive and negative dc circuit buses were verified.
- AC circuit tests. Analog voltage and current signals were applied to the panel ac circuit. Signal phasing and polarity at the input of the relay and meters were checked.
- IED configuration. IED settings files specific to the microgrid PCM system were loaded and verified in the IEDs.

The objective of the panel functional tests was to validate the logic settings applied to the IEDs. These tests required injecting three-phase ac signals using a relay test set and also applying logic input signals using a custom-built substation simulator. The ultimate goal was to verify the proper performance of the PCM system, as seen from the panel terminal blocks.

The objective of the integrated system tests was to validate the proper operation of the whole PCM system. These tests were performed as part of the commissioning tests with the system fully connected in the substation. These tests included the following:

- Communications tests. The objective was to check all the system communications links.
- HMI tests. The objective was to check the HMI functionality. Visual inspections of each screen and manual tests were performed, including:
  - Manual control of the breaker.
  - Analog measurement displays.
  - Digital signal displays (status and alarm).

B. Microgrid System Testing

At the end of the commissioning process, the microgrid system was tested as a whole, which allowed us to collect additional information on the PCM system performance. In particular, we confirmed the following:

- The integrated system properly and timely reports data to the remote SCADA centers.
- The local and remote HMIs display the data correctly.
- The automation platform performance is not compromised by the amount of information processing required to provide the protocol conversion, HMI and SCADA server functions, and control and automation functions.
- The breaker opening and closing operations from the local and remote HMIs perform correctly.

In particular, during the microgrid testing process, we found and solved a data logger problem. As explained in Section VI, after the data logger discovers a device in the SMA Net network, this device is inserted into its assignment table with a unique unit ID number. However, we found that the automatic assignment of the unit ID number fails for either of two situations: when the data logger is requested to discover a new device in the SMA Net network and when the data logger is restarted.

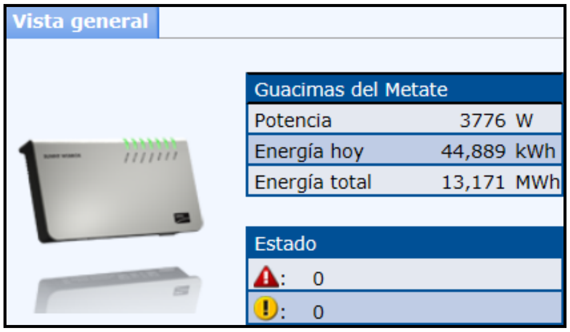
In these cases, a unit ID number of 255 was mistakenly assigned to any existing, added, or modified device in the SMA Net network. A change in the unit ID value of a given device prevents the automation platform from recognizing it and affects communication. As a result, the data coming from the SMA Net network cannot be accessed and monitored.

To solve this problem, we programmed logic using the IEC 61131-3 programming language module available in the automation platform. Based on the serial number and device ID fields of each register in the assignment table, the logic automatically rewrites the corresponding unit ID for each device that has a unit ID number of 255.

C. Microgrid Operational Experience

The microgrid systems have been operating since April 2013 with no service interruptions. The operational information collected so far confirms that the integrated PCM systems perform properly and continuously provide monitoring data. The protection systems have not been tested yet in the real world because the systems have experienced no faults.

For example, Fig. 17 displays the instant power (*Potencia*), the energy generated today (*Energía hoy*), and the total generated energy since the beginning of operation (*Energía total*) for the Guásimas del Metate microgrid. No error or warning messages appear on the screen.

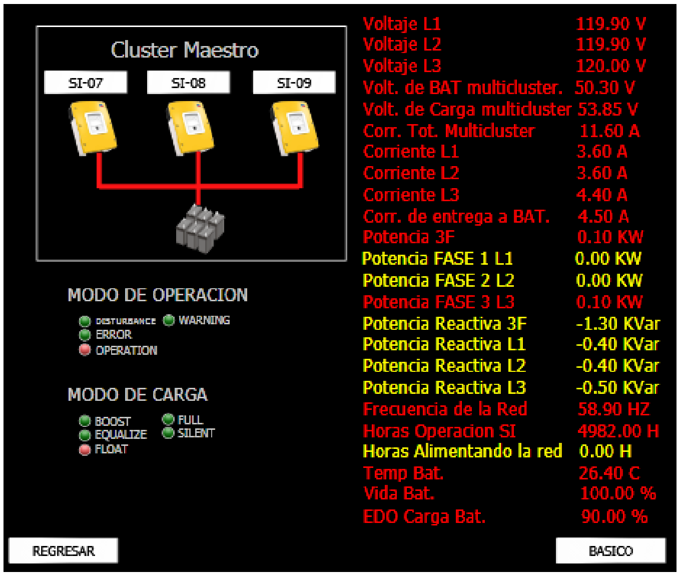


Guacimas del Metate	
Potencia	3776 W
Energía hoy	44,889 kWh
Energía total	13,171 MWh

Estado
⚠: 0
❗: 0

Fig. 17. Real-time power and energy data for the Guásimas del Metate microgrid (courtesy of Greenergy).

Fig. 18 shows an HMI screen capture corresponding to the master array of battery system inverters of the Guásimas del Metate solar farm.



Voltaje L1	119.90 V
Voltaje L2	119.90 V
Voltaje L3	120.00 V
Volt. de BAT multicluster.	50.30 V
Volt. de Carga multicluster	53.85 V
Corr. Tot. Multicluster	11.60 A
Corriente L1	3.60 A
Corriente L2	3.60 A
Corriente L3	4.40 A
Corr. de entrega a BAT.	4.50 A
Potencia 3F	0.10 KW
Potencia FASE 1 L1	0.00 KW
Potencia FASE 2 L2	0.00 KW
Potencia FASE 3 L3	0.10 KW
Potencia Reactiva 3F	-1.30 KVar
Potencia Reactiva L1	-0.40 KVar
Potencia Reactiva L2	-0.40 KVar
Potencia Reactiva L3	-0.50 KVar
Frecuencia de la Red	58.90 HZ
Horas Operacion SI	4982.00 H
Horas Alimentando la red	0.00 H
Temp Bat.	26.40 C
Vida Bat.	100.00 %
EDO Carga Bat.	90.00 %

Fig. 18. Real-time data of the master array of battery system inverters in the Guásimas del Metate solar farm (courtesy of Greenergy).

Fig. 19 depicts an oscillographic record of one of the microgrids under actual operating conditions, provided by the meter at the transformer low-voltage side. We detected the C-phase current to be significantly greater that the other two currents. The inverter control systems keep the voltages balanced. This current unbalance condition indicates an uneven distribution of load between the three phases. CFE is currently working to solve this problem.

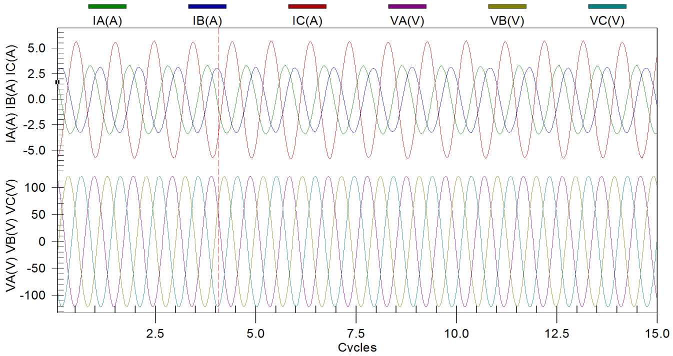


Fig. 19. Oscillography of currents and voltages taken at the low side of the transformer.

Microgrid system maintenance, a very important activity in a remote location, received special attention in these projects. Greenergy trained CFE engineers in the maintenance of the battery system and inverters. Greenergy also trained people from the communities to conduct solar panel maintenance activities. The involvement of the local population in maintenance activities has a positive effect in that they develop new skills and a sense of system ownership.

IX. CONCLUSION

This paper describes the solar-powered microgrids that provide electric service to two communities belonging to the Huichol indigenous group, which are both located in the mountains near Tepic, Nayarit, Mexico. We can conclude the following:

- Photovoltaic systems are a good solution for providing electric service to isolated communities in Mexico.
- Computer simulation allows for the understanding of solar-powered microgrid behavior during normal operation and fault conditions.
- The inverter control systems include an undervoltage detection function that shuts down the inverter for voltage sags. This function is the primary fault protection in the microgrid.
- Undervoltage (27), voltage unbalance (60), and volts-hertz (24) elements of a multifunction relay are used to provide backup protection for faults and inverter control system failures.
- An integrated IED network collects and processes data, performs protocol conversion, and functions as a SCADA server to send data to remote CFE control centers.
- Local and remote HMIs display information and allow manual breaker opening and closing from the control enclosure and the control centers.
- The PCM systems were thoroughly tested in the factory and the field. The operational information collected so far confirms that the systems perform properly and continuously provide monitoring data. The microgrids have experienced no faults.
- The local population participates in solar panel maintenance activities, which contributes to the development of new skills and creates a sense of system ownership.
- The control systems of the inverters used in these projects can be remotely adjusted. Parameters such as current and voltage limits, battery bank charging rate, and others can be controlled. This capability allows for future system enhancements that include the following:
  - Remote manual control of these parameters by the control center personnel.
  - Parameter automatic control by the automation platform.
- The operational experience and lessons learned from the Guásimas del Metate and Tierra Blanca del Picacho projects will serve as a guideline for future CFE White Flag Program projects.

X. REFERENCES

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XI. BIOGRAPHIES

Carlos Eduardo Ortiz received his BS in Physics Engineering in 2006 from the Monterrey Institute of Technology and Higher Education in Monterrey, Mexico, and an Energy Specialization from the Hong Kong University of Science and Technology. In 2007, he became the director of Greenergy Energía no Convencional in Guadalajara, Mexico. Mr. Ortiz has served as a project consultant and developer for federal electrification programs using solar power since 2009. He has been invited by several government offices and private companies to create grid-tied photovoltaic systems from 100 kW to 1 MW and above. Mr. Ortiz was an international speaker at the 2nd Symposium for Off-Grid Solutions, Ulm, Germany, 2011; the 25th European Photovoltaic Solar Energy Conference and Exhibition; and the 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain, in September 2010. He has also attended several conferences, including the Green Expo, Mexico City, 2012; the International Energy Saving Congress, Guadalajara, 2010, 2011, and 2012; the IIE Photovoltaic Forum, Querétaro, 2010; Electricon 2012, Guadalajara; and Solar Future Mexico 2013, Mexico City.

José Francisco Álvarez Rada received his BS degree in industrial maintenance engineering in 2011 from the Jalisco Technological University in Guadalajara, Mexico. During college, he worked as a senior designer in the metal-mechanic industry as a designer of mechanical seals for fluid pumps for the mining, power generation, wastewater treatment, pulp and paper, chemical, and refining industries. Mr. Álvarez Rada joined Greenergy Energía No Convencional in 2011, where he led a project to design support structures for photovoltaic modules, which served as his BS degree thesis topic. He then moved to new product development and was in charge of selecting specific systems to meet the needs of electrification projects using renewable energy. Mr. Álvarez Rada is currently responsible for the Greenergy supply chain.

Edson Hernández received his BS degree in electronic engineering in 2006 from the Technological Institute of San Luis Potosí, Mexico. He served as an associate technician at the San Luis Potosí Institute for Scientific and Technological Research, doing projects related to laboratory automation and nanotechnology device research and development, and also worked in the steel industry. Mr. Hernández joined Schweitzer Engineering Laboratories, Inc. in 2008, where he is currently an automation engineer designing control and automation solutions for national and international projects. His experience includes control and automation system design, device integration, and SCADA system design. His main professional interests are in device integration, process control and automation, cybersecurity, smart grids, and renewable energies.

Juan Lozada received his BSEE degree in 2002, his MSc degree in electrical engineering in 2005, and his management specialization in 2007, all from the Polytechnic, Experimental and National University (UNEXPO) in Puerto Ordaz, Venezuela. He also received an advanced studies diploma from the Polytechnic University of Madrid in 2010. From 2002 to 2010, he worked at EDELCA, a utility in charge of the generation, transmission, and distribution of electricity in Venezuela, where his roles related to the operation and protection of power systems. From 2004 to 2010, Mr. Lozada served as an electrical engineer at the BS and MSc programs of UNEXPO. He joined Schweitzer Engineering Laboratories, Inc. in January 2011, where he is currently a senior protection engineer. He also serves as an adjunct professor at the Monterrey Institute of Technology and Higher Education in San Luis Potosí, Mexico.

Alejandro Carbajal received his BS degree in electronic engineering in 2008 from the University of San Luis Potosí, Mexico. He worked as an instrumentation technician for Degrémont Suez. Mr. Carbajal joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2009, where he spent two years in an engineering development program that allowed him to learn about factory acceptance testing, engineering design, and technical support. He is currently an SEL commissioning engineer working mostly in CFE and industrial substations. His main professional interest is in designing integrated control and automation systems using different platforms.

Héctor J. Altuve received his BSEE degree in 1969 from the Central University of Las Villas in Santa Clara, Cuba, and his Ph.D. in 1981 from Kiev Polytechnic Institute in Kiev, Ukraine. From 1969 until 1993, Dr. Altuve served on the faculty of the Electrical Engineering School at the Central University of Las Villas. From 1993 to 2000, he served as professor of the Graduate Doctoral Program in the Mechanical and Electrical Engineering School at the Autonomous University of Nuevo León in Monterrey, Mexico. In 1999 through 2000, he was the Schweitzer Visiting Professor in the Department of Electrical Engineering at Washington State University. Dr. Altuve joined Schweitzer Engineering Laboratories, Inc. (SEL) in January 2001, where he is currently a distinguished engineer and the dean of SEL University. He has authored and coauthored more than 100 technical papers and several books and holds four patents. His main research interests are in power system protection, control, and monitoring. Dr. Altuve is an IEEE senior member.

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