DESIGN, CONTROL, AND OPERATION OF A HYBRID ELECTRICAL GENERATION SYSTEM BASED ON RENEWABLE ENERGY SOURCES

Luiz A. de S. Ribeiro[1], Osvaldo R. Saavedra[1], José G. de Matos[1], Shigeaki L. Lima[1], Guilherme Bonan[2], Alexandre S. Martins[2]
[1]Laboratório de Energias Renováveis/Instituto de Energia Elétrica/Universidade Federal do Maranhão – NEA/IEE/UFMA
Av. dos Portugueses, s/n, Campus Universitário do Bacanga, 65080-040, São Luís – MA, Fone: +55(98)3301-9202
[2]CP Eletrônica, Rua da Várzea 379, CEP 91040-600, Porto Alegre – RS, Fone: +55 (51) 2131 2407
e-mail:[luiz_ribeiro, osvaldo, gomes, shigeaki]@dee.ufma.br; [bonan, saccol]@cp.com.br

***Abstract* – Around the word a significant number of villages may never have access to electricity due to their remoteness. For the people living in these isolated communities, access to renewable energy sources is the only solution to meet their energy needs. In these communes the electricity is mainly used for household purposes such as lighting. One of the main problems of such systems, located in isolated areas of difficult access, is the reliability. The coordination protection and operation, distribution network, inverters, control strategies, and maintenance are aspects that must be well designed to get a reliable system. Furthermore, in these applications the system should have the following features: expansion flexibility and robustness, high efficiency, and adequacy to operate in adverse environmental conditions. The results presented in this paper will address these problems with special attention to the control strategies, and system operation. The paper will present experimental results showing the robustness and viability of a pilot renewable hybrid electrical generation system in the Lençóis´s Island, northeast of Brazil.**

***Keywords* - Hybrid renewable energy systems; Solar energy; Standalone micro-grid; Wind energy**.

I. INTRODUCTION

The supply of electricity to isolated communities in Brazil and other developing countries, in general, is still done in a precarious way, using diesel generators, which operate for 3 to 4 hours per day. This has been driven almost always due to the high costs associated with the expansion of the conventional power grid so that power can reach into these communities. In some cases, technical and environmental constraints also have been factors that have prevented the full electrical service in these communities, especially those located on oceanic islands [1],[2].

For the societies to get or try to get a maintainable development it is necessary a lot of effort in the discovery and use of renewable energy sources as well as in the increase of the efficiency in the process of use of these sources. In this aspect, the electric power generation, based on solar photovoltaic and wind turbines technologies have been effective in distributed generation systems and also in standalone systems for supplying isolated communities. In standalone systems, those solutions have been shown appropriate for areas of difficult access, dispersed, with environmental restrictions or with a population of low personal incoming. However, these characteristics also contribute for critical sustainability. Fails and supply interruptions are difficult to solve due to the non availability of technical assistance. The delay of remote assistance leads to long periods of lack of electrical service, causing loss of credibility in this kind of system. Thus, to overcome these difficulties, isolated systems must be projected taking into account reliability, minimizing the dependence of maintenance and human intervention, because it is expensive and often not available.

Even though there are different kinds of combinations of energy sources [1], the most common combination is the solar photovoltaic and wind turbines [2]. These systems have shown to be adequate for standalone applications in areas of difficult access [3][4] being responsible for the decreasing or even the elimination of diesel usage. In [5] an interesting review of practical applications using hybrid systems is presented. The major reported problems have to do with cost, performance and reliability, and institutional problems. These challenges have required considerable effort to achieve small isolated systems that are both economically and technically sustainable. In order to optimize the design and operation of hybrid systems several articles have been published.

In [6] the optimal design of a hybrid wind and solar power system for either autonomous or grid-linked applications is proposed. The method employs linear programming techniques to minimize the average production cost of electricity while meeting the load requirements in a reliable manner, and takes environmental factors into consideration both in the design and operation phases. In [7] an automatic procedure to perform the optimal sizing of a grid connected Hybrid solar and wind Power System based on fuzzy logic and multi-objective optimization has been proposed. Both technical and economical objective functions are taken into account in the optimization procedure; the technical objective, related to system reliability, is expressed by the Energy Index of Reliability. In [8] a support technique to help decision makers study the influencing factors in the design of a hybrid solar and wind power system for grid-linked is presented.

In [9] the development of a computational model for optimal sizing of solar and wind hybrid energy system is presented. The performance of solar and wind system is evaluated through more accurate and practical mathematical

Manuscript received on 26/05/2010. Revised on 05/11/2010. Accepted for publication on 13/11/2010 by recommendation of the Editor João Onofre P. Pinto.

models, combining with hourly measured meteorological input data and load data.

In practice, reliability, cost and sustainability factors are strongly linked. Systems with low reliability are not attractive either for consumers or investors. This leads to stagnation of the economy in places without electrical energy. Under this motivation, this paper presents the design and implementation of a stand-alone hybrid power generation system that meets the following requirements:

- Provide electrical energy 24 hour a day to consumers, with reliability and quality similar (or better than) to big cities;
- The system must be robust and operate without the intervention of specialized people;
- Equipments must be projected to operate in a centralized way and in adverse conditions (marine environment and high tropical temperatures);
- The system must be projected to be monitored remotely, by using satellite communication service;
- Explore the available primary clean energy resources;
- Efficiency: where energy is limited, efficient procedures and equipments are required;
- Expansion flexibility: future expansions must be allowed;
- Accomplish environmental pressure.

Taking into account these requirements, a robust renewable energy –based stand alone system to bring electrical energy to isolated communities has been developed. It is a hybrid system based on solar photovoltaic and wind energies, conceived in such a way to fully provide electricity to the energy demand with quality, reliability, sustainability, robustness, and without degrading the environment. This is a pilot project in Lençóis's Island, Cururupu, MA, in the northeast of Brazil.

The main contribution of this work was to include in the various critical stages of the project, requirements to improve the overall reliability of autonomous systems based on renewable energy. By applying control and automation technology it is possible to provide a continuous energy service, minimizing emissions and maximizing the trust and credibility of costumers and investors in the electric service provided. The practical results validate the proposal.

In the following sections the system description, operation features, and experimental results will be presented.

II. DESCRIPTION OF THE IMPLEMENTED SYSTEM

Stand alone micro-grids are associated to remote isolated small communities, some geographically concentrated, other spatially distributed in a given region, with electrical service provided by a single or several sources such as: diesel generators, photovoltaic systems, wind micro-turbines, hybrid systems, frequently available only a few hours by day.

These communities are far from the conventional electrical grid due to the following reasons, among others:

a. Natural obstacles, such as mountains, rivers, natural reserves;
b. Communities located in islands;
c. Environmental constraints;
d. High distance from conventional electricity networks.

The local weather, geographic location and environmental characteristics of these small isolated demands do not allow the formulation of a unique technical solution for any scenario. Rigorously, each case is its own. Nevertheless, it is possible to identify critical issues with hard impact in the definition of most appropriated solutions for electrical service to a given isolated community. Some of these critical issues are the following:

- *Poor communities:* small communities with a low development index are not attractive for energy investments. Very low demand is critical for sustainability of electrical service. Usually, governmental actions have subsidized initial investments in order to promote economical evolution of these communities and future sustainability of the energy service.
- *Environmental and ecological issues:* some communities are located in areas with environmental constraints such as reserves, ecological parks, etc. In these cases, pollutant generating sources are alternatives to be excluded and clean primary sources such as solar and wind, micro–hydro, tidal, etc. are candidates to be considered.
- *Weather issues:* weather includes sunshine, rain, cloud cover, winds, hail, snow, sleet, freezing rain, flooding, blizzards, ice storms, thunderstorms, steady rains from a cold front or warm front, excessive heat, heat waves and more. These issues determine what kind of generating source is more appropriate. Good and regular wind speed is attractive for the exploration of wind energy. Analogously, in case of good solar incidence.
- *Hazardous environment:* this term is usually used to define the destructive action of the surrounding environment on a material. For instance, exposed structures and components in the marine environment are subjected to several factors causing or conditioning mechanical, physical, chemical, electrochemical and biological breakdowns. This is the case on islands and coastal areas; the project must consider these issues in the development of the generating system and the maintenance policies as well.

It is very important take into account theses issues in order to obtain a technical well adapted solution, keeping the equilibrium among the user´s needs, the investments and the environmental constraints fulfillment. For example, equipment design not adapted to the environmental conditions has critical sustainability, due to frequent fails and growth of operational costs is expected.

A. Sizing the hybrid system

The sizing of the hybrid system was based on [6]. However, the limited availability of types of micro-turbines and PV panels on the local market that met the requirements of logistics, simple installation and adaptation to climatic conditions has considerably reduced the space for optimization. Thus, the decision variables were assumed discrete and define the number of micro-turbines, PV panels, KW diesel and KWh battery to be installed respectively. The problem can be formulated as follows:

$$\text{Min } \sum_{i=1}^{4} c_i x_i$$

$$\text{s.t.} \quad E_1(t)x_1 + E_2(t)x_2 + E_3(t)x_3 + E_4(t)x_4 \geq E_L(t) + losses(t)$$

$$E_4(t)x_4 = \alpha(E_L(t) + losses(t))_d$$

Where c_i is the equivalent unitary cost in present value (including initial cost, residual value and O&M per year) of a wind micro-turbine, a photovoltaic panel, a KW of diesel generator and KWh of battery, respectively. In the case of diesel generator, an environmental penalty factor is added. x_i is the decision variable that indicates the amount of wind turbines, photovoltaic panels, KW of diesel generator and KWh of battery capacity to be installed, respectively.

E_i represents the energy provided by source *i* in the period *t*. E_L is the energy that must be met in the period *t* and *losses* represents the losses in conversion devices and the power grid in the same period.

The suffix d in the second constraint refers to average energy and losses projected for a day. The parameter α determines the level of autonomy of the battery bank. E_4 is a function of battery capacity, depth of discharge allowed and battery efficiency. The monthly average solar and wind energy are calculable from historical data of wind and solar incidence in the region.

In the formulation of the problem, it is assumed that the load is always met. In the case of deficit of primary energy, the generator must complete the balance of load assuming the role of slack generator. It is expected that the participation of the diesel generator in the overall operation will be minimal. The problem formulated above was solved using commercial software packages. The reference values of costs are summarized in the Appendix. The system obtained and implemented is described below.

B. The implemented hybrid system

The system of the pilot project in Lençóis Island is composed by:

- A centralized hybrid generation system;
- Three-phase 380 VAC – 60 Hz aerial distribution network;
- Public lighting based on high efficient lamps.

This hybrid system began operation in June of 2008, at Lençóis Island located in the northeast area of Brazil. The island has 90 houses, and a population of approximately 393 habitants. The actual residential energy consumption is approximately 4,134 kWh/month, with a demand of 9.5 kW. If it is considered to have a growth rate of 1.5% a year, the projected consumption and demand in 10 years will be approximately 4,800 kWh/month and 12 kW, respectively. Therefore, the generation system has enough power to supply the costumers for at least 10 years without any increase in the generation sources.

When the system was conceived, the community energy was supplied by a 30 kVA diesel generator. It worked for just 4 hours a day (18:00 h – 22:00 h). The total cost of energy (corresponding to O&M cost only) was approximately U$ 9 per month for each house. Now the system is working 24 hours a day and the mean value of energy is U$13.6 per month per house.

The average value of U$ 13.6 per costumer was estimated taking into account small maintenance costs and the formation of a reserve fund to change the battery bank at each average period of their life span, in general two years. Assuming an average consumption of 45 kWh / month per consumer, the price per kWh would be U $ 0.3022. This value is not commercially competitive taking into consideration the cost of investment. However, considering the indirect benefits of such a project as for example the improvement of life´s quality of local people and the environmental damage avoided, it can be argued that such systems are important and should be supported in greater numbers by the public sector.

The simplified block diagram of the hybrid power center is presented in Figure 1. The solar subsystem is composed of 9 PV strings, in parallel, each formed by 18 PV panels in series. Each string has a charge controller to provide the correct changing of the battery bank. The total maximum power of this subsystem is approximately 21 kW. The wind subsystem is formed by three wind turbines, each with nominal power of 7.5 kW and specifications showed in Table I. These turbines are placed approximately 500 m from the power house and are connected by three independent three-phase underground cables.

TABLE I
Specifications of the wind turbines

Start up wind speed	3.1 m/s
Cut-in wind speed	3.5 m/s
Rated wind speed	12.4 m/s
Furling wind speed	15.7 m/s
Maximum design wind speed	50 m/s
Rotor speed	0 - 350 RPM
Rated power	7.5 kW

The wind generators are permanent magnet synchronous type, and the generated AC voltage is rectified to charge the battery bank. These two subsystems work in parallel to charge a bank composed of 120 batteries, arranged in 6 lines, each line formed by 20 batteries of 150 Ah in series. The nominal voltage of the bank is 240 VDC. The rated capacity of this battery bank is 900 Ah at 240 Vcc that correspond to 216 kWh. To improve the use of intermittent energy from renewable sources, the charging voltage of the bank is limited in the range of 287 V to 296 V. This corresponds to a voltage of 14.35 V to 14.80 V per battery, which is approximately the voltage equalization of the batteries used as stated in the manufacturer's manual. The charge of the bank is monitored by a PLC that controls the sources so that the charging current does not exceed 10% of the rated bank and the DC bus voltage is limited to a maximum of 296 V. In the case of the contribution of the PV generator to the charging of the bank a shunt-type controller is used, which short-circuits the strings of the photovoltaic generator when the charging current and / or the voltage of the bank tend to reach values exceeding the limits mentioned. Assuming the batteries are fully charged and a maximum allowable depth of discharge of 30%, the battery bank would be able to meet the actual system load for a continuous period of approximately 8 hours. This value is based on a current average consumption of 5.8 kWh / h and an overall efficiency of the system estimated at 70%.

There is a 53 kVA/48 kW diesel generator as a backup unit to be used eventually during the lack of each of the primary sources of energy or in case of system maintenance.

The DC bus is the input of the inverter subsystem, which is formed by 3 inverters configured to work in parallel, sharing equally the load. In this early stage of operation just 2 inverters are necessary for supplying the load. With this mode of operation the mean time before failure (MTBF) of the overall system increases. The supervisory control is done by a programmable logic controller responsible to coordinate the parallel operation of all sources with special attention to efficiency, the charge control of the battery bank, the load control of the diesel generator (eventually when it is turned on), and the measurement and transmission of all the variables. The system will be monitored at the Institute of Electrical Energy/Federal University of Maranhão that is located 333 km away from the island.

One of the features of standalone hybrid renewable generation systems is its small energy consumption motivated mainly by the low personal incoming/house. If the system is projected to supply energy during, for example, 20 years it will be working a long time at almost no-load condition. In this scenario the system's efficiency will be very low during the first years of operation. Therefore, it is fundamental that the overall generation plant works at its maximum possible efficiency.

For example, take a 20 kVA inverter, with 88% efficiency (typical for inverters of this size in Brazil). This efficiency is measured at full load, corresponding to 2.4 kW of power loss for this inverter. In the most optimistic situation the inverter no-load loss is in the range of 1 kW. Now, suppose that the wind speed is 1/3 of rated speed. At this operation point, the wind turbine generated power would be 1/9 of rated value. With the wind turbines used in the project, this corresponds to approximately 0.833 kW. For this situation, more than one wind turbine would be necessary just to supply the inverter losses.

The same occurs to the diesel generator backup. It should work only when there is a complete lack of renewable energy. With field measurements it was verified an oil consumption at no-load of approximately 40 % of the rated oil consumption. This is approximately the same consumption observed in the datasheet of the diesel generator´s manufacturer. So, if the diesel generator is expected to be used, it must work near its full load condition, which represents the maximum possible efficiency point.

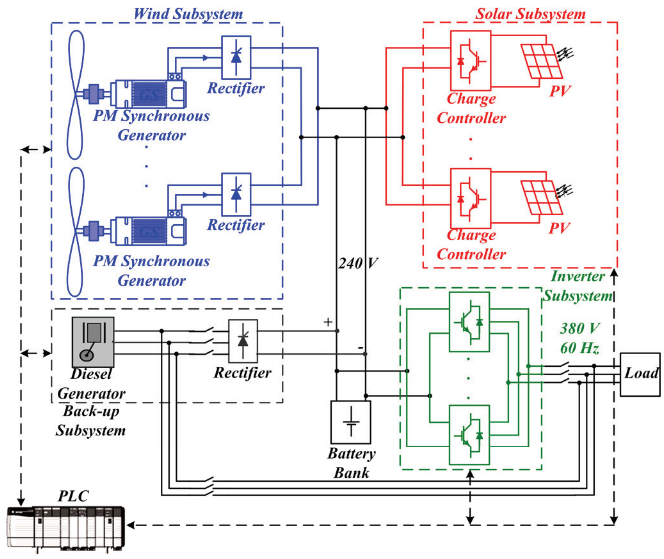

Fig. 1. Block diagram of the Power Center.

III. INVERTERS

The inverters proposed in this work were developed to fulfill the main weakness of renewable hybrid systems: efficiency, expansion flexibility, and robustness. The necessity of a reliable system is due to the long distance and difficult access to isolated communities. Furthermore, the system must be robust against the weather: high temperatures and humidity. The expansion capacity must be taking into account because these systems are conceived to improve the development of the region where they are working.

A. Reliability and Robustness

By considering the basic structure of an inverter, field measurements reveal a MTBF = 60,000 hours for a standalone unit working without using any kind of transfer switch to another grid in case of failure. This number means an expected operation of 6 years without failure in supplying energy to the costumers. Actually, the prediction of the MTBF used here was based on historical data collected from a company in Brazil that manufactures similar equipments (UPSs). During the calendar year of 2008 the measured MTBF = 120,000 in these UPSs. This result was calculated based on (2).

$$MTBF = \frac{\sum_{i=1}^{n} 24 D_{NB_i}}{\sum_{i=1}^{n} F_{NB_i}} \qquad (1)$$

where: D_{NB_i} is the number of days of operation of the equipment within the calendar year of monitoring; F_{NB_i} is the number of failures of the equipment within the calendar year of monitoring; n is the number of equipments monitored. This is the traditional approach to predicting the reliability of devices in field using the exponential or constant failure rate model [10], [11].

Due to the fact that the inverters developed for this application are new products that are exposed to high temperatures and humidity, it was decided to take a conservative number and it was predicted an MTBF equal to half the value measured with similar equipments.

Based on the MTBF, the probability of failure in the first year of operation can be calculated using the equation (2) [12].

$$P_N = \frac{h_{year}}{MTBF} \tag{2}$$

where: P_N is the probability of failure, and h_{year} is the number of working hours per year. Based on the predicted MTBF, the probability of failure in one year of operation is 14.6%.

By using two inverters operating in parallel, sharing equally the load in a mode called *N + 1*, the MTBF of the system is much higher, drastically reducing the probability of failure. In such configurations, *N* equipment works in parallel supplying all the load energy, and 1 more redundant equipment is added to the system. Figure 2 shows this configuration, with two inverters. For this case one inverter (*N*) is able to supply energy to the load. The other inverter (*+1*) is redundant. Figure 2 represents the configuration that is working in the island.

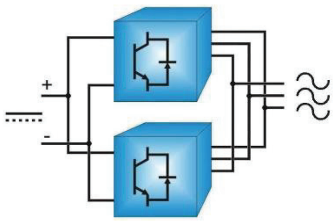

Fig. 2 Inverters operating in parallel, configuration N+1.

For this case, it is required the failure of both inverters for the system to stop supplying the load. This situation happens only if two events occur. Using the binomial distribution and the individual probability of each inverter [12], the probability of failure during one year will be approximately 2.1%. Based on this probability the MTBF of the overall inverter system can be calculated, which is 410.000 hours. This corresponds to 47 years of uninterrupted operation. It is clear that the expected life of this equipment is not even close to this value. However, it serves as a metric that reflects the high probability obtained with the configuration.

B. Expansion Capability

The utilization of an inverter set with several renewable sources in an isolated island is necessary because of the pulsating nature of the sources. To be used by the costumers, the energy must be converted and regulated. The inverter converts the CA energy generated by the sources in CA energy useful to costumers.

The presence of electrical energy in small, isolated communities is responsible for the improvement of human kind's quality of life. In several cases the steadily increasing use of energy is more than expected. Thus, the expansion flexibility is one essential aspect that must be observed when designing such systems. If just one commercial inverter is used, in a couple of years, the inverter will be shown insufficient to supply the load demand that increases. As a result, in some years the inverter must be replaced. The total cost of the replacement is high. With the proposed system, as the load demand increases, more inverter units can be placed in parallel with the existing ones.

C. Efficiency

The efficiency of the inverters was based on a compromise between switching frequency, bandwidth of the controllers, and size of the filters. The better efficiency was due to the decreasing in the inverter loss and power used to cool the system. The efficiency results measured in laboratory is shown in Table II. It is observed that the overall efficiency is comparable to that of equipments of the same size with isolation transformers.

TABLE II
Efficiency Results

Overall Efficiency measured with True RMS equipments			
Equipment	**Input Power (kW)**	**Output Power (kW)**	**Efficiency (%)**
Inverter 1	20,5	19,1	93,17
Inverter 2	19,1	17,4	91,09

D. Implemented Topology

The hardware design was based on a 20 kVA, a three phase IGBT inverter. The output of 60 Hz voltage was regulated based on a space vector pulse width modulation (SVM) with a 4 kHz switching frequency. An output low pass filter was used in each phase to eliminate the high frequency harmonic content due to the inverter switch action. Furthermore, an isolation transformer was used to provide galvanic isolation and change the output voltage level. As a final component there is output impedance (*Z*) used to share equally the load between the units. There are different methods to connect inverters in parallel [15], but in the Drooping method the inverters present an electrical behavior similar to that of generators working in parallel [14],[16],[17]. In this method the output impedance is responsible to share the reactive power throughout the units connected in parallel. With the increase of the output current, the output voltage has a proportional drop. The block diagram of the inverter system is presented in Figure 3. It can be seen that there are two controllers: one for the q-axis voltage (V_q^{ref}), and another for the d-axis voltage (V_d^{ref}).

It has been observed that the transformer together with the output inductor improved the reliability of the inverter because they limit the current variation (*di/dt*) and make easier the protection against short circuits. In Figure 3 there are just two inverters but it is possible to include other units as the load level increases. The original project was designed to have three inverters. The third one will be included as soon as the load level increase.

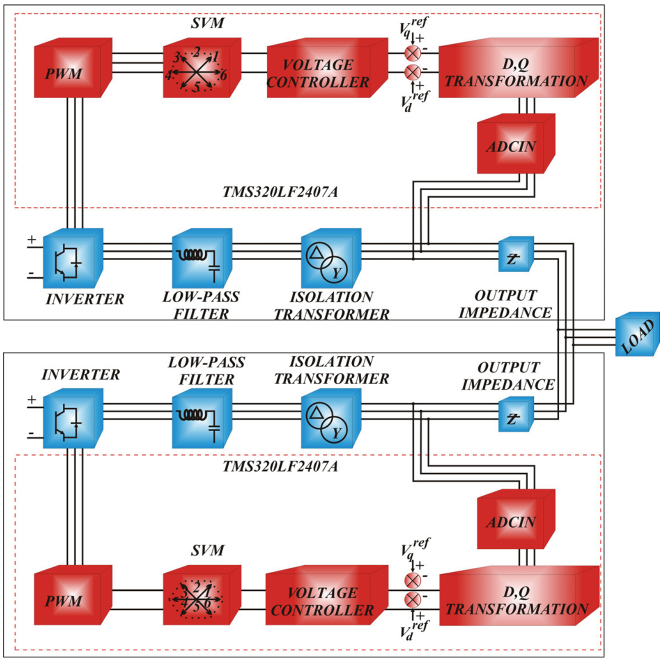

Fig. 3. Block diagram of 2 inverters in parallel (N+1).

The inverters were developed to give the biggest possible reliability and robustness to the system. The protections against overload were realized considering different temporizations for several current levels. The protection against inrush currents due to non linear loads was also considered, and was included in the current regulator loop a limitation of the PWM pulses every time the currents exceed a predefined maximum limit.

For protection against short circuits in the consumers' installations, it was used circuit breakers with thermo magnetic tripping curve type B (IEC 947-2) to correct operates the selectivity of the system. In these situations the inverters keep operating for approximately 16 ms. During this period, the inverters limit the over current to a safe value supported by the IGBTs, waiting for circuit breakers trip. In case the short circuit does not disappear, the inverters disconnect the load. The system has another protection against short circuit and overcharge that is the monitoring of the voltage V_{CE} of the IGBTs. In case of over current the voltage V_{CE} increases as a function of the current. In case this voltage exceeds a predefined maximum limit the IGBTs pulses are suppressed.

E. Inverters operation

The operation mode used here is a quasi parallel mode [13],[14]. In this mode, whenever the load is below ¼ of the nominal load one of the inverters is switched off. Thus, the efficiency of the system at low load is improved because one of the inverter's losses are not supplied by the sources. A PLC controls the operation of the inverters. In case of failure of the unit that is supplying the load, an automatic signal starts up the other one. Even with this operation mode, the worst probabilistic case would be when the two inverters were simultaneously working in parallel, as predicted before.

The voltage control is based on a DSP TMS320LF2407A, which implements a discrete PID voltage regulation as shown in Figure 4. In this figure it is shown the control block diagram of just one inverter. The other inverters working in parallel have the same control topology. Because there are two controllers, one for each voltage component (d and q voltages), and the diagram was drawn using rotating vectors: two lines in the diagram stands for voltage vector. The control of the system is accomplished by two loops: an inner loop responsible for the fastest dynamics, and an outer loop responsible for the slowest dynamics. The inner loop is based on a proportional + derivative (PD) controller that has a widespread use in industry and easy to tune. It is responsible to track the sinusoidal voltage reference. Due to its sinusoidal reference, and the plant model this controller has been shown appropriated to track the reference. The steady state error is eliminated by a second outer loop. Its output is multiplied by the sinusoidal reference (unit rotating vector). This second loop is implemented by a proportional + integral (PI) controller. Since its reference is the voltage RMS value that is a dc constant, the steady state error is zero. The output dq reference voltages of the controllers is transformed to abc reference voltages in the block called dq → abc. These voltages are the reference for the PWM generator. The measure voltages must be converted to dq voltages, and this is done by the block called abc → dq.

To obtain a system totally autonomous, it was implemented a method of parallelism that doesn't use any communication interface among the units, called "Drooping Method" [15]. In this method the inverters present an electric behavior similar to that of generators operating in parallel. Whenever an increase in the load active power occurs, the generators tend to reduce their rotation, reducing their frequency proportionally. In the developed system this idea was implemented. Each inverter has its own circuit to accomplish the Drooping Method, where the frequency decreases to compensate for the variations in the active power.

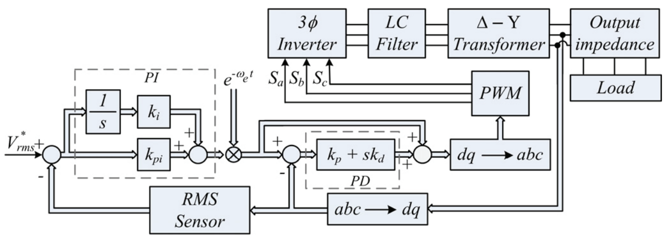

Fig. 4 Block diagram of the inverter output voltage control

Other important aspect is the start up of the inverter subsystem after a fault or intentionally turns off for maintenance or any other reason. It must be observed that any time the inverter subsystem is turned off for maintenance, the diesel generator automatically is turned on keeping the supply of energy to the load. In case of short circuit on the grid, this subsystem tries reconnect the load three times. Due to the limited capacity of the inverters the inrush currents of the equipments to be energized (in this specific case refrigerators, freezers, lamps and TVs) could eventually disconnect the inverters because the protection against over currents. To mitigate these problem two procedures were tested:

1) Any time the system has to be turned on the following sequence must be applied:

- Turn on the diesel generator and supply the load;
- Turn on the first inverter;
- Turn on the second inverter and parallelize with the other one that was turned on previously;
- Transfer the load to the inverter subsystem;
- Turn off the diesel generator.

2) In this second procedure the load is sectioned in several circuits. For the specific case of the Island there are 4 circuits, called north, south, east, and west. So the inverter subsystem is turned on following the same steps described in the first procedure, and then the load is sequentially added, sector by sector. This second scheme was preferred since it is not necessary to turn on the diesel generator.

However, the first scheme will eventually be used in case one of the inverters has a problem. It must be observed that this is a special case that will be implemented to avoid service interruption of electricity supply.

IV. FIELD RESULTS

Figure 5 shows the three wind turbines installed in the field. The AC generated energy is transmitted by three three-phase underground cables to the power house. There, the voltages are rectified and linked to a single DC bus. The underground alternative was the safest and most adequate for the dune area.

Fig. 5 Wind turbines installed in the island

Figure 6 shows the control and power house of the system. Here, the energy from different sources is processed and regulated for use by consumers fulfilling the distribution standards. The power house is divided into two rooms: the Power and Control room and the Batteries room. Power inverters, charge controller, rectifiers, monitoring and control center are at the first one. Only the battery bank is placed at the second one.

The aerial distribution network should be based on insulated cables with the objective of dealing with the aggressive marine environment. The public illumination must also be protected against the hazardous environmental conditions. Due to limited energy resources the public illumination is based on compact fluorescent lamps. The solution implemented in the proposed system is presented in Figure 7.

Fig. 6 Control and power house.

The system has been operating since July of 2008, supplying energy 24 hours a day. At the beginning, some events happened, most related to bugs in the PLC program. After three months no events with supply interruption have occurred. The first year - 160 days - was considered as a testing period and 2009 as steady state operation. There are many indices for measuring reliability. The most common are referred to as SAIFI and SAIDI, defined in IEEE Standard 1366 as system average interruption frequency index and system average interruption duration index, respectively. These indices are equivalent to FEC and DEC, respectively, used in Brazil.

As a reference, a typical distribution company of Sao Paulo reported in 2008 SAIFI = 5.87 and SAIDI= 6.85 hours. From July 20th to December 31st of 2008, the indices obtained from Lençois system were: SAIFI = 3 and SAIDI = 72 hours. In this first year, just 24 hours were provided by diesel generator, representing only 0.609 % of the period (164 days or 3936 hours). Therefore, during 99.390 % of this time the demand was supplied by renewable solar and wind sources.

At the second (2009), and third (2010) years no supply interruptions have been registered, leading to SAIFI =0 and SAIFI =0. These good reliability indices are attributed to the good automation degree of the system and to the small scale distribution network as well, adequately prepared for the conditions in the marine environment.

In relation of the composition of the supplied energy, January – June is the rainy season, where the availability of renewable resources drops significantly. This lead to the use of the back-up diesel generator in some days, for some hours in order to match the power demand and avoid excessive discharge of the battery bank. For the second year, the diesel generator was committed about 400 hours over a total of 8760 hours of continuous energy service. This means that, despite the adverse situation of the rainy season, 95.43% of time the power supply was provided by renewable sources that fully supplied the demand. Table III summarizes the indices of the system operation over the last three years.

Fig. 7 View of the aerial distribution network.

TABLE III
System operation indices

System Operation				
	SAIFI	SAIDI	Renewable energy operation	Diesel operation
1st year (3936 hours)	3	72	99.390%	0.609 %
2nd year (8760 hours)	0	0	95.43%	4.56%
3rd year (2544 hours)	0	0	95.30%	4.70%

An important aspect related to the system operation is the control strategy of the battery bank [13] that allowed during this period of functioning only 16 batteries to present problems. This corresponds to 13 % of a total of 120 batteries. As reported by the manufacturer, the problem of four of these batteries was due to incorrect transportation. In relation to the other ones (12 batteries), the problem was associated to incorrect charging for a long period of time during the initial six months of operation. This was due to the low voltage that was using during the charge process of the battery bank. After a discussion with the manufacturer this value was increased to a value compatible for the application.

During this period of operation the load never gets to the levels indicated in Table I. The maximum load power registered was 10 kW. Therefore, the inverters efficiency measured was lower than the efficiency obtained in the laboratory tests, especially because the inverters supply non-linear loads in the Lençóis Island. Figure 8 shows the input and output powers, and efficiency measured in a typical day of February/2010. The maximum efficiency was approximately 90.5 %, registered at the time instant of maximum load.

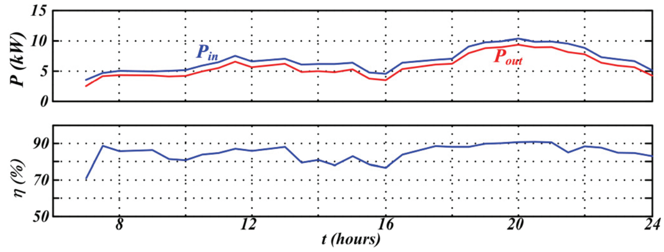

Fig. 8 Power and efficiency of the inverters measured at operation in the island

The actual demand of the system is presented in Figure 9 that show the RMS value of the phase and neutral currents of the inverter, measured during approximately 10 hours. These values were measured in December/2009. It can be observed that the system is unbalanced and that the currents present a large harmonic content which implies in a large neutral current.

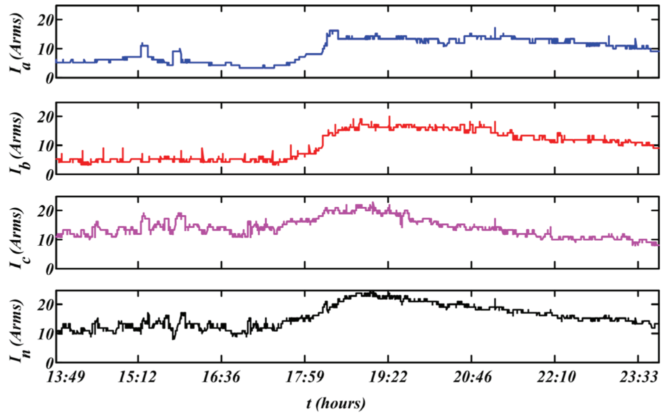

Fig. 9 Phases and neutral RMS currents

The harmonic content of the currents can be observed in Figure 10 that show the total harmonic distortion of the phase currents (THD_i) measured during the same period of time showed in Figure 9. The high current distortion is justified fundamentally due to the features of the loads, composed by compact fluorescent lamps with low power factor, refrigerators, freezers, and TVs.

However, even with the high current harmonic distortion, and load unbalance, the voltage total harmonic distortion (THD_v) at the output of the inverters is lower than 7 %, as can be seen in Figure 11. This value is within the standards established by the Brazilian regulatory agency ANEEL (Standard Nº 395, December, 15th 2009), that established a maximum value of 10 %. Furthermore, none of the individual harmonic is bigger than the levels established in the same standard that are 6.5 % for the third harmonic and 7.5 % for the fifth harmonic. The measured values are presented in Figure 12, that show the main voltage harmonics (3rd and 5th) for each phase voltage.

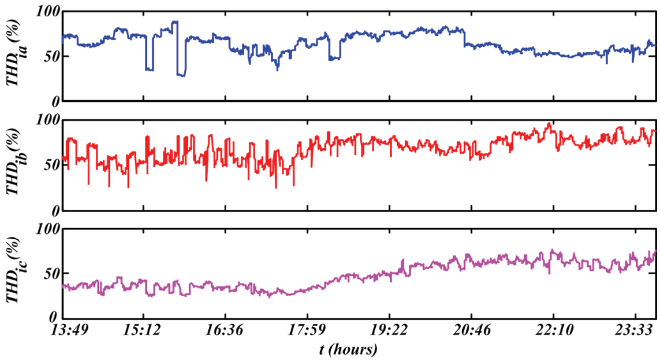

Fig. 10 Total harmonic distortion of the phase currents

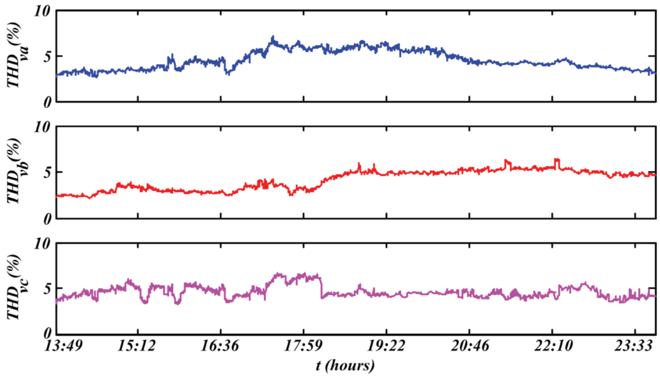

Fig. 11 Total harmonic distortion of the phase voltages

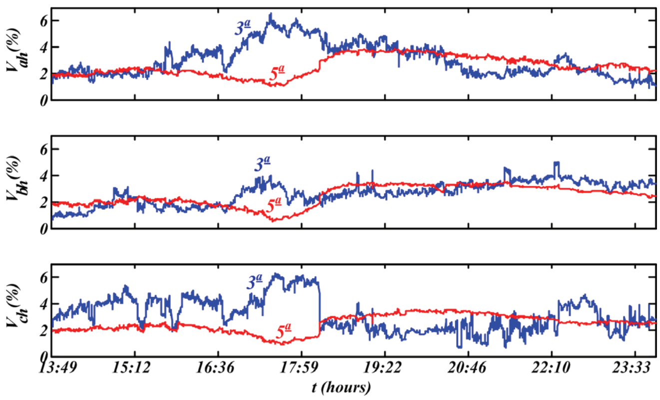

Fig. 12 Third and fifth harmonics of the phase voltage

V. CONCLUSION

This paper presented the design and operation of a renewable hybrid generation system based on solar photovoltaic and Wind energies. The innovations introduced in this kind of system are related with the requirements imposed and adequately fulfilled, i.e., reliability of the service, adaptability to the climate conditions and high level of robust automation in order to reduce maintenance needs. Typical isolated communities in Brazil have low energy demand and difficult access. These requirements are addressed to make sustainable this kind of standalone energy systems.

The experimental results presented show the quality of the generated energy, within the Brazilian standards. The main contribution of this work was to show that isolated systems based on renewable energies are viable to be implemented and operated if in the design guidelines it is taking into account the system reliability, considering the peculiarities of the load, climatic, environmental and logistical. The system is working in perfect conditions since June 2008 at Lençóis Island, Cururupu, MA, northeast of Brazil.

ACKNOWLEDGEMENT

The authors would like to thank the financial support and motivation provided by the Ministry of Mines and Energy, CP Eletrônica S.A, CNPq and Federal University of Maranhão (UFMA).

REFERENCES

[1] T. Senjyu, T. Nakaji, K. Uezato, and T. Funabashi, "A Hybrid Power System Using Alternative Energy Facilities in Isolated Island," *IEEE Transactions on Energy Conversion*, vol. 20, no. 2, pp. 406 – 414, June 2005.

[2] N. A. Ahmed, and M. Miyatake, "A Stand-Alone Hybrid Generation System Combining Solar Photovoltaic and Wind Turbine with Simple Maximum Power Point Tracking Control," *in Proc. of IEEE-IPEMC,* pp. 1 – 7, 2006.

[3] G. Boyle, *Renewable: power for a sustainable future*, Oxford, 2004.

[4] L. Mendez, L. Narvarte, A.G. Marsinach, P. Izquierdo, L.M. Carrasco, and R. Eyras, "Centralized stand alone PV system in microgrid in Morocco," *in Proc. of 3rd World Conference on Photovoltaic Energy Conversion*, vol. 3, pp. 2326 – 2328, 2003.

[5] V. C. Nelson, R. E. Foster, R. N. Clark, and D. Raubenheimer, "Wind Hybrid System Technology Characterization. *NREL – National Renewable Energy Laboratory*, pp. 01 – 50, 2002.

[6] R. Chedid, and S. Raiman, "Unit sizing and control of hybrid wind-solar power systems," *IEEE Transaction on Energy Conversion*, vol. 12, no. 1, pp. 79 – 85, 1997.

[7] G. La Terra, G. Salvina, and T. G. Marco, "Optimal Sizing Procedure for Hybrid Solar Wind Power Systems Fuzzy Logic," *in Proc. of IEEE MELECOM*, pp. 865 – 868, 2006.

[8] R. Chedid, H. Akiki, and S. Raiman, "A decision support technique for the design of hybrid solar-wind power system," *IEEE Transaction on Energy Convertion*, vol. 13, no. 1, pp. 76 – 83, 1998.

[9] S. C. Gupta, Y. Kumar, and G. Agnihotri, "Optimal Sizing of solar-wind hybrid system," in *Proc. of ICTES* pp. 282-287, 2007.

[10] M. G. Pecht, F. R. Nash, "Predicting the Reliability of Electronic Equipment," in *Proc. of the IEEE*, vol. 82, no. 7, 1994.

[11] A. P. Wood, "Reliability-Metric Varieties and Their Relationships," in *Proc. of the Reliability and Maintainability Symposium*, pp. 110 – 115, 2001.

[12] E. E. Lewis, *Introduction to Reliability Engineering*, John Wiley & Sons Inc., 1987.

[13] L. A. de S. Ribeiro, G. Bonan, A. S. Martins, O. R. Saavedra, and J. G. de Matos, "Small Renewable

Hybrid Systems for Stand Alone Applications," in *Proc. of the IEEE Power Electronics and Machines in Wind Applications*, pp. 1 – 7, 2009.
[14] G. Bonan, A. S. Martins, L. A. de S. Ribeiro O. R. Saavedra, and J. G. de Matos, "Parallel-Connected Inverters Applied in Renewable Energy Systems," in *Congresso Brasileiro de Eletrônica de Potência*, p. 993 – 999, 2009.
[15] I. J. Gabe, J. P. Costa, M. Stefanello and H. Pinheiro,"Modulação Space Vector Estentida a Conversores Estáticos com Braços Em Paralelo", *Eletrônica de Potência* – SOBRAEP, vol. 12, no 3, pp. 206 – 216, November 2007.
[16] S. J. Chiang and J. M. Chang, "Parallel Control of the UPS Inverters with Frequency-dependent Droop Scheme," in *Proc. of IEEE PESC*, vol. 2, pp. 957 – 961, 2001.
[17] Ernane A. A. Coelho, Porfírio C. Cortizo, and Pedro F. D. Garcia, "Análise para Pequenos Sinais de um Sistema CA Composto de Inversores e Conectados em Paralelo," *Controle e Automação*, vol. 13, no. 2, pp. 171 – 180, May-August, 2002.

APPENDIX

In Table IV it is shown the input data used in the sizing process. Each cost c_i includes initial investments, present worth of the salvage value of component *i* and present worth of the operation and maintenance. These costs reflect the Brazilian reality and the logistic difficulties for installing the system in a place without any infrastructure and services. In order to minimize the participation of the diesel generator, an additional penalty factor is used in its equivalent cost. This factor (β) was assumed equal to 1000.

The estimated average monthly consumption of the load in a horizon of 10 years was 6,800 kWh per month. This load is divided in two parts: 4,800 kWh / month are due to residential loads and community loads (school, health center, public lighting, etc.) and 2,200 kWh / month due to a small ice plant. This plant works 6 hours / day and has an estimated production of 720 kg of ice per day. The estimated demand for the system at the end of 10th year was 28 kVA. The O&M costs have been extracted from [6]; the inflation rate was 10% per year. The 7.5 kW Excel wind micro-turbine and a 130Wp PV-panel were adopted as available and considered in the sizing process.

TABLE IV
Input data of sizing process

Equivalent costs			
C1	C2	C3	C4
9920 US$/kW	5622 US$/kW	1966 US$/kW	691 US$/kWh

BIOGRAPHIES

Luiz Antonio de Souza Ribeiro was born in São Luís, Maranhão, Brazil, in 1967. He received the B.S. degree from Federal University of Maranhão, São Luís, Brazil, in 1991, the M.S and Ph.D degree from Federal University of Paraíba, Campina Grande, Brazil, in 1995, and 1998, all in electrical engineering.

From August 2004 to February 2006, he was a Visiting Researcher at the University of Wisconsin, Madison. From 1991 to 2008, he has been with the Electrical Engineering Department, Federal Center of Technological Education, Maranhão. Since 2008 he is an Associate Professor in the Electrical Engineering Department, Federal University of Maranhão, São Luís, Brazil. His topics of interest include control systems, high-performance ac drive control, sensorless control, power electronics, and renewable energy systems.

Osvaldo Ronald Saavedra received the M.Sc. and Ph.D. degrees from the State University of Campinas, Campinas, Brazil, in 1988 and 1993, respectively. From 1983 to 1986, he was with Inecom Engineers Ltd, Arica, Chile. From 1994 to 1997, he was a Visiting Lecturer at the Federal University of Maranhão, Maranhão, Brazil. Since 1997, he has been a Professor in the Electrical Engineering Department and the Head of the Power System Group and Renewable Energy Center, Federal University of Maranhão. His topics of interest include intelligent applications to power systems, power systems operation and renewable sources.

José Gomes de Matos was born in Currais Novos, Rio Grande do Norte, Brazil, in 1957. He received the B.S. degree, and the M.S degree from Federal University of Campina Grande, Paraíba, Brazil, in 1980, and 1986, all in electrical engineering.
Since 2008 he is an Associate Professor in the Electrical Engineering Department, Federal University of Maranhão, São Luís, Brazil. His topics of interest include control systems, high-performance ac drive control, sensorless control, power electronics, and renewable energy systems.

Shigeaki Leite Lima received the B.Eng. and M.S. degrees from the Federal University of Maranhão in 2005 and 2007, respectively and is presently a P.h.D. student there. He is a Research in the Institute for Electrical Engineering. His current work includes intelligent systems for Power Systems, Renewable Energy, and engineering applications.

Guilherme Bonan was born in Santo Ângelo-RS, Brazil in 1978. He received the B.S. degree from Federal University of Santa Maria, Brazil, in 2001, and the M.S. degree from Catholic University of Rio Grande do Sul, Brazil, in 2010, both in electrical engineering.
He is a Development Engineer at the research department of CP Eletrônica. His topics of interest include digital control of converters, Power electronics, and renewable energy sources.

Alexandre Saccol Martins was born in Santa Maria-RS, Brazil in 1970. He received the B.S. degree from Federal University of Santa Maria, Brazil, in 1993, and the M.S. degree from Federal University of Santa Catarina, in 1995, both in electrical engineering.
He is a Development Engineer at the research department of CP Eletrônica. His topics of interest include power electronics, and renewable energy sources.