Isolated Micro-Grids with Renewable Hybrid Generation: The Case of Lençóis Island

Luiz A. de S. Ribeiro, Osvaldo R. Saavedra, Shigeaki L. Lima, José G. de Matos

***Abstract*--In Brazil around 2,000,000 families have not been connected to an electricity grid yet. Out of these, an important amount of villages may never be connected to the national grid due to their remoteness. For the people living in these 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. There is little scope for the productive use of energy. It is recognized that electric service contributes particularly to inclusive social development and to a lesser extend to pro-poor growth as well as to environmental sustainability. In this article, we present the specification, design and development of a standalone micro-grid supplied by a hybrid wind-solar generating source. The goal of the project was to provide a reliable, continuous, sustainable and good-quality electricity service to users, as provided in bigger cities. As a consequence, several technical challenges arose and were overcome successfully as will be related in this paper, contributing to increase of confidence in renewable systems to isolated applications.**

***Index Terms*— Stand-alone micro-grids; hybrid energy systems; solar energy; wind energy**.

I. Introduction

THE motivation behind the use of renewable energy sources is the reduction of CO_2 emissions and improvement of human kind's quality of life. This is especially true in isolated, standalone, small islands where the access to renewable energy sources is the only solution to meet their energy needs. An alternative is the use micro-grid supplied by centralized hybrid systems, where the combination of several natural resources guarantee a steadily energy generation.

Micro-grids are the centralized alternative to distributed one to supply electrical energy to homes in isolated communities. The main advantages are relative lesser maintenance cost and best exploration of the installed power.

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In recent years a growing interest for micro-grids has been observed in the technical literature. Recent technical publications include analytical modeling, studies focusing operation and performance, pilot projects and other advanced topics. Issues related to voltage controller design methods for DC-AC converters supplying power to a microgrid and protections have been addressed by several recent works [1-5]. In [6] the feasibility of control strategies to be adopted for the operation of a micro-grid when it becomes isolated are described and evaluated. In [7] the operation of a central controller for micro-grids is described. The goal is to optimize interconnected operation, by optimizing the production of the local distributed generations (DGs) and power exchanges with the main distribution grid. In [8] an overview of the micro-grid operation is presented including experiences from different countries. In [9-11] relevant issues related to dynamic behavior of micro-grids both under grid connected and autonomous operation are covered.

Even though there are different kinds of combinations of internal energy sources [12], a common combination for isolated micro-grids is the solar photovoltaic and wind turbines [13]. These systems have shown to be adequate for standalone applications in areas of difficult access [14][15] being responsible for the decreasing or even the elimination of diesel usage. In [16] an interesting review of practical applications using hybrid systems is presented. The major problems reported are related to 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 [17] the optimal design of a hybrid wind-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 [18] an automatic procedure to perform the optimal sizing of a grid connected Hybrid Solar 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 [19] a support technique to help decision makers study the influencing factors in the design of a hybrid solar-wind power system for grid-linked is presented.

In [20] the development of a computational model for optimal sizing of solar-wind hybrid energy system is presented. The performance of solar and wind system is evaluated through more accurate and practical mathematical models, combined 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;
- Robustness: the system must have robust operation without the intervention of specialized people;
- Equipments must be designed to operate in a centralized way and in adverse conditions (marine environment and high tropical temperatures);
- Remote monitoring: due to difficult access the system should be designed to be remotely monitored, 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 north of Brazil.

The main contributions of this work are:

- To introduce micro-grid concepts in the development of this kind of application;

- To include in the various critical stages of the project, requirements to improve the overall reliability of autonomous systems based on renewable energy.

- Application of control and automation technology 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. Stand-alone Micro-grids

Micro-grids are low-voltage distribution networks comprising various distributed generators, storage devices, and controllable loads that can operate either interconnected or isolated from the main distribution grid as a controlled entity [21].

Stand-alone micro-grids (SAMG) are permanently disconnected from an external network and consequently external sources cannot cooperate to meet load requirements. For this reason SAMG should strengthen and diversify their internal sources to ensure reliable supply of electrical energy to the load.

SAMGs are associated to remote isolated small communities, some geographically concentrated, others 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, etc, frequently available only a few hours a 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 defining the 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, the solar photovoltaic energy exploration is more appropriated;

- *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 in islands and the coast; 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.

III. Description of the System

In this section, the sizing of the system, implemented configuration and control issues are described.

A. Sizing the hybrid system

The sizing of the hybrid system was based on [17]. 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 defined the number of micro-turbines, PV panels, KW diesel and KWh battery to be installed. The problem can be formulated as follows:

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

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

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

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 calculated 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 north 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 – 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/month per house.

IV. SAMG Structure

Figure 1 illustrates the structure of the proposed SAMG. The overall reliability of SAMG is enhanced in three levels. At generation level, providing several sources linked together. At the DC/AC conversion level, providing redundancy, as will be detailed in the next section. At the distribution network level, by considering configuration and coordination protections and equipment adapted to corrosive environment as well.

An interesting review of network configuration for distribution systems with high integration of DG is presented in [22]. Typical low-voltage network are built in a radial structure. In our case, the three-phase low voltage network was projected in a star topology, using isolated cable with each branch protected by a low-voltage high-breaking-capacity fuse. This configuration is still the most appropriate for this application [22][23]. The cable sizing was calculated considering a maximum voltage drop of 5%. On the other hand, micro-turbines are linked to power centre by independent underground 3-conductors insulated aluminum cables. The cable sizing was defined considering maximum losses of 6%.

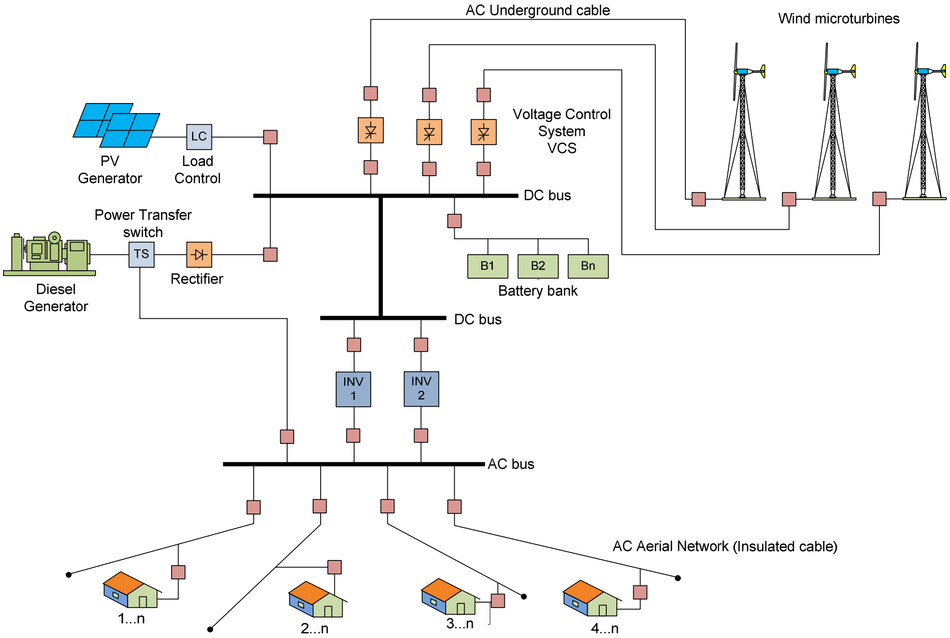

Figure 1: Micro grid structure

A. Power Center

The simplified block diagram of the renewable hybrid generation system is presented in Fig. 2. 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 (at wind speed of 13.8 m/s). These turbines are placed approximately 500 m from the power house and are connected by three independent three-phase underground cables.

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. 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 University that is located several miles away from the island.

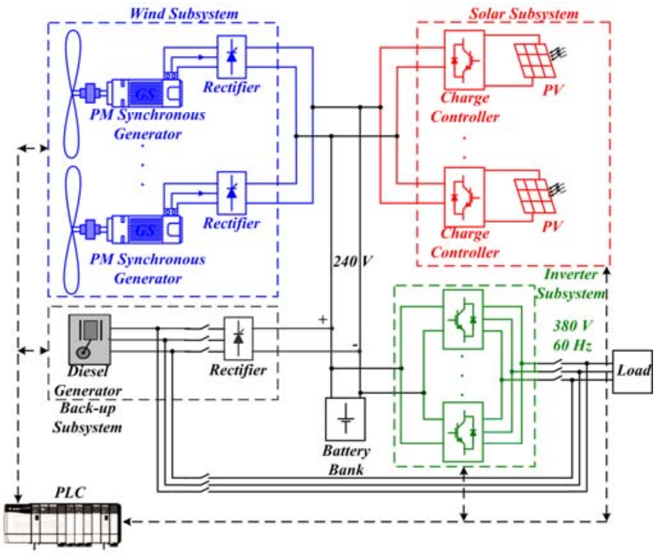

Figure 2: Block diagram of the Power Center.

B. Monitoring and Control

Figure 3 shows the monitoring and control structure. A centralized control system monitors relevant AC/DC variables, taking decisions to provide reliable supply by using efficiently the available resources and preserving the useful life of battery bank. All data are stored in database system with periodicity defined by user.

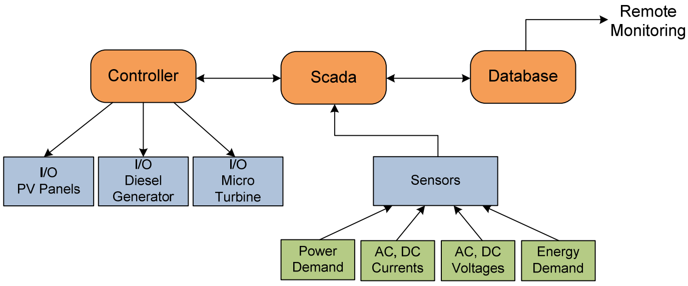

Figure 3: Monitoring and control structure

At the SCADA system relevant DC and AC electrical variables are monitored and stored. Current, voltage and temperature transducers at DC side have been installed to monitor the charge/discharge of battery bank, to monitor the room temperature and to measure the contributions of the photovoltaic system and wind turbines (after rectifying) as well. This data is used by the PLC in the charge control process (turn on/off PV rows), to startup/shutdown the backup generator, to control the load transfer between the backup subsystem and the inverter subsystem, to estimate the state of charge of the batteries, etc.

At the AC side, three multivariable digital indicators (MDI) were used, measuring three-phase demand, active and reactive powers, power factor, etc., in all operating scenarios.

C. Criteria for operation and control

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. 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. This is done by controlling the output current of the rectifier used in the diesel generator. The idea is use the generator to charge the battery bank with the part of its power. Whenever the load is low, the spare power of the generator is used to charge the bank in such a way that the diesel generator is always working approximately at a full load. The flowchart of the diesel generator and rectifier control is showed in Fig. 4.

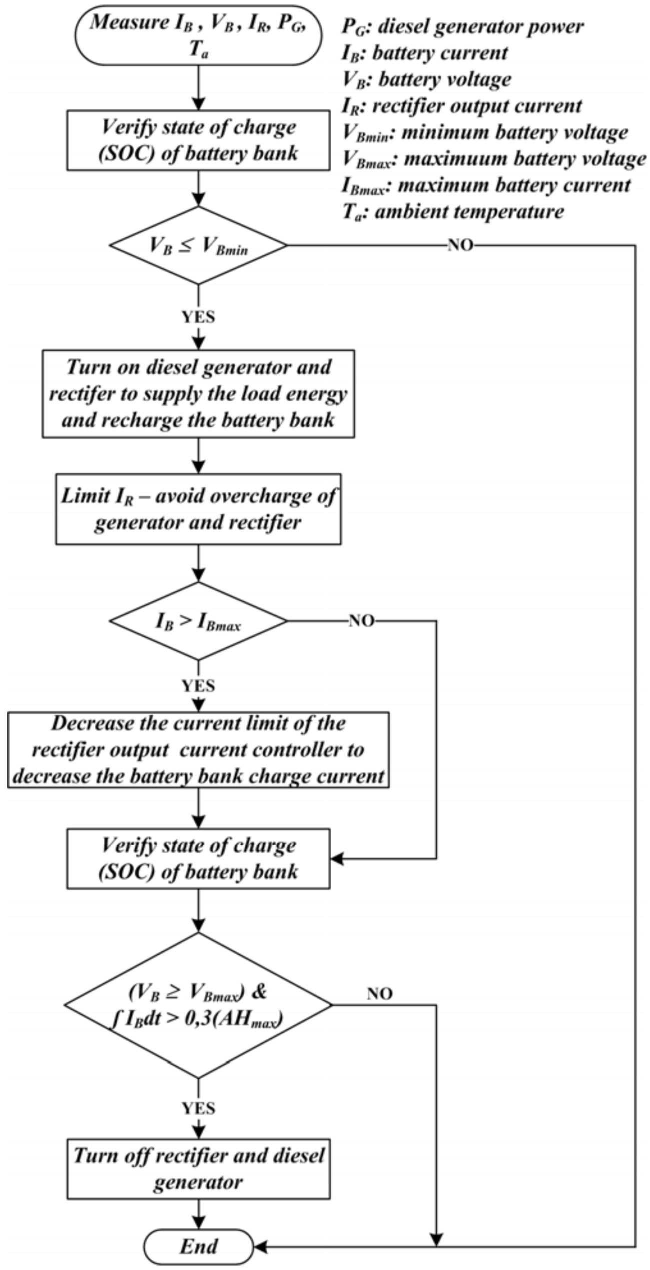

Figure 4 Flowchart of the diesel generator and rectifier control.

Initially the systems variables are measured and the state of the charge of the battery bank is analyzed based on the voltage level and the Ampere-hour count (AH - integral of I_B). Anytime that the battery bank is discharged (30% discharge) and the voltage level is below a minimum value (V_{Bmin} = *243 V*) the diesel generator and rectifier at its output are turned on. Because the other sources (wind and PV) are still in parallel with the rectifier at the output of the diesel generator, its output current must be controlled to avoid over current of the battery bank. This can happen if the wind or sun radiation or both increases during the time the rectifier is turned on. Furthermore, the current that feeds the battery bank must be controlled to not overcharge the diesel generator itself. Therefore, if the load increases the current that goes to the bank due to the rectifier must be decreased.

The diesel generator and rectifier are turned off as soon as the battery bank is completely charged. This state is verified by the amount of AHs sent to the bank and the maximum voltage level (V_{Bmax}). This V_{Bmax} is controlled by the ambient temperature (T_a). The manufacturer states that this limit must be decreased by 0.03 V/°C above 25 °C. As a result, the range of V_{Bmax} is: 287 V ≤ V_{Bmax} ≤ 296 V.

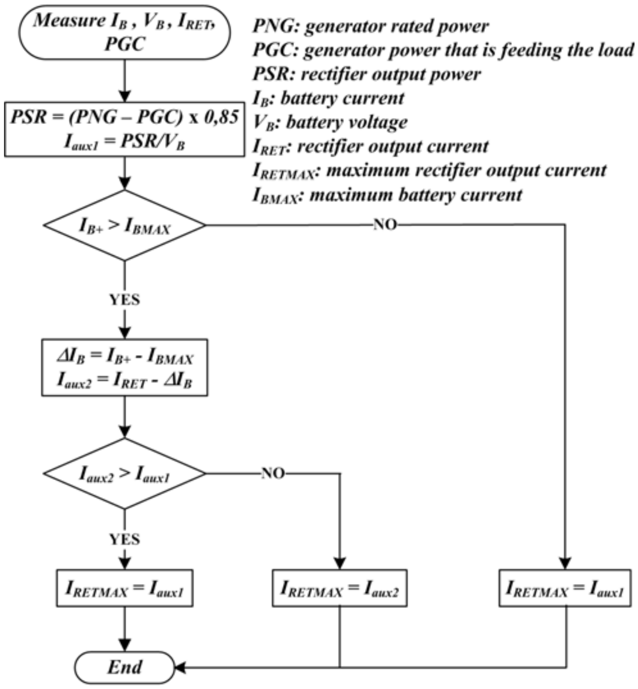

Figure 5 Flowchart of output current control of rectifier.

The flowchart representing the current control showed in Fig. 4 is described using Fig. 5. First, the battery bank current, voltage, and the output power of the diesel generator that is feeding the load (PGC) are measured. Based on field measurements, the rectifier efficiency is approximately 85%. Using that information it is possible to calculate the auxiliary current I_{aux1}. Afterwards, the battery charge current is checked: if it is smaller than the maximum charge current (I_{BMAX}) then a new maximum value for the rectifier current maximum current (I_{RETMAX}) is calculated; if it is greater than I_{BMAX} the excess current is calculated (ΔI_B), and a new value for I_{RETMAX} that is equal to the difference between the actual rectifier current (I_{RET}) and ΔI_B. Using this algorithmic it is guaranteed that battery charge current is always equal or less than the maximum allowed level (in this case 10% of the nominal Ah of the battery). Furthermore, anytime the diesel generator is on, it will be working near its rated power.

V. Inverters

For this SAMG, inverters are critical components and were developed to fulfill the main weakness of renewable hybrid systems: efficiency, expansion flexibility, robustness and reliability. 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 (UPS). During the calendar year of 2008 the measured MTBF = 120,000 in these UPSs. This result was calculated based on (1).

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

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 [24], [25].

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 (2) [26].

$$P_N = \frac{h_{year}}{MTBF} \quad (2)$$

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. Fig. 6 shows this configuration, with two inverters.

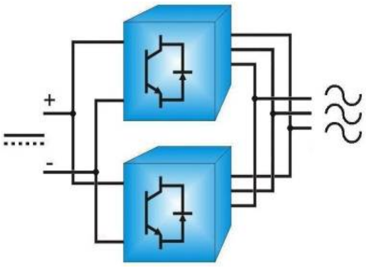

Figure 6: Inverters operating in parallel, configuration N+1.

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 [24], 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. The same analysis could be done for the N+2 configuration. Even though this is not the configuration used in this work, Table I shows a comparison between the three cases.

TABLE I
RELIABILITY OF THE SYSTEMS

MTBF		
Operation Mode	**Hours**	**Probability of failure in 1 year**
Single	60.000	14,6%
Parallel N+1	411.000	2,1%
Parallel N+2	2.815.000	0,3%

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 obtained in this application was due to the decreasing in the inverter losses 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 3% to 5% bigger than the existing equipments (in Brazil) for the same power.

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, three phase IGBT inverter. The output of 60 Hz voltage was regulated based on a space vector pulse width modulation (SVPWM) 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 used to share equally the load between the units. This isolation is necessary to protect the load and the equipments connected in parallel. The block diagram of the inverter system is presented in Fig. 7.

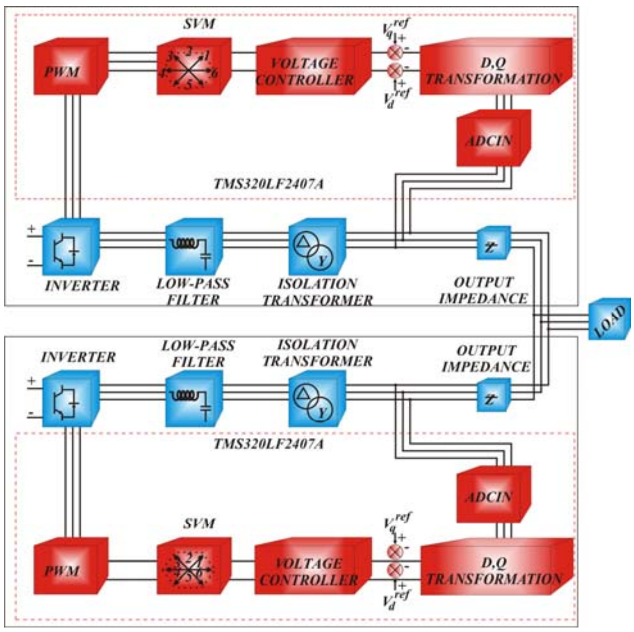

Figure 7 Block diagram of 2 inverters in parallel (N+1).

The operation mode used here is a quasi parallel mode. 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 is not supplied by the sources. The probability of failure calculated previously does not change if the 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.

The voltage control is based on a DSP TMS320LF2407A, which implements a discrete PID voltage regulation as shown in Fig. 8. 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), 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 dynamic, and an outer loop responsible for the slowest dynamic. The inner loop is based on a 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, an integral action must be avoided in this controller since it would result in a dc level to the PWM signal command. 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 PI controller. Since its reference is the voltage RMS value that is a dc constant, the steady state error is zero [13].

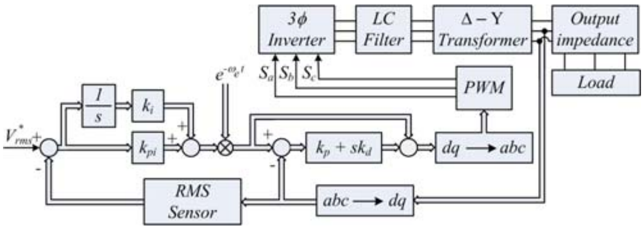

Figure 8 Block diagram of the inverter output voltage control

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” [28]. In this method the inverters present an electric behavior similar to that of synchronous 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 by changing the frequency of the output voltages. Each inverter has its own circuit to accomplish the Drooping Method, where the frequency decreases to compensate for the variations in the active power.

VI. Field Results

Fig. 9 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. 10 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 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.


Figure 9: Wind turbines

2009 was an atypical year with long rain periods from March to June. Low wind and solar energies lead to the automatic starting of the back-up generator at some point in the night. The operation was limited to 4 hours, since this period has showed appropriate to recover the battery charge. After June, the load is completely supplied by renewable sources.


Figure 10: Control & power house

A. Power Quality

In operation at the Lençóis Island, the system works fairly well with non-linear loads. The load current is not sinusoidal, but the controller regulates the inverter voltages with small THD. Fig. 11 shows the voltage (biggest waveform) and current measured with the systems supplying energy to the entire island.

It can be observed that even with a huge current THD (Fig. 12); the inverter output voltage has a THD smaller than 5% (Fig. 13).

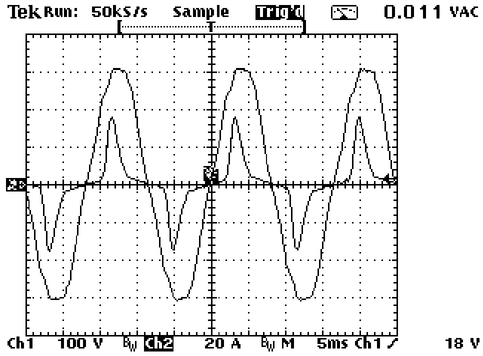

Figure 11: Inverter output voltage (highest waveform) and current with the system working at the island.

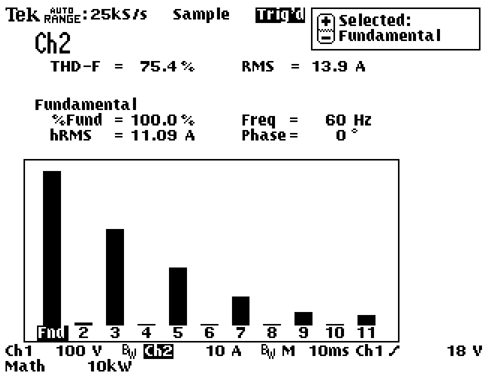

Figure 12: Inverter output current THD with today's island load.

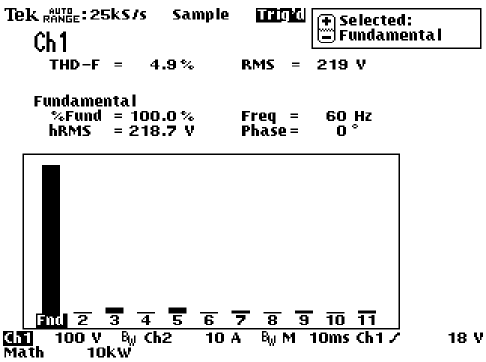

Figure 13: Inverter output voltage THD with today's island load.

B. Reliability

The system has been operating since July, 20th 2008. 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 wind – solar sources.

At the second year (2009), 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 this 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 two years.

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%

VII. CONCLUSIONS

This paper reported the project and design of a micro-grid with centralized renewable hybrid generation system based on solar photovoltaic and wind energies. The innovations introduced in this kind of system are related to 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.

It was shown that part of these requirements can be fulfilled with parallel operations of inverters specially designed for these applications. The system described here definitely helps to bring energy to isolated islands and to decrease the CO_2 emissions.

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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 [17]; the inflation rate was 10% per year. The 7.8 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

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