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Renewable Energy System for an Isolated Sustainable Social Centre

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Abstract. This paper describes the development of the power converters and control algorithms to implement an isolated microgrid based in renewable energy sources used to feed a Sustainable Social Centre in a remote place. The microgrid is designed to work with photovoltaic panels, micro-wind and micro-hydro turbines, or even with diesel generators. The control system of the power converters is totally digital and implemented by means of a TMS320f28335 Digital Signal Controller (DSC) from Texas Instruments. One of the most important requirements imposed for the microgrid power system is the capability of providing a sinusoidal supply voltage with low harmonic distortion even in the presence of non-linear electrical loads. The hardware topologies and the digital control systems of the power converters are evaluated through experimental results obtained with a developed laboratory prototype. This work is focused in the DC-AC converter of the renewable energy system for the isolated Sustainable Centre.

Keywords: Renewable energy, microgrid, power electronics converters, digital control.

1 Introduction

The present energy challenges that the world faces are forcing the shift to a new energy paradigm and the search of new energy sources. The problems associated with greenhouse gas emissions resulting from the use of fossil fuels, and the nuclear power safety issues, as well as the increased energy demand, are the main drivers to expand the use of renewable energy sources. If during several years the renewable energy sources were not intensively explored to the production of electrical energy (except hydroelectric energy), today’s energy challenges are forcing the diversification of renewable energy sources. Wind and solar photovoltaics are the most promising renewable energy sources, considering that the costs of the wind and photovoltaic systems are lowering consistently each year [1]. Also the energy access problems, particularly in small, isolated and standalone communities, where the access to renewable energy sources may be the only solution to meet their energy needs, is contributing to the expansion of the use of renewable energy sources [2]. In fact a large share of the world's population still has no access to electrical energy, depending only on traditional energy sources, such as wood, kerosene and candles to provide heat and lighting [3]. Considering that, remote and small communities with low economical index are not attractive to energy investments [2], one way to take electricity to these people homes is the development of stand-alone grids. Besides, the cost of creating a stand-alone grid can be lower than connecting the remote location to the electrical power grid [4]. Stand-alone micro-grids are isolated from any external network, which means that every load requirement must be sustained by the local available energy sources. The main advantages of this approach are the inexistence of costs associated with the long distance of the connection with the main grid, the local production enabling, the reduction of losses by placing the generation near the demand, and the social improvement resulting from the energy supply to isolated communities [5][6].

This paper describes the development of the power electronics converters to create an islanded microgrid based in renewable energy sources. The main objective is to develop a flexible solution to provide energy to the electrical loads of a Sustainable Social Centre, or medical assistance point, or even a school in remote villages of economically emerging regions. The system integrates several distributed power generating units to produce electrical energy, creating an islanded single-phase microgrid with conventional and stable characteristics: 230 V, 50 Hz. This includes the production of electrical energy from renewable sources and from a motor-generator set (bio-diesel), an energy storage system, and an electrical system with linear and non-linear loads. This paper presents the power converter topology and the control architecture of the proposed solution. Then are presented experimental results, and is done an analysis of the performance of the developed prototype. Finally are drawn several conclusions.

2 Architecture of the Power Converters

The energy provided by renewable sources is very dependent on the climate conditions, and as such, the production is intermittent and is difficult to reliably predict the production capability even for a near future. Considering this, a power system based in this kind of energy sources needs to be supported by energy storage elements. For an islanded power system with a nominal power lower than 10 kW, in terms of storage elements, electrochemical batteries can be a compromising solution in terms of usability, storage capacity, initial and operating costs [7].

In order to ensure the energy conversion, necessary in the various stages of the system, power electronics converters are the best solution. In Fig. 1. is presented a block diagram of the proposed renewable energy system for the isolated Sustainable Centre. As it can be seen in Fig. 1., the system is composed by several DC-DC and AC-DC power converters that interface the various energy sources with a DC-link. The interface between the DC-link and the storage batteries is done by a bidirectional DC-DC converter. Finally a DC-AC converter is used to produce a sinewave voltage to feed the Sustainable Social Centre electrical loads.

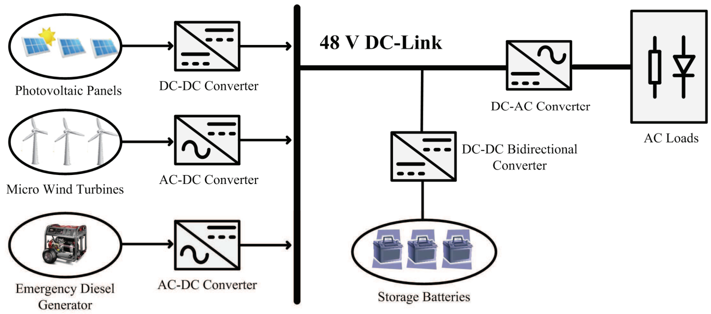

Fig. 1. Block diagram of the renewable energy system for the isolated Sustainable Centre.

The system was designed to work with 48 V in the DC-link and with a load voltage of 230 V/50 Hz. There are several publications in literature about DC-DC converters and Maximum Power Point Tracker (MPPT) algorithms for solar photovoltaic systems [8] and micro-wind turbine systems [9]. In this case was implemented a Perturbation & Observation algorithm for the wind turbine system, and an Incremental Conductance algorithm for the photovoltaic panels. These algorithms ensure that the microgrid receives all the energy generated by the renewable energy sources.

This paper is more focused in the DC-AC converter of the renewable energy system for the isolated Sustainable Centre. It is important to explain that the DC-AC converter can be implemented by a single-stage [10] or by a multistage converter topology [11-13]. In order to accommodate the large difference between the voltage level in the DC-link and the voltage level required to produce the output sinewave voltage without compromising the converter efficiency, the adoption of a converter topology with isolating transformer is a good solution.

The topology selected for the DC-AC converter is based in a multistage converter composed by a full-bridge isolated DC-DC converter followed by a full-bridge DC-AC converter. The topology of the multistage DC-AC converter with isolating transformer is presented in Fig. 2.

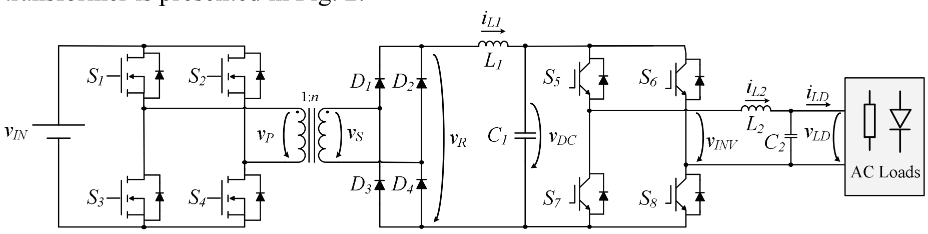

Fig. 2. Multistage DC-AC converter with isolating transformer.

2.1 Full-bridge Isolated DC-DC Converter

The full-bridge isolated DC-DC converter is composed by an active full-bridge in the primary side of the isolation transformer (S_1 - S_4), a full-bridge diode rectifier in the secondary side of the isolating transformer (D_1 - D_4) and a LC output filter (L_1 and C_1). The objective of this converter is to produce a constant voltage around 400 V from the 48 V DC-link. To accomplish with these requirements was selected a transformer with a ratio of 1:13.

Considering that the active full-bridge in the primary side of the isolating transformer is connected to the DC- link, and that the maximum voltage in these power switches is 48 V, power MOSFETs are the more proficient technology for this part of the converter [14].

The active full-bridge is used to produce a high frequency (40 kHz) square wave to be applied to the primary winding of the isolating transformer. The voltage in the secondary winding of the transformer (v_S), will present the same shape as the primary one (v_P), but with amplitude thirteen times higher as consequence of the relation in the winding turns number. The voltage of secondary winding of the transformer is rectified by the diode full-bridge, resulting in a positive square wave (v_R) with a fixed frequency (double the switching frequency of the active bridge). The LC filter is used to remove the high-frequency component, resulting in a constant output voltage. The constant output voltage presents amplitude equal to the mean value of the square wave at the input of the LC filter (v_R), and so, it is possible to control the value of the output voltage by adjusting the duty-cycle of the square wave. Table 1 presents the circuit parameters of the full-bridge isolated DC-DC converter.

Table 1. Circuit parameters of the full-bridge isolated DC-DC converter.

Parameter	Description	Value
$S_1 - S_4$	Power MOSFETs	IXFQ50N50P3
$D_1 - D_4$	Ultrafast recovery diode	STTH3012
L_1	Iron powder core inductor	3 mH
$C1$	Electrolytic capacitor	3.4 mF
T_1	Ferrite core transformer	1:13
fs	Sampling frequency	40 kHz
f_{SW}	Switching frequency	40 kHz

2.2 Full-Bridge DC-AC Converter

The full-bridge DC-AC converter is composed by an active full-bridge ($S_5 - S_8$) and a LC output filter (L_2 and C_2). The objective of this converter is to produce a 50 Hz sinewave voltage with amplitude of 325 V from the 400 V DC voltage provided by the previous converter. As the active full-bridge is connected to the 400 V DC-Link, this part of the converter is composed by IGBTs technology [14].

In order to produce a sinewave from a DC voltage it is used a bipolar Sinusoidal PWM (SPWM) technique with a switching frequency of 40 kHz. By controlling the duty-cycle applied to the IGBTs it is possible to adjust the mean value of the voltage produced by the converter. The LC output filter extracts the high frequency components of the voltage produced by the converter to obtain a sinusoidal voltage at the output (v_{LD}). The circuit parameters of the full-bridge DC-AC converter are presented in Table 2.

Table 2. Circuit parameters of the full-bridge DC-AC converter.

PARAMETER	DESCRIPTION	VALUE
$S_5 - S_8$	Power IGBTs	FGA25N120
L_2	Ferrite core inductor	50 µH
C2	Film capacitor	20 µF
fs	Sampling frequency	40 kHz
f_{SW}	Switching frequency	40 kHz

3 Control Algorithms Architecture

Modern power electronics controllers are implemented totally digital by means of microcontrollers units (MCUs), digital signal processers (DSP) or field programmable gate arrays (FPGAs). The main advantages of digital controllers over analog controllers are the flexibility, and the robustness against aging in the components and influence of environmental degradation.

The control system of the DC-AC converter was implemented in the digital platform Texas Instruments TMS320F28335. It was also implemented a signal conditioning circuit that receives the measured signals from Hall-effect current and voltage sensors, and adjust these signals to the range of values of the DSP ADCs. The implemented switching technique was a Pulse-Width Modulation (PWM). The determination of the conduction time for each semiconductor of the power converter is done by the controller circuit.

3.1 Control of the Full-bridge Isolated DC-DC Converter

The objective of the full-bridge isolated DC-DC converter is to produce a constant DC voltage of 400 V from the 48 V DC-link. The controller of this converter needs to maintain the output voltage at the reference value independently of number of electrical loads connected in the Sustainable Social Centre. It is important to explain that more electrical loads connected consume more energy, and so the full-bridge isolated DC-DC converter needs to transfer more energy from the DC-link to the output, maintaining the voltage in the reference value. Other important aspect is the fact that electrical loads are connected and disconnected randomly and the control algorithm needs to respond adequately to these perturbations. Although these previous constraints, the DC-AC converter has a large capacitor in the DC side that works as a short term energy storage device, facilitating the converter controller design. In fact, it is allowed that the output voltage slightly oscillates around the 400 V value without compromising the entire system performance.

To accomplish with these requirements, the full-bridge isolated DC-DC converter uses a Proportional Integral (PI) controller to eliminate the error between the output voltage (v_{DC}) and the reference (v_{DC}*). The output of the PI controller is used to adjust the duty-cycle of the power MOSFETs by means of bipolar PWM switching technique. The block diagram of the full-bridge DC-DC controller is presented in Fig. 3.

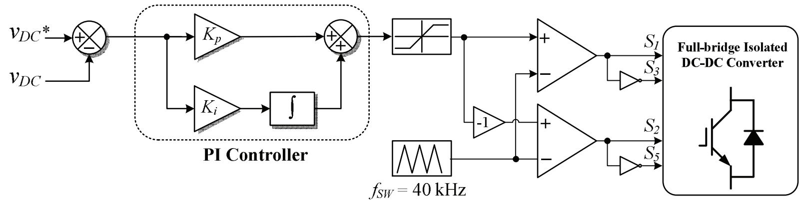

Fig. 3. Block diagram of the full-bridge isolated DC-DC controller.

3.2 Control of the Full-bridge DC-AC Converter

The objective of the full-bridge DC-AC converter is to produce a 50 Hz sinewave voltage with amplitude of 325 V from the 400 V DC voltage provided by the previous converter. To ensure that all electrical loads operate properly, it is necessary to ensure a good quality waveform in any operating condition.

To produce a sinusoidal voltage is relatively simple in the presence of linear loads that consume sinusoidal currents. However, in the presence of non-linear loads, that consume distorted currents, the quality of the produced waveform can be easily degraded if the controller is not fast enough to compensate the voltage deformations. This problem is more pronounced in the presence of loads with high *di*/*dt* or during transients caused by connection or disconnection of loads.

Most of the modern electrical loads that can be connected in the Sustainable Social Centre, like computers, TV sets, radio-sets, led-lamps, cell-phone chargers, and other communication equipment, are known to present a very non-linear voltage current characteristic. This type of equipment drains currents with very high Total Harmonic Distortions (THD), thus requiring a voltage controller with good performance for the DC-AC converter. To accomplish with this task in this work, it is used a predictive deadbeat controller based in [15].

In accordance with Fig. 2 the space state equations of the full-bridge DC-AC converter with LC output filter can be expressed as in (1).

$$\begin{bmatrix} \dfrac{di_{L2}}{dt} \\ \dfrac{dv_{LD}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \dfrac{-1}{L_2} \\ \dfrac{1}{C_2} & 0 \end{bmatrix} \begin{bmatrix} i_{L2} \\ v_{LD} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_2} \\ 0 \end{bmatrix} v_{INV} + \begin{bmatrix} 0 \\ \dfrac{-1}{C_2} \end{bmatrix} i_{LD} \tag{1}$$

Equation (1) shows that the load current (i_{LD}) acts as a disturbance in the output voltage (v_{LD}) and the output voltage as disturbance in the inductance current (i_{L2}) [15]. Considering a given sampling period T_S, the state equations can be re-written as:

$$x[n+1] = \phi(T_S)\, x[n] + \Gamma(T_S)\, v_{LD}[n] + \Delta(T_S)[n] \tag{2}$$

where:

$$\phi(T_S)=\begin{bmatrix}\cos(\omega T_S) & \frac{-1}{\omega L_2}\sin(\omega T_S)\\ \frac{1}{\omega C_2}\sin(\omega T_S) & \cos(\omega T_S)\end{bmatrix}=\begin{bmatrix}\phi_{11} & \phi_{12}\\ \phi_{21} & \phi_{22}\end{bmatrix}, \tag{3}$$

$$\Gamma(T_S)=\begin{bmatrix}\frac{1}{\omega L_2}\sin(\omega T_S)\\ 2\sin^2\left(\frac{\omega T_S}{2}\right)\end{bmatrix}=\begin{bmatrix}\gamma_1\\ \gamma_2\end{bmatrix}, \tag{4}$$

$$\Delta(T_S)=\begin{bmatrix}2\sin^2\left(\frac{\omega T_S}{2}\right)\\ \frac{-1}{\omega C_2}\sin(\omega T_S)\end{bmatrix}=\begin{bmatrix}\delta_1\\ \delta_2\end{bmatrix}. \tag{5}$$

The resonance frequency of the LC filter is:

$$\omega=\frac{1}{\sqrt{L_2 C_2}}. \tag{6}$$

It must be referred that:

$$x[n]=\begin{bmatrix}i_{L2}[n]\\ v_{LD}[n]\end{bmatrix}. \tag{7}$$

As said before, the load voltage (v_{LD}) acts as a disturbance in the inductor current (i_{L2}) and the load current (i_{LD}) acts as a disturbance in the output voltage (v_{LD}) so, to improve the load voltage controller performance, it is possible to add the values of the disturbances to the voltage controller and current controller. This improves the controller response and its robustness. These values are calculated as shown in (8) and (9).

$$v_{dist}[n]=-\frac{\gamma_2}{\phi_{21}}v_{INV}[n]-\frac{\delta_2}{\phi_{21}}i_{LD}[n] \tag{8}$$

$$i_{dist}[n]=-\frac{\phi_{12}}{\gamma_1}v_{LD}[n]-\frac{\delta_1}{\gamma_1}i_{LD}[n] \tag{9}$$

To increase the performance of the controller it is also possible to add two feed-forward components (10) and (11) to the control loop, that incorporate $v_{LD}^*[n]$, $v_{LD}^*[n+1]$, $v_{LD}^*[n+2]$ and the estimated values of $\hat{\phi}(T_S)$ and $\hat{\gamma}(T_S)$. It must be referred that v_{LD}^* consists in a sinusoidal waveform previously stored in a look up table with 800 positions, so the n+1 and n+2 samples can be easily accessed. The values of $\hat{\phi}(T_S)$ and $\hat{\gamma}(T_S)$ can also be estimated considering the values of ωT_S for the n+1 sample.

$$FF_1[n] = \frac{v_{LD}^*[n+1] - \hat{\phi}_{22}\ v_{LD}^*[n]}{\hat{\phi}_{21}} \tag{10}$$

$$FF_2[n] = \frac{v_{LD}^*[n+2] - 2\hat{\phi}_{11}\ v_{LD}^*[n+1] + \hat{\phi}_{11} v_{LD}^*[n+1]}{\hat{\phi}_{21}\ \hat{\gamma}_1} \tag{11}$$

Finally, the current and voltage errors are multiplied by two gains, G_i and G_v, respectively, which can be calculated as:

$$G_i = \frac{2\phi_{11}}{\gamma_1} = \frac{2\omega L\cos(\omega T_S)}{\sin(\omega T_S)} \tag{12}$$

$$G_v = \frac{\phi_{11}}{2\phi_{21}} = \frac{\omega C\cos(\omega T_S)}{2\sin(\omega T_S)}. \tag{13}$$

To obtain the power converter switching signals, the output value of the controller is passed through a limiter, and after that, the output value is compared with a triangular carrier with a frequency of 40 kHz. In Fig. 4 it can be seen the block diagram of the control architecture for the full-bridge DC-AC converter.

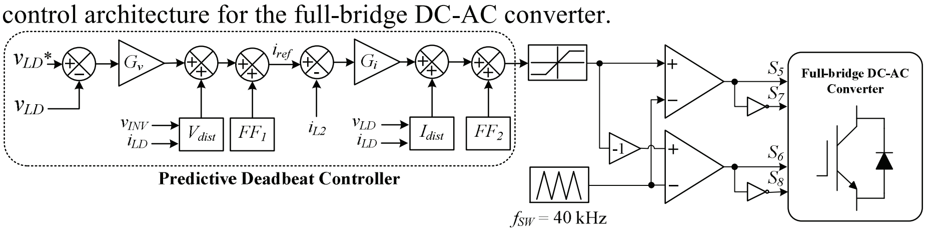

Fig. 4. Block diagram of the predictive deadbeat controller.

4 Experimental Validation

To assess the behavior of the predictive deadbeat controller was developed a laboratory prototype (Fig. 5.) of the converter shown in Fig. 2. This converter, controlled by predictive deadbeat controller, was tested using a non-linear load constituted by a single-phase full-bridge rectifier with a RC load placed in the DC side.

In Fig. 6. it is possible to see the experimental results obtained with the aforementioned load. This figure shows that although that the load presents a highly distorted current (i_{LD}), with a THD of 107% (Fig. 6. (c)), the voltage produced by the DC-AC converter (v_{LD}) is nearly sinusoidal. This is confirmed by the harmonic spectrum shown in Fig. 6. (b) that shows a THD of 2.7%. This value is perfectly acceptable for most loads, and is in accordance with standard EN 50160. Also, it is important to highlight that the voltage waveform does not present any sign of resonance motivated by the passive filter.

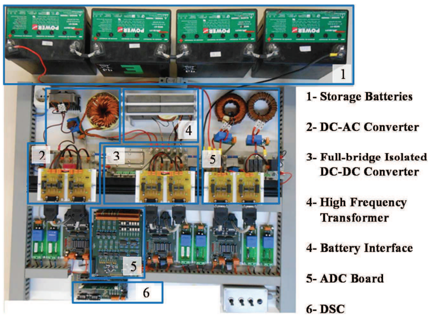

Fig. 5. Developed laboratory prototype of the multistage DC-AC converter.

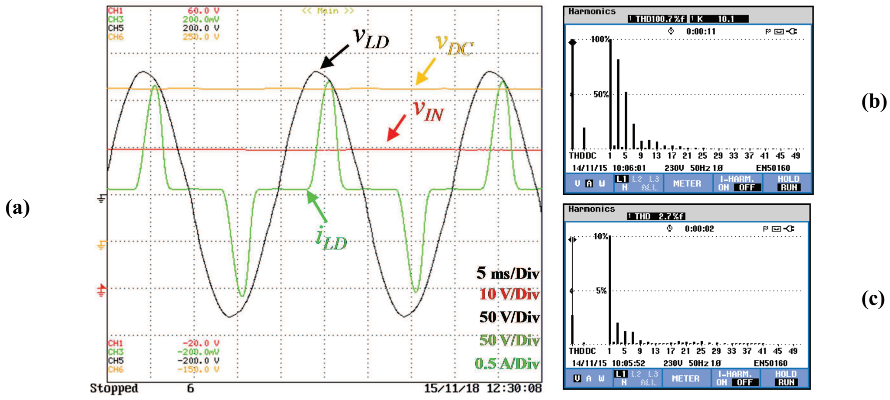

Fig. 6. Experimental results of the DC-AC converter operating in steady state with a non-linear load: (a) input voltage (v_{IN}), DC voltage (v_{DC}), output voltage (v_{LD}) and load current (i_{LD}); (b) Harmonics and THD of output voltage; (c) Harmonics and THD of load current.

5 Conclusions

In this paper was presented the development of power electronics converters to create an islanded microgrid, based in renewable energy sources, to feed the electrical loads of an isolated Sustainable Social Centre. This system integrates several power converters, in order to convert the energy from the renewable energy sources like photovoltaic panels, micro-wind and micro-hydro turbines, to be stored in a battery pack, which translates in added flexibility. The conversion between the DC-link bus and the loads is performed using a multistage DC-AC converter which is controlled by a PI and a predictive deadbeat controller. The topology and the control algorithms of the presented DC-AC converter were validated through experimental tests. These tests show that the implemented control shows a good performance even in the presence of non-linear loads, which consume a current with high level of distortion. This type of current usually causes distortion in the output voltage that is difficult to be compensated by the control algorithms. With the developed system was achieved a voltage with a THD value lower than 3% even with a load current with a value of THD greater than 100%.

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