Perspectives for DC distribution adoption in Brazil

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***Abstract*—The main purpose of this paper is to discuss possible means for DC distribution adoption in Brazil in medium term, basing the discussion on the perspective of an emerging country. A main path to be explored is the progressive adaptation of PV residential and commercial distributed generation systems into a DC microgrid, allowing energy efficiency, power quality and energy management improvements. A DC microgrid testbed in current development in the Federal University of Minas Gerais (UFMG) will also be described and simulated results will be used to demonstrate the behavior of the proposed architecture.**

I. Introduction

Lately low voltage DC distribution has been receiving considerable attention as a mean to achieve better integration with renewable energy resources and improve distribution system energy efficiency. Recent studies estimate that DC power can reduce in 5-15% the power losses in residential and data center systems in comparison with conventional AC distribution [1], [2]. In developed countries, the need to increase the penetration of renewables into a highly fossil fuel based energy matrix and to reduce the future electricity demand calls for the development of net zero energy solutions, hence a great effort in developing new technologies and solutions for DC low voltage distribution and its application to households, data centers and other commercial environments can be recognized [3], [4].

In emerging countries, as Brazil, DC distribution is also a promising solution to overcome several infrastructural issues of the electrical system. However, the evolution of DC based technologies and solutions is somewhat timid, with no major initiative advocating for its deployment, but conceptual studies and projects carried out in Brazilian universities. Outside academia, DC powered circuits have been incorporated to renewable based off-grid systems with DC buses serving as a backbone to where local power generation, energy storage and other elements can be integrated more simply and efficiently [5], [6]. The interest in off-grid systems is justified by the need to employ feasible solutions to supply remote or isolated rural communities in Brazil, especially in the Amazon region and islands, where physical or economical challenges preclude their integration to the national or local electrical grid [7]. In 2010, over 720,000 households in Brazil had no electricity access, of which 250,000 were located in the Amazon [7]. In order to achieve universal electricity access, a goal defined by the national program *Luz Para Todos - LPT* (Energy for All) to 2018, the deployment of off-grid system will be the main approach.

According to the Normative Resolution No. 493 of 2012 of the Brazilian Electricity Regulatory Agency (ANEEL), off-grid systems can be divided into individual systems and isolated microgrids. Pilot-projects, also funded by the LPT program, were deployed to assess technical and economical challenges of installing, maintaining and operating off-grid systems in remote regions of Brazil. The main pilot-project for individual systems was initiated in 2005 in the municipally of Xapuri-Acre, northern Brazil, where 103 individual PV systems were installed in three rubber tapper communities. Each system was designed to provide 13 kWh per month and an autonomy of 48h. Three different distribution configuration, one for each community, were considered: i) 120 VAC distribution; ii) 12 VDC distribution and iii) Hybrid AC/DC distribution. Figure 1 illustrates the Hybrid distribution configuration and its components. The availability of 12 VDC compatible light bulbs and electronics in local markets enabled 90% of the household load to be supplied in DC. As most system losses were concentrated in the inverter, the Hybrid and DC distribution topologies allowed initial installation cost reductions of 2.2% and 9.7%, respectively, in relation to the 8,871.92 BRL (Brazil Real) cost of the AC system and an energy availability improvement in the order of 7% to 15% [5].

Regarding isolated microgrids, a pilot-project was established in 2008, in *Ilha dos Lençóis* in the municipally of Cururupu-Maranhão, northeastern Brazil. This project consists of a 40 kVA centralized microgrid, illustrated in Figure 2, with 21.06 kW solar PV and 22.5 kW wind power generation and a 53 kVA backup diesel generator, supplying 90 households, a school, a health center and a small ice factory, and dimensioned to meet the community's electricity demand for over 10 years [6]. 120 lead-acid 150 Ah batteries compose a 240 VDC bus into which all components are connected. Two paralleled 20 kVA inverters produce a three-phase 380V/220V AC system to supply the community, complying with current distribution regulation. The system design enabled long daily periods of renewable energy use with low battery bank discharge depth and diesel consumption. The employment of a DC bus backbone allowed simpler integration of the microgrid multiple sources and automatic system management, mitigating the need for several synchronized inverters and reducing possible failure points. A two year period monitoring showed that the diesel generator was only needed for 4.5% of the evaluated time and the system presented only three failures, occurred in its first 5 months of operation [6]. The robustness of the project substantially reduces maintenance, allowing an energy cost of approximately 0.65 BRL/kWh, a price compatible with grid-tie generation and no additional subsidy is demanded. Similar isolated microgrid projects are currently installed in other 17 communities supplying 348 consumers.

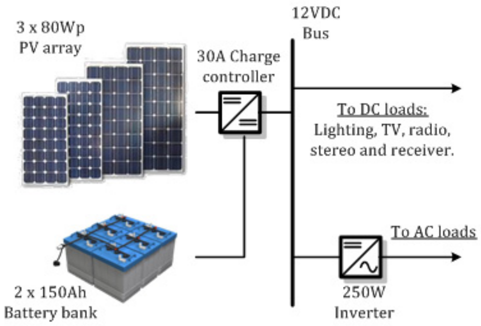

Fig. 1. Hybrid individual photovoltaic system installed in Xapuri-Acre.

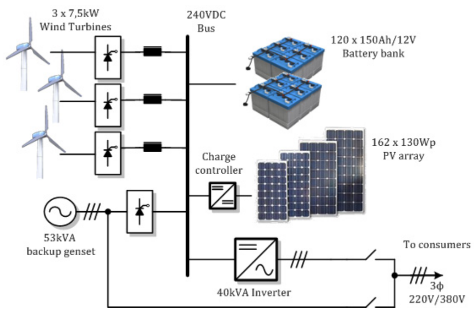

Fig. 2. *Ilha dos Lençóis* isolated microgrid diagram [6]

Besides the great social impact brought by off-grid systems, the development of grid-tied solutions in the distribution level can provide an even greater benefit for the Brazilian power system. However, unlike off-grid systems, conventional low voltage distribution have been treated very conservatively by regulatory agencies and utilities, supporting a centralized generation model and AC based distribution. Nevertheless, despite the adverse scenario, recent incentives for smart grid and distributed generation development may provide a propitious environment for DC microgrid proliferation. This paper will discuss perspectives for DC distribution adoption in Brazil in medium term, focusing on solutions for residential and commercial environments. A DC microgrid testbed topology in current development in the Power Electronics Lab of the Federal University of Minas Gerais will also be presented to illustrate the proposed solutions. The remainder of the paper is organized as follows: Section II discusses the Brazilian energy scenario, its current reality and future challenges to be addressed; Section III revises possibilities and advantages to embed DC distribution systems into residential and commercial environments; Section IV describes the DC microgrid testbed architecture and operation and Section V presents the paper conclusions.

II. Energy Scenario and Challenges for Brazil

Hydropower has been the main primary energy resource for electricity generation in Brazil, accounting for over 70% of the installed power capacity and 80% of the power generation in the last decade [8], thus granting the Brazilian electricity matrix a highly renewable and *"green"* status. The total hydropower capacity is estimated to be 135.2 GW, of which 63.5% are currently being explored [8] and are concentrated in the basins of south and southeastern Brazil. The remainder of the estimated capacity lies mostly on the northern region, where environmental concerns over the impacts of building large water reservoirs in the Amazon may hampers

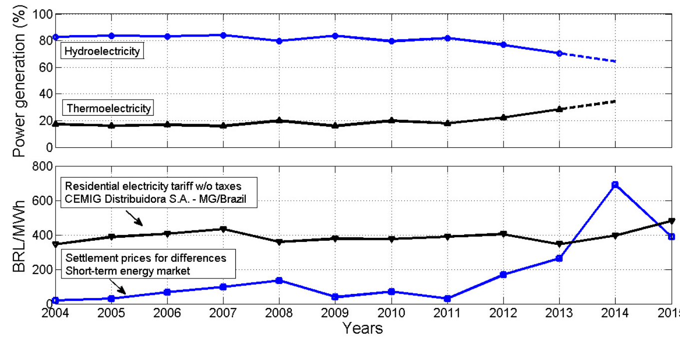

Fig. 3. Contribution of hydro and thermoelectricity to the power generation and evolution of residential electricity tariff and settlement prices for differences [8], [9].

a widely development of new power plants. Thermoelectric plants, based on biomass, natural gas, coal, oil derivatives and nuclear power complement the power generation and act as an energy backup in long dry seasons. Wind and solar power still represents only 1% of the power generation [8]. Thermoelectric plants receive a fixed revenue for their availability and are granted an extra remuneration to cover the production costs when the actual power generation is demanded, what considerably increases their marginal cost cost.

This electricity matrix composition makes the Brazilian electrical system highly vulnerable to climate variations. A long dry season reduces the level of the reservoirs and demands a more intense use of thermoelectricity, increasing the average energy cost and in extreme cases leading to energy rationing, as occurred in 2001. Since 2011, Brazil is facing longer dry seasons and less rainfall during wet seasons, resulting in a higher employment of the thermoelectric plants, as seen in Figure 3. It can be noticed that an increment in thermoelectricity utilization influences the short-term energy market settlement prices, which affect directly the revenues of utility companies and large industries. The impact on the residential tariffs is not evident for small variations in the energy matrix composition, however a continuous elevation of the share of thermoelectricity, as seen since 2011, inevitably pushes the residential tariffs up.

Although the main reason for thermoelectricity use has been drought, the increase in hydroelectric installed capacity has been slowing down, presenting an average growth rate of 2.5% per year since 2004, while the thermoelectricity has been growing 7.3% per year [8]. This implies that in short-term the demand for thermoelectricity will increase, as will the energy cost. This can be very concerning, considering that the official projections expect a 45% increase in electricity demand by 2023 [10]. The energy cost in Brazil is also influenced by the electrical system power losses, which have been fluctuating around 17% since 2004 [8]. The continental proportions of the country, a centralized generation approach and a concentration of the electricity consumption in the south and southeastern regions require the employment of long transmission and distribution lines, what have a substantial importance on the total power loss. Another issue is non-technical losses, as electricity theft and measuring problems, which can represent 5% of the total consumed energy [9].

Considering this scenario, its evident that Brazil needs a paradigm shift, in order to diversify the energy matrix and reduce the system losses. The development of a smart

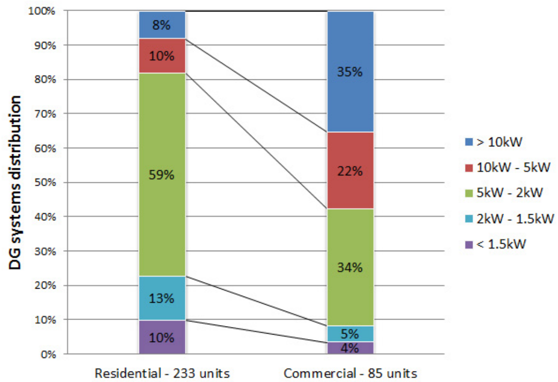

Fig. 4. DG systems distribution in classes and installed capacity range.

grid, with the utilization of smart metering and a higher system operation automatization in the low voltage distribution level may mitigate the non-technical losses. Currently, smart grid R&D projects in Brazil are being conducted by utility companies and electric material industries in association with universities, and it is expected to have a broader participation in the electrical system by 2020. Another approach that covers the issues aforementioned is the proliferation of distributed generation (DG) in the distribution systems. The diversification of the energy matrix is achieved by a greater employment of solar and wind resources and the proximity to the consumers contributes to reduce the distribution operational losses. In 2012, low voltage distribution DG was regulated by ANEEL through the Normative Resolution No. 482, establishing special characteristics for grid connection to system below 1MW and a billing method based on net metering. Since then, 318 systems have been installed comprising 295 PV units, 20 small wind turbine units and 3 biomass units, totaling a 4.3MW capacity. Figure 4 presents the distribution of the DG systems in residential and commercial classes. Official projections expect DG systems to reach grid parity in this decade, increasing its growth and representing 0.1% of the power generation in 2020 and 5.7%in 2050 [11]. This projections however do not consider the impact of new business models, products and services on the DG market.

Even with the development of smart grid technologies and the expansion of DG systems, there will be a need for more energy efficient equipments and methods in order to optimize the gains of these solutions and reduce even further the net energy demand. In this context, DC power distribution can become an interesting alternative, promoting loss reductions inside the DG units, *i.e.*, raising the energy availability, and coping with smart grid concepts as well. The authors do not envision that an abrupt transition to DC power distribution will occur, since current regulations do not contemplate this possibility, rather a gradual incorporation of DC subsystems into DG units is more likely. This architectural upgrade can provide features as local power management, online adaptation of consumption to energy tariffs, higher power quality and efficiency, hence, opening new market possibilities that can encourage a faster penetration of DG into the electrical system.

III. DC DISTRIBUTION APPLICATION TO RESIDENTIAL AND COMMERCIAL DG SYSTEMS

Assuming that DG systems will be the base for DC microgrids evolution and proliferation in medium-term, any configuration proposition must focus on residential and commercial environments, since the great majority of low voltage distribution DG is associated with these sectors. According to 2014 Brazilian energy balance [8], residential, commercial and public buildings represented 48% of the total electricity demand. Therefore, reducing the net demand of buildings, through local generation and energy efficient systems, is an interesting alternative to restrain the electricity consumption increase in the future. This section will discuss the application of DC distribution to residential and commercial systems, and present possible configurations for DC microgrids.

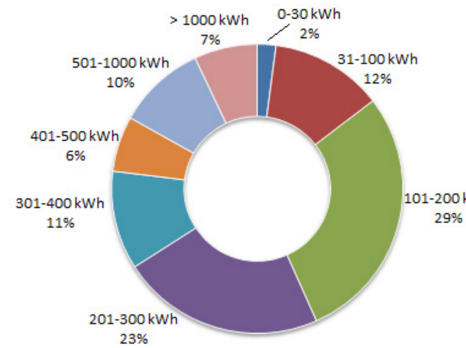

Fig. 5. Residential distribution by consumption rate. [12].

A. Residential systems

In 2013, the total residential consumption of Brazil was 124.9 TWh, distributed in over 63 million households [12] and representing 28% of the country's electricity demand. As seen in Figure 5, 66% of the total residential electricity demand is concentrated in households which consume less than 300 kWh per month, of which 20% are considered low income and enjoy an energy tariff up to 35% lower than the conventional tariff [9]. Assuming an average daily solar irradiance of 5 kW/m^2, the great majority of this low consumption households could be supplied by a 2 kWp PV system, however, in current economic stage, this low power DG system is hardly feasible due to high installation cost, of around 7-8 BRL/W, taxes regulation and reduced tariffs which make it difficult to achieve grid parity in medium-term. It is estimated that the potencial market for PV-based DG comprises households with 400 kWh per month or higher consumption, *i.e.*, approximately 3.3 million consumers, of which only 55% would possess appropriate technical conditions for PV modules installation [13]. Considering the 318 DG systems registered so far as an example, as depicted in Figure 4, there are 233 residential units, totalling 1.2 MW, of which 78% have an installed capacity over 2 kWp, with the great majority in the range of 2 kWp-5 kWp, which accounts for 59% of the total residential DG units. In order to increase the quantity of DG systems, grid parity must be achieved in all Brazilian territory, which requires the increase of the electricity tariff or the reduction of the system installation cost. As both mechanisms are currently being observed, grid parity must be reached still in this decade leveraging the DG system installations [11].

A DC microgrid can be developed over the architecture of conventional PV-based distributed generation systems, supplanting the grid-tie inverter by a bidirectional grid interface converter (BGIC) and establishing a main DC bus to interconnect the BGIC, the PV array, through a DC/DC converter and

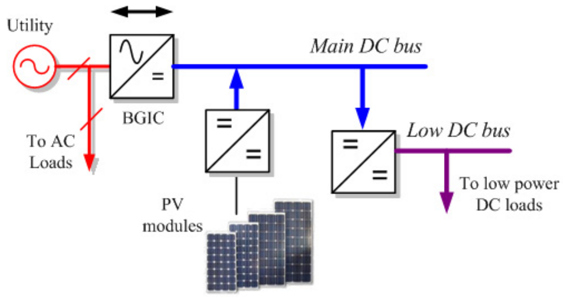

Fig. 6. DC microgrid diagram for residential systems.

TABLE I. RESIDENTIAL ENERGY END USE [16]

Air-conditioning	8%	Refrigerator	18%
Freezer	5%	Lighting	16%
Electric shower	18%	Wash machine	2%
TV	13%	Others*	20%

*Relates to stereos, computers, video-games, printers, scanners, dish washers, etc.

local loads as depicted in Figure 6. This configuration allows the insertion of new PV arrays over time, without the need for redesigning the system or matching the new modules with the old ones. The BGIC also regulates the main DC bus providing an energized feeder even in periods with low solar irradiance. A low voltage DC bus, of 12 to 48V voltage level, may also be available to supply LED lighting and other low power DC loads and provide a safer circuit to be handel by the residence occupants.

The voltage level of the main DC bus must be designed to supply local loads and comply with standards adopted by electronics manufacturers. Internationally, a voltage level of about 380V is being considered to DC microgrids [3], [14], however, considering that the availability of 380V compatible products in the Brazilian market may be an issue in short and medium-term, a 311V DC bus is more appealing for faster adoption of DC circuits in residential installations. Most electronics can operate normally when supplied by a DC voltage equal to the peak value of its AC voltage rating [15], therefore, in medium-term the use of 311V can enable the utilization of 220/127 VAC electronics without requiring the development of a new market for DC products. According to Table I, almost 40% of total residential consumption is due to electronics (Lighting, TV, stereo, computers, etc) which could easily be supplied by a DC bus, which could lower household consumption up to 6%, assuming a 15% reduction in power losses due to the employment of DC distribution [2].

Energy storage could also be associated with the DC microgrid, turning the system into a controllable and dispatchable generator that could schedule the energy exported to the utility grid according to tariff variations or reduce the household's peak demand. This solution, however, can increase the cost of the system substantially, since the main available storage device in Brazil are lead-acid batteries which present a lifespan of 3 to 4 years and costs around 400-600 BRL/kWh. Since grid parity is crucial for the employment of DG systems and DC distribution solutions as well, a storage system can, in medium-term, make the DC microgrid unattractive. An alternative is to use electric vehicles (EV) and plug-in hybrid (PHEV) as energy buffers and promote energy management operations during peak demand, when this vehicles will be commonly connected to the system. EV and PHEV are expected to represent 3% of the national fleet in 2030 and experience a quick evolution since then, achieving 61% of the fleet in 2050 [11]. Therefore, the use of an energy storage system would only be feasible in long-term.

B. Commercial systems

The total consumption of the commercial sector in 2013 was 83.7 TWh representing 19% of the electricity demand [12]. There are over 5.4 million commercial establishments in Brazil, of which approximately 3 million are attended by low voltage distribution and could benefit from the DG regulations. The applicability of DG systems to commercial consumers will depend on a variety of factors, as level of consumption, required installation area availability and the ownership of the commercial spot. These restrictions are reflected in Figure 4, where only 85 commercial DG units have been registered yet. These few units however help to identify installed capacity niches for DG systems. 91% of the registered DG systems have installed capacities higher than 2kW, and the interest is bigger in the 2kW to 5kW range and for systems above 10kW. Most of the low power units comprise demonstration systems and small commercial establishments, as inns, restaurants, health clinics, small stores and elementary schools, while the higher power systems relate to small industries, university buildings, soccer stadiums and public control centers, making it harder to define an energy end use profile.

In both cases, a DC distribution configuration as discussed for residential systems can be employed. Conventional lighting devices, computers, sound equipment and other electronics could be supplied by a 311V DC bus and the low voltage buses would provide telecommunication, automation and alarm systems. However, the impact of the DC distribution on system losses must be evaluated case-to-case. Moreover, commercial systems with critical loads, such as servers, surveillance, food storage, etc, can benefit from the employment of an energy storage system, since the DC bus would act as a centralized uninterrupted power supply (UPS), maintaining normal operation even with disturbances in the utility grid. High quality AC circuits could be define through inverters connected to the DC bus, in order to supply AC critical loads. Energy management can also be an useful feature allowing the system to reduce utility grid energy consumption in peak demand time zones, without restricting production. A communication network must be established inside the microgrid to provide information exchange among the converters and make energy management algorithms more effective. In these cases, the high cost of the energy storage can be compensated by the improvement in power quality and energy management. Figure 7 presents the DC microgrid architecture considered to supply commercial systems. Its is important to mention that in long-term, when smart grid solutions become more mature and scattered and the cost of DG systems and storage devices achieve more affordable levels, this more complete microgrid architecture would also be employed in residential systems, possibly converging to international standards both in terms of communication protocols and voltage levels.

IV. PROPOSED DC MICROGRID TESTBED

Prior to the development of DC distribution systems and their insertion into households and commercial buildings electrical infrastructure, there are several issues regarding personal

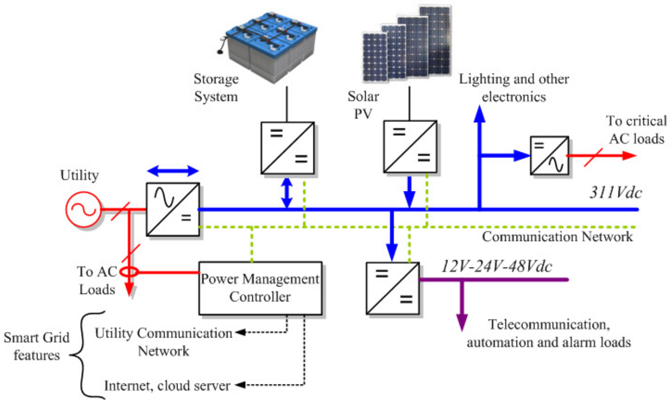

Fig. 7. DC microgrid diagram for commercial systems.

safety, control methods, system stability and system design procedures that must be resolved. In order to provide a practical environment where DC microgrid and power converter technologies can be developed and the impact of DC distribution in terms of equipment power supply, energy efficiency gains and coordinated protection can be assessed, the Federal University of Minas Gerais (UFMG) is currently developing a small scale 5kW DC microgrid testbed, which covers most residential applications and low power commercial systems. The microgrid architecture is based on the DC microgrid discussed for commercial purposes and depicted in Figure 7, since it consists of a more general system that could be employed in commercial buildings and residential systems as well. The local power generation will be based on a 3kW PV array connected to the main DC bus through a DC/DC Renewable Resource Converter (RRC), responsible for MPP tracking. The local storage system will be based on a 12kWh Lead-acid battery bank and a 5kW Energy Storage Converter (ESC), responsible for battery charge/discharge control. All power converters must comply with the microgrid requirements for main DC bus connection in order to assure system stability in all possible operating conditions.

The DC microgrid was conceived to be flexible and expandable, meaning that new elements can be incorporated to the microgrid, without the need for redesigning the system or executing complex reconfigurations. In order to fulfill this goal, the power converters integration will follow a hierarchical control approach [17]. The considered control method is illustrated in Fig 8, where the Power Management Controller (PMC) operates in both secondary and tertiary control levels, gathering information about the converters operation, through local communication network, and utility grid conditions and establishes control set points for the microgrid converters in order to achieve an optimal operation point. Since control parameters are informed by this centralized supervisory system, the configuration of new elements to be added to the microgrid becomes simpler.

The primary control level ensures local converter stability and a basic communicationless power management based on DC Bus Signalling (DBS) [18]. This method uses the DC bus voltage level as a communication link, allowing the DC bus to vary in a voltage deviation window, which is divided in sections representing different operation modes for the converters. Voltage droop control permits that in each section multiple converters operate in voltage mode, regulating the DC bus in an adequate level. In the proposed testbed, a ±

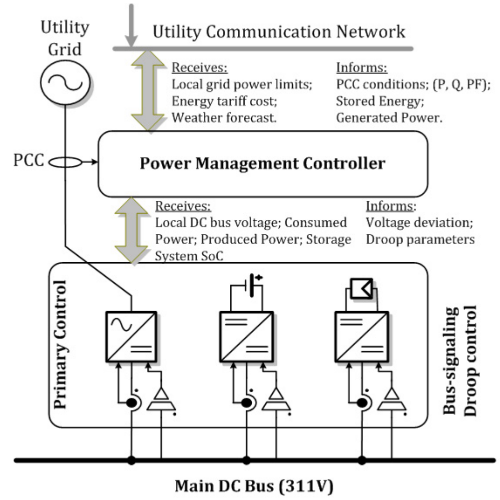

Fig. 8. DC microgrid testbed hierarchical control diagram.

TABLE II. DC MICROGRID TESTBED PRIMARY DBS CONTROL MODES.

Mode	Voltage section	Converter behavior
I	327V-319V	RRC: Source in voltage droop mode; BGIC: Load in current mode; ESC: Load in battery charge mode.
II	319V-311V	RRC: Source in MPPT mode; BGIC: Load in voltage droop mode; ESC: Load in battery charge mode.
III	311V-303V	RRC: Source in MPPT mode; BGIC: Source in voltage droop mode; ESC: Load in voltage droop mode.
III	303V-295V	RRC: Source in MPPT mode; BGIC: Source in current mode; ESC: Source in voltage droop mode.

16V voltage window, divided in 8V sections, was considered and the operation modes for each converter were defined as shown in Table II. The voltage deviation is compensated by the PMC in secondary level, thus in steady state the DC bus will present a 311V voltage.

Figure 9 presents simulation results, conducted in PSIM, for the proposed DC microgrid for three different operating conditions. In situations A and B, the system operates in Mode III, where both BGIC and ESC operate in voltage droop mode, the solar irradiance is set to 1 kW/m^2 and the PV array generates 3kW. The load power is set to 3kW in the first situation, what is supplied by the PV converter, and the BGIC only provides enough power to charge the battery bank, with 1.3kW, and compensate system losses. In situation B, the load power is increased to 8kW, the BGIC then injects the remainder 5kW into the DC bus, reaching saturation, and the ESC stops draining power from the system, it can be seen that the DC bus voltage vary from 308V to 303V, *i.e.*, stabilizing in the division between Mode III and Mode IV. In situation C, the solar irradiance is lowered to 500W/m^2, reducing the power generation to 1.5kW. Since the BGIC is already saturated, the ESC assumes the voltage regulation injecting into the DC bus the needed 1.5kW. The system operates in Mode IV, with a 301V DC bus voltage. The operation of the secondary level control, executed by the Power Management Controller, is also represented in Figure 9. The centralized controller gathers information about the local parameters of each converter via the communication network, it computes the error between the instantaneous DC bus voltage value and the 311V reference and then informs the converters, in a 100ms interval, a voltage deviation correction value that should be added to the voltage

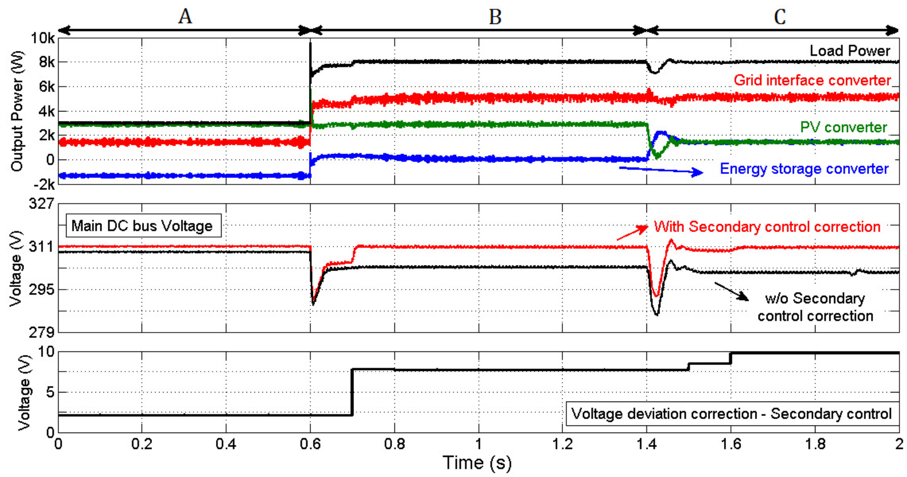

Fig. 9. Simulated behavior of the DC microgrid for load step and solar irradiance variation.

droop references of the primary control loop. Consequently, the DC bus will present in steady state a voltage equal to the reference. In all situations the primary control allows the proper sharing of the load power among the converters and the PMC corrects the droop voltage deviation.

V. Conclusion

This paper have discussed the application of DC powered microgrids to address several issues of the Brazilian electrical system, either by promoting universal access to electricity through hybrid AC/DC off-grid systems or reducing hydropower dependency and power losses through being embedded in residential and commercial distributed generation (DG) systems. Upgrading a conventional PV based DG system to a DC microgrid with a 311VDC bus allows conventional electronics to be directly supplied in DC, what can produce a 6% reduction in residential losses. For commercial systems, battery energy storage can provide considerable power quality and energy management improvements. Simulations results of a DC microgrid topology, with hierarchical control and primary level DC bus signalling power management shown that this architecture can provide proper load sharing among multiple power sources and stable DC bus for different operation conditions being suitable to be employed in residential and commercial environments. Future work will assess the impact of the microgrid architecture in a real system efficiency, safety and operation.

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