Application of the DAB Converter to a Hybrid System for Hydro-PV and Battery

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***Abstract*— This paper demonstrates the application of a DAB converter in a hybrid generation system composed by hydro and PV sources, with battery energy storage. More specifically, the use of the DAB converter has the objective of realizing the MPPT, besides the interface between the DC bus of the DSTATCOM with the PV system and the battery bank. In addition, it is proposed to use the Buck-Boost converter to carry out the loading and unloading of the battery bank. The purpose of this work is to obtain a reliable system, considering that the proposed converter is galvanically isolated, bidirectional and allows to control the flow of energy between the power supplies. Simulation results are presented aiming to demonstrate the operation of the proposed system.**

Keywords*— *Hydro, PV, DSTATCOM, DAB, ELC, ESS.

I. Introduction

The demand for electricity is closely related to world population and economic growth [1]. Consequently, the techniques of energy generation go through constant evolutions, aiming to supply the energy demand, increasing even in remote places. Another important aspect that deserves attention is the effect characterized as global warming. In this sense, sustainable energy sources have been gaining ground with increasing population awareness [2].

With the use of renewable energy sources, it is hoped, in addition to reducing environmental impacts, to solve the energy problems caused by not meeting the required demand [3]. Several factors can hinder power supply, especially in isolated and remote locations. In this case, the generation of electric power from local sources becomes attractive, considering the cost of implementation and losses associated with transmission lines [4-5]. In addition, in [6] it is emphasized that it may be advantageous to use more than one energy source, since the sources employed may have some kind of complementarity in time, space, or both. This complementarity enables a system to present better technical and economic conditions than a system based on only one of these sources. In this context, [7] suggest the supply of electricity through the integration of two sources, one hydric and the other PV, having as primary source of power the hydroelectric system, while the photovoltaic system acts in a complementary way, aiming to improve the reliability in the energy supply. Hybrid systems are interesting strategies from the point of view of energy reliability [8].

Currently, in the state of the art there are several topologies of hybrid systems using Hydro and PV sources, in most of them the system has an ESS (Energy Storage System), usually composed of battery banks. However, there are cases in which the batteries are connected directly to the DC bus, such as the one proposed by [9], which, although it is simpler, because it does not have an element for charging and discharging the batteries, can cause voltage fluctuations in them, thus reducing the life and efficiency of the batteries.

Similarly, in [10], the batteries are connected to the DC bus of a Voltage Source Converter (VSC). In this topology, the voltage applied on the battery bank comes from the Boost converter connected to the PV panel. By using a VSC, this strategy makes it possible to serve only single-phase loads.

The system developed by [11] makes use of an ESS connected to a common DC bus through a Buck-Boost converter. It allows only three-phase loads to be serviced, besides not having reactive compensation. The systems proposed by [12] and [13], consists of a hybrid system, composed of PV and Hydro sources, and also a battery bank. A bidirectional DC-DC converter is employed to connect the battery to the DC bus, and control the charging current in Buck mode and discharge the battery in Boost mode. The maximum power of the PV array is obtained by the Boost converter. The latter also regulates the DC voltage of the three-phase inverter bus. However, according to [14], the efficiency of the Boost converter decreases rapidly in a high duty cycle. In addition, a limiting factor about the Boost converter is its static gain (ratio of output voltage to input voltage), which is usually limited by five times.

This paper proposes the use of the DAB (Dual Active Bridge) converter in a hybrid energy generation system composed by Hydro and PV sources. The DAB converter aims to realize the MPPT (Maximum Power Point Tracker) of the PV system, as well as the interface between the PV system and the Distribution Static Compensator (DSTATCOM) DC bus, in addition to reducing the associated losses, when compared to the use of the Boost converter. It is also proposed to use a bidirectional Buck-Boost converter to connect ESS batteries to PV generation. It should be noted that the batteries can be charged by both PV and Hydro generation, depending on the operating mode of the system. The AC part of the system is composed of an

Induction Generator (IG) mechanically coupled to a Primary Machine (PM) of constant velocity and torque, in addition, for the auto-excitation of the generator, a bank of capacitors connected in the star configuration , from which the neutral conductor is derived, characterizing the system as a four wire generation system. In the block diagram illustrated by Fig. 1, the power flows of the proposed system are presented. In it, it is observed that the DAB converter interfaces between the DC bus while the DSTATCOM transfers energy between the system's AC and DC buses and is responsible for the injection of currents that regulate the AC bus voltage.

II. Proposed System

It is proposed, for the hybrid power generation system, as shown in Fig. 2, the use of two bidirectional DC-DC converters, Buck-Boost and DAB. The first, through switches S_2 and S_3, together with an *LC* filter (L_2 and C_2), will have as its main function to regulate the flow of energy from renewable energy sources to the batteries. The second one will be used to realize the interface between the PV generation and batteries with the DSTATCOM DC bus, increasing the voltage supplied by the PV system and the batteries to the desired DC voltage level of 660 V. This voltage level is intended to enable DSTATCOM to provide both single and three phase voltages.

As shown in Fig. 2, the proposed system is three-phase four-wire, capable of supplying both three-phase and single-phase loads, either linear or non-linear, since the system makes it possible to supply reactive energy demands through the DSTATCOM. In addition, the proposed system has an Electronic Load Control (ELC) connected to the DC bus of DSTATCOM, which is used to dissipate active energy in critical situations in which there is a surplus of energy that can not be used or stored in the ESS. The ELC acts in conjunction with the ESS in managing the surplus energy generated.

A. *Dual Active Bridge Converter (DAB)*

In high-power applications, Full-Bridge converters are indicated because they allow flexibility to be adapted to the most varied situations, in which to increase or reduce the input voltage becomes necessary [15]. A bidirectional converter is usually used to control active power flow and regulate DC bus voltage during changes in voltage source or load [16]. To enable bidirectionality, two isolated Full-Bridge converters are used, being denominated like DAB converter. The DAB converter was initially proposed in [17]

More specifically, the DAB converter consists of a high-frequency transformer and two Full-Bridge converters, one on the primary side and the other on the secondary side of the transformer. The energy flux is controlled by the switching of both Full-Bridge converters, applying an appropriate phase shift (δ) between the voltages imposed by the bridges on both sides of the transformer [18]. By making use of a transformer, the bridge switches are controlled in such a way that the duty cycle is constant and does not exceed 50% of the driving time in each arm of each bridge, this strategy aims to avoid transformer saturation [19].

The modulation applied to the DAB converter is the Phase-Shift Modulation (PSM), since it is simple to implement and has high power transfer capacity [20]. With the use of traditional PSM modulation, the power transfer in the DAB converter occurs in a bidirectional way, through the lag between the input signals of the input and output bridges [21]. Through the gap between the bridges of the DAB converter, the operation can be in Boost mode or Buck mode according to the operating mode of the system. The DAB converter, according to [20], becomes an interesting option in applications that require high voltage gain, high power and bidirectional energy flow, besides having galvanic isolation and working with higher switching frequencies, decreasing associated losses. Due to its characteristics, the application of the DAB converter in the Hydro-PV hybrid system becomes an interesting strategy, offering flexibility and robustness to the system. The driving modes of the DAB converter are shown in [22-24], while the DSTATCOM is shown in [25-27]. Energy Storage System (ESS)

By using a stochastic and intermittent power source, PV generation at certain times of the day may become non-existent and, when referring to energy reliability, this intermittence in power generation becomes undesirable from the point of view of stability in supply of energy. To work around this problem, and to maintain power supply, an ESS based on stationary batteries is used. When the system operates under normal load conditions, ie without intermittent generation or overloading, surplus energy can be stored in the ESS via the Buck-Boost converter, assuming the power supply at any failure of the main power system. Between the battery bank and the bi-directional converter was used a low pass filter *LC* which, according to [28], is intended to reduce current oscillation in the battery bank.

When the load connected to the system is of great importance (critical load) and its supply can not be interrupted, or even an intermittence in one of the generation sources makes the power supply unfeasible, it is possible to use, through the Buck-Boost converter, the energy stored in the ESS batteries. Thus, DC bus voltage levels are maintained through the DAB converter so that DSTATCOM can provide the surplus energy required by the load. The use of stored energy tends to provide autonomy and reliability to the system.

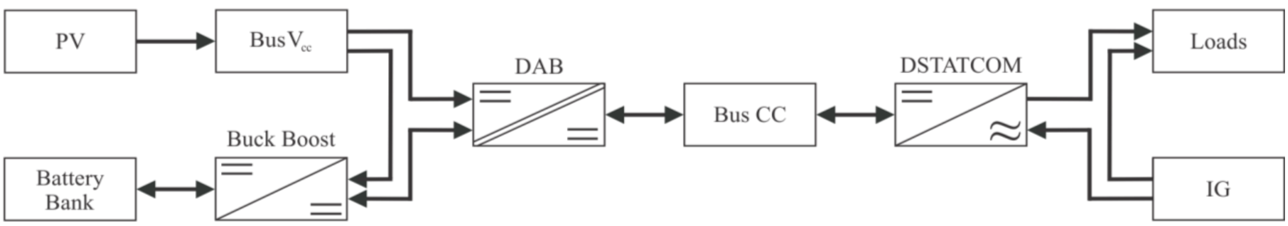

Fig. 1. Block diagram of the proposed system.

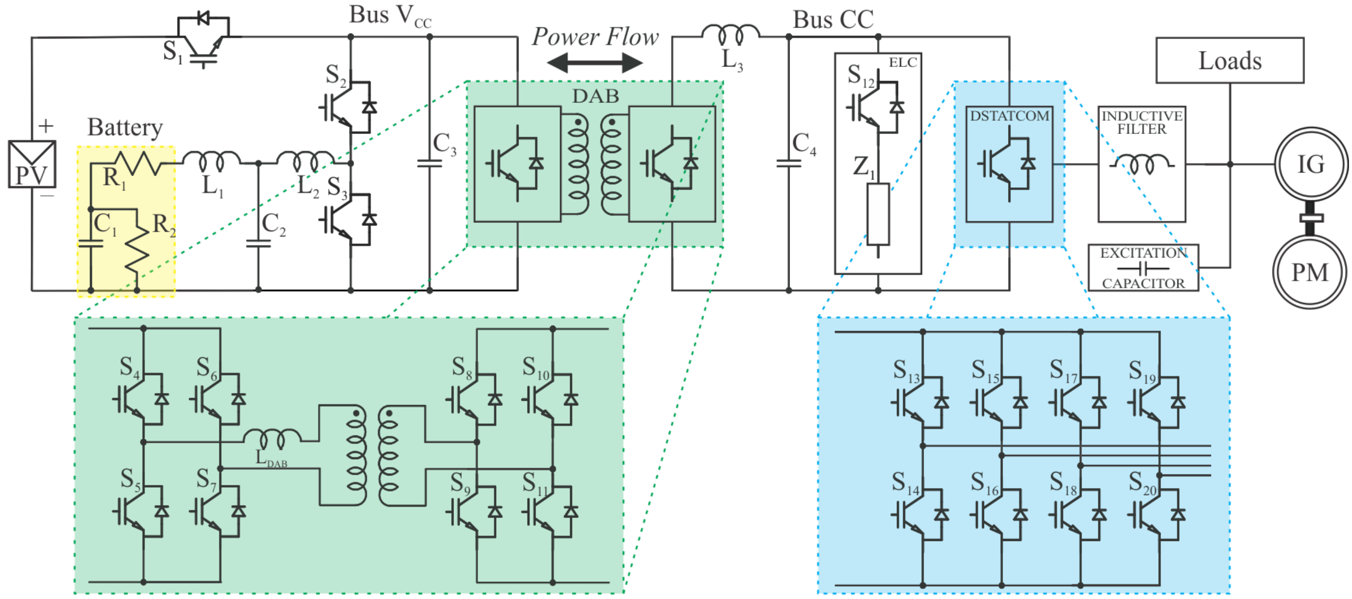

Fig. 2. Proposed System.

B. *Mode of Operation of the Hybrid System*

Depending on the condition of the loads, the system can operate independent of each other or in a complementary way, this configuration characterizes Mode A of operation. Another aspect about Mode A is that the PV generation can still be used to charge the ESS batteries through the Buck-Boost converter, the active power flow with the system operating in Mode A can be seen in Fig. 4a. When the battery power is used in conjunction with PV generation to supply an increase in demand, triggering a critical load, the system starts to operate in mode B, shown in Fig. 4b. In that it is noticed that the active power flow in the batteries presents opposite direction with respect to Mode A shown in Fig. 4a. During the absence of solar irradiance, the batteries are energized and at this point the system will operate in Mode C, shown in Fig. 4c. Operation of the system in Mode C is intended to keep DC bus voltage levels stable so that DSTATCOM can provide the surplus energy required by the loads or service of a critical load. While Hydro generation maintains the power supply to the loads and while the PV system does not generate power, the ESS batteries are charged by surplus energy from the Hydro generation through DSTATCOM and the bidirectional DAB and Buck-Boost converters. In addition, when both sources are generating, surplus generated energy that is not consumed by the load can be stored in the ESS battery bank, this action describes the Mode D operation of the system, shown in Fig. 4d, where it is noted that the excess active power flows are oriented to the batteries. However, the surplus of generated energy that is not consumed or stored must be dissipated in order to maintain system regulation. It should be noted that, with regard to the surplus energy generated, the system has two modes of operation, Mode E and Mode F. The first one has as priority the storage of the surplus in the batteries, while the surplus that can not to be stored is dissipated in the ELC, as seen in Fig. 4e. It is observed that the energy coming from the PV system is in part used to maintain and/or charge the ESS batteries, while the energy surplus is dissipated in the ELC, as well as the energy surplus of the hydro generation. In all operating modes of the system, the DAB converter will, in addition to interfacing the DC busbars, operate in the Maximum Power Point (MPP) tracking of the PV system and, when found, should operation Mode F. This mode is intended to prevent a large amount of energy from being dissipated in the ELC while the batteries are fully charged. In this case, the DAB converter will cause the PV system to exit the MPP and take it to a Disconnect Point (DP), shown in Fig. 3, in which the power is such as to allow the safe disconnection of PV generation from the rest by the key S_1. When the S_1 switch is open and the PV generation does not contribute to the power supply, and the batteries are fully charged, the Buck-Boost converter is also turned off, so as not to damage the batteries by overload or to waste energy from them. Already, the DAB converter will shut down as soon as the S_1 switch is open and the Buck-Boost converter is inoperative. Thus the power dissipated in the ELC becomes smaller and originates only from the surplus of the hydro generation, Mode F of operation can be observed in Fig. 4f.

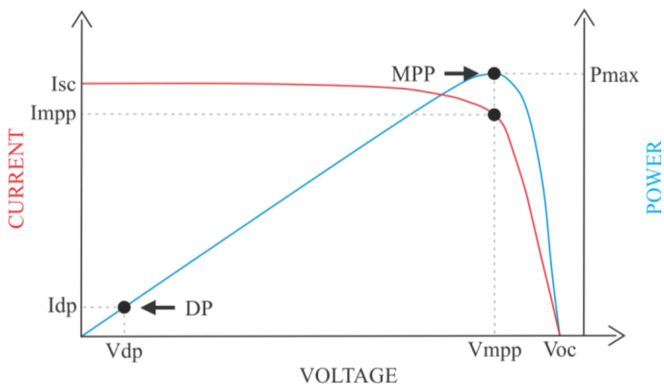

Fig. 3. I x V x P curve, illustration of the operation at maximum power and point of disconnection.

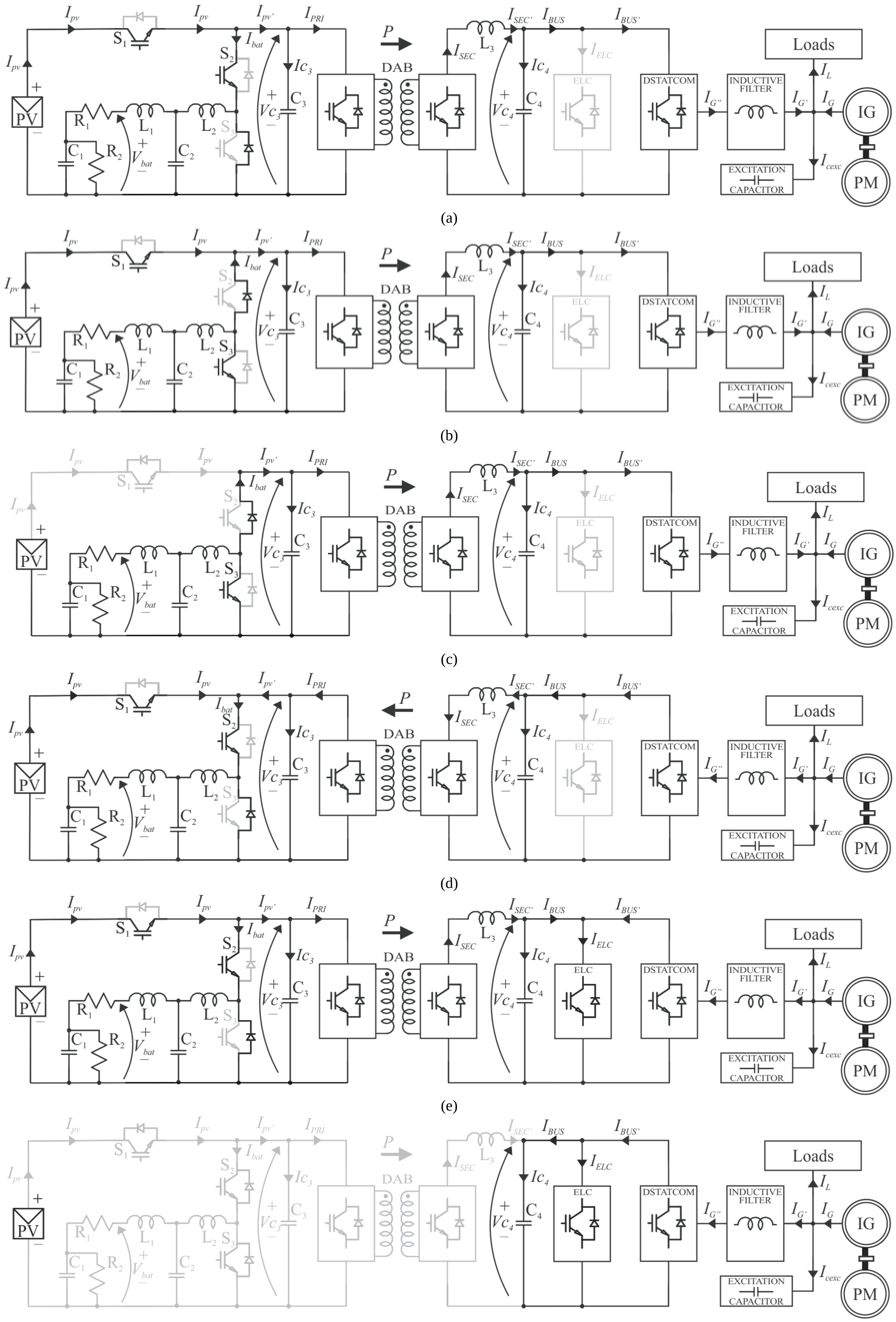

Figura 4 – Modes of operation of the proposed system: (a) mode A, (b) mode B, (c) mode C, (d) mode D, (e) mode E and (f) mode F.

III. Simulation Results

In order to partially validate the proposed system, simulations were performed in the LTspice software. The simulation parameters are presented in Table 1. In addition, it should be noted that the PSM technique was used for the DAB converter. The Buck-Boost converter was modulated with Pulse Width Modulation (PWM), both with switching frequency (f_s) of 50 kHz. It should be noted that the values of the resistances and capacitance of the battery (R_1, R_2 and C_1) were reduced in order to optimize the simulation period.

The system operates in open loop, with the exception of the charging and discharging of the batteries that has a PID controller.

TABLE I. Variables and their respective magnitudes.

Variable	Value
R_1	0.05 Ω
R_2	5 kΩ
C_1	1 F
C_2	480 μF
C_3	1000 μF
C_4	4700 μF
L_1	38 μH
L_2	1.8 mH
L_3	1.2 mH
L_{DAB}	940 μF
$V_{bus} = V_{C4}$	660 V
V_{bat}	48 V
S_{oc}	24 V
V_{charge}	55 V
$V_{cc} = V_{pv} = Vc_3$	126.8 V
f_s	50 kHz
δ_0	20°

Regardless of which power generation system supplies power, the Buck-Boost converter response will be the same for PV, Hydro or both, providing power to charge the batteries. The dynamic response of the voltage in the battery bank in both charge and discharge mode can be seen in Fig. 5, where the initial state (S_{oc}), of the batteries is 24 V. When charging the batteries (Buck mode) the tension will be raised smoothly, there being no abrupt voltage fluctuations. The voltage on the battery bank stabilizes at 55 V, V_{charge}. In the discharge mode (Boost mode), the voltage in the battery bank will decrease, and to prevent deep discharges in the batteries, the voltage will be stapled to the value of S_{oc}, observed in the right corner of Fig. 5.

Fig. 6 shows the voltage waveforms for the operating modes: A, B and C. In Mode A, when the PV system feeds the DC bus of the DSTATCOM and charges the batteries, there is a voltage attenuation in the V_{cc} DC bus, located on the primary side of the DAB converter (capacitor C_3), caused by the charging of the batteries. This feature will be observed whenever the ESS batteries are charged. When shading occurs on PV panels, the generation voltage will decrease instantly. Therefore, the energy previously stored in the batteries will be used through the Buck-Boost converter, operating in Boost mode, characterizing Mode C. It is observed that there are four voltage transients, the first happens at the time the shading occurs and the batteries start to maintain the voltage level of the DC bus (V_{cc}) and the system starts to operate in Mode C. The second occurs when the generation voltage of the PV system returns to the nominal value and the batteries stop feeding the V_{cc} bus and then reloaded, the system will now re-operate in Mode A.

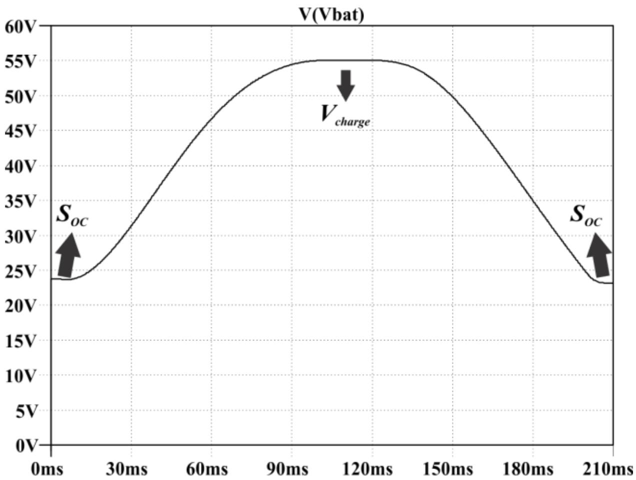

Fig. 5. Battery bank voltage in charge and discharge mode.

At the moment a critical load is triggered, requiring more energy from the system and, starting from the premise that the system is already operating at nominal conditions in Mode A, the system will switch to Mode B. Because the PV and Hydro generations are already in nominal operating conditions and will not have the power to supply this surplus demand. At the moment the load is triggered, the third voltage transient occurs and the batteries start to work together with the system to maintain the power supply. At the moment the load is disconnected, the transient voltage room occurs and the system changes the operating mode promptly, switching back to Mode A, charging the batteries.

Due to the high capacitance of the DC bus of the DSTATCOM, the voltage thereon will show few variations due to oscillation in the V_{cc} bus caused by absence of solar irradiance or the increase of energy demanded by the drive of loads on the AC side. However, due to battery bank load, the DC bus voltage of the DSTATCOM (V_{bus}) will suffer a slight attenuation while the voltage reaches its nominal value, this behavior is illustrated by Fig. 6.

The power of the PV system, the IG and the battery bank are 5 kW, 3.7 kW and 2 kW, respectively. Regarding the output of the system, it was considered a permanently coupled *RL* load on the AC side, whose active power per phase is 2.2 kW with an angle of 45°, corresponding to a power factor of 0.7, resulting in 3 kVA per phase. Because it is a three-phase load, the total power of this load is 9 kVA, being delta-connected to the DSTATCOM output, which operates in open loop. In addition, loads of 3 kW and 4.5 kW were driven on the V_{cc} and DC bus of the DSTATCOM (V_{bus}), respectively.

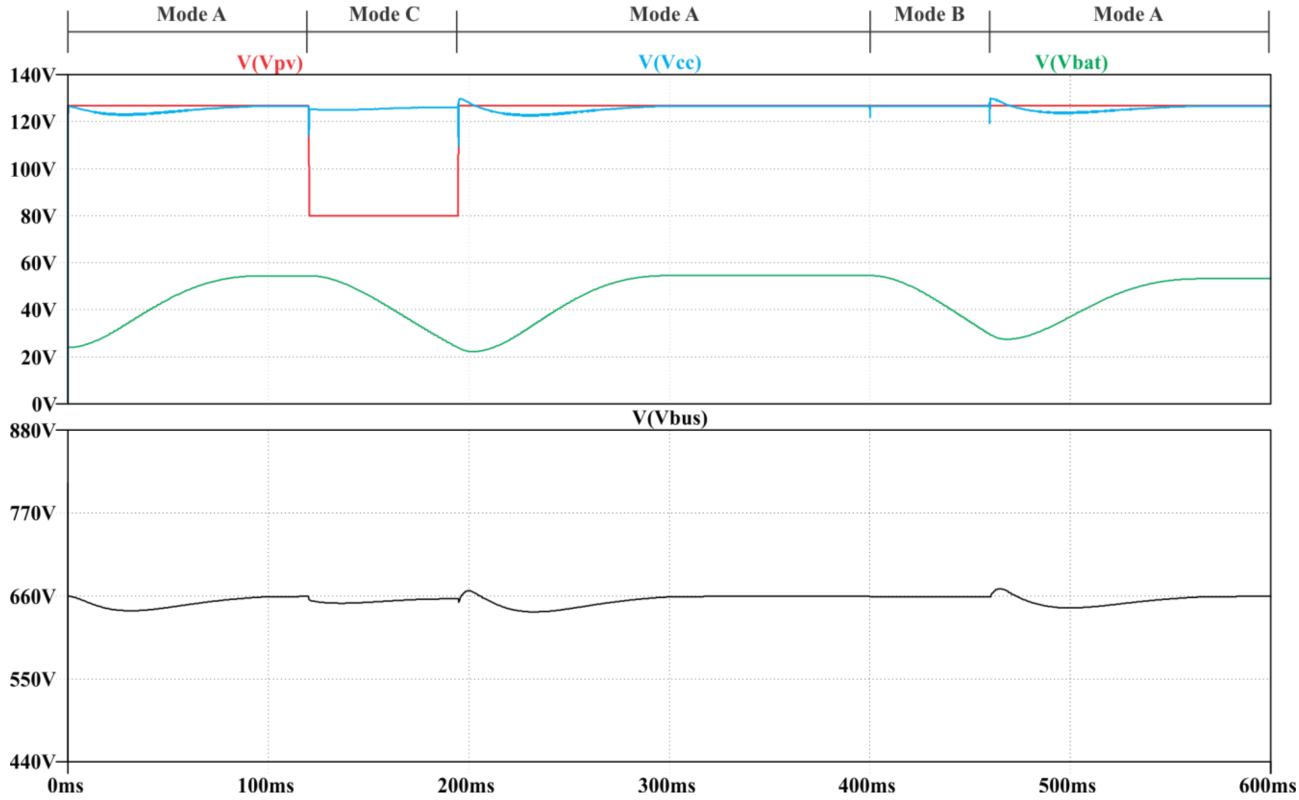

Fig. 6. Generation voltage of the PV system (V_{pv}), battery bank (V_{bat}) and DC bus of V_{cc} and DSTATCOM (V_{bus}).

It should be noted that the transients presented are due to the transition between modes with the use of a basic PID controller not optimized precisely to show the transient modes. Emphasizing that the focus of this paper lies in the topology of the converter and not in its control. The use of laws of faster controls and projected according to the mathematical models of the plant will contribute to the reduction of the transients of tension in the moments of transition between the modes. In addition, it is emphasized that the parameters of the batteries were reduced in order to optimize the simulations and that the obtained results are in agreement with the expected behavior, being presented only in a smaller time scale. The results obtained are fully satisfactory, demonstrating the dynamics of the system against parametric variations in PV generation and in the service of surplus loads.

In order to analyze the quality of the energy supplied to the loads, the influence and importance of the harmonic components in the output of the system was verified, since the harmonic components, when present in the output signals, degrade the quality of the same. In addition, since the load coupled to the DSTATCOM output is three-phase and delta-connected (phase-phase), the theoretical voltage applied to it is 380 V_{RMS}. However, due to the operation of the system, the voltage applied to the load will not usually present this exact value, and it is of the utmost importance that the magnitude is as close as possible to the ideal. The results obtained through the simulation of the proposed system are fully satisfactory, since they present values close to the standard ones, demonstrating that the system is able to supply energy with quality and little Total Harmonic Distortion (THD), according to:

- AC current THD at 0.132% load.
- AC voltage THD at 0.569% load.
- Effective load voltage of 379.97 V_{RMS}.
- Effective voltage on the DC bus of 652,45 V_{RMS}.
- Effective voltage on the V_{cc} bus of 126.03 V_{RMS}.

In Fig. 7 it is possible to observe the AC current components in the output of the DSTATCOM that are sinusoidal waveform, frequency of 60 Hz and are lagged at 120°, taking into account the requirements of the loads connected to the output of the system. It is worth mentioning that the variations in the current magnitudes are derived from the DSTATCOM open loop operation and that the starting transient can be negligible since it does not affect the analysis of the system.

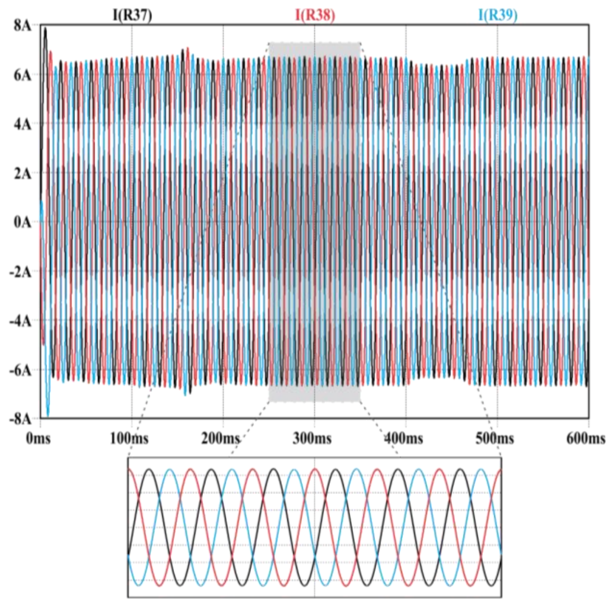

Fig. 7. AC output current of 9 kVA load.

IV. CONCLUSIONS

In this paper it was proposed the use of the DAB converter in the hybrid system of energy generation, composed by hydro and PV sources. In addition, a power storage system was used, using a Buck-Boost converter to perform the loading and unloading of the batteries. Simulation results were presented, which demonstrate the expected performance from the point of view of system functionality. In this aspect, it can be stated that the strategy employed was adequate, being able to control the flow of power between the loads and the generation systems, presenting bidirectionality and galvanic isolation between the generation systems. The Buck-Boost converter also showed satisfactory response, both in charge and discharge of the batteries.

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