Modeling and Simulation of Buck Converters and their Applications in DC Microgrids

León Felipe Serna-Montoya, León Alexis Buitrago-López, Juan Bernardo Cano-Quintero, Nicolás Muñoz-Galeano, Jesús María López-Lezama

***Abstract*—This paper presents the modeling and simulation of Buck converters for DC microgrid (DC-MG) applications. These include maximum power point tracking for solar and wind generators, battery charging for stationary storage and electric vehicles, drivers for electric pumps and DC coupling between DC-link buses. This paper summarizes the most relevant issues for each application. It was found that most DC-MG applications require the control of input voltage; nevertheless, most authors model the Buck converter input as a constant voltage source, neglecting the dynamic behavior of the system. In consequence, as a main contribution of this paper, it is proposed the use of a capacitor and a variable current source for a more realistic approximation of the Buck converter when used in DC-MG applications. Taking into account these considerations, large- and small-signal models were deduced. Furthermore, a transfer function that relates the input voltage and duty was obtained and validated through simulations; also, its corresponding PI controller was tuned. A DC-MG was implemented for showing the applicability of the Buck converter. The operation of the microgrid was detailed with its corresponding transitory behavior and most critical point. In general terms, the Buck converter in the simulated DC-MG successfully regulates the DC bus when perturbations and changes in generation and loads are applied.**

***Index Terms*—Buck converter, DC Microgrids, mathematical modelling, Power electronics.**

I. Introduction

MICROGRIDS have become one of the new alternatives for satisfying the growing energy demand since they allow the integration of Distributed Energy Resources DERs. In general terms, MGs are electrical systems that incorporate controllable loads, energy storage systems, and Distributed Generation (DG). Also, MGs can operate in grid-connected and islanded modes [1]. Microgrids involve different kind of devices which integration is usually implemented through Power Electronic (PE) converters. PE devices are commonly used in MGs due to their flexibility, robustness, and high performance. Some remarkable applications of PE converters in MGs include: PV inverters [2], [3], [4], [5], [6], wind turbines coupling [4], [7], [8], Battery Energy Store Systems (BESS) [6] and Vehicle to Grid (V2G) applications [9], [10]. One of the most extended PE devices in MGs is the Buck converter. This device is basically used for reducing DC voltages and coupling different DC-DC systems [4], [7], [8], [11], [12], [13], [14], [15], [16].

Many Buck converter applications in MGs have been reported in the technical literature. In [4], [7], [8], [11], [12], [17], several configurations of Buck converters are presented for controlling and supporting the energy of the DC-link bus. The Buck converter is also used for controlling the DC-link voltage in Programmable Electronic Loads (PELs). A PEL emulates load profiles to test elements such as UPS or inverters. Furthermore, Buck converters are used in the DC side of PELs for avoiding DC voltage increments due to the unidirectional flow of energy that PELs can emulate (active power). Basically, the Buck converter at the DC side of PELs provides power balance, dissipating the energy excess of the DC bus [13], [14], [15]. Another relevant application is PV and wind systems that use Maximum Power Point Tracking (MPPT) devices for increasing energy production. The Buck converter has been used in the following MPPT applications [2], [3], [4], [5], [6]. In DC-MGs, Buck converters regulate the DC bus, coupling elements such as loads and Battery Energy Storage Systems (BESS). All of these elements deliver variable energy to the DC bus; therefore, a device such as the Buck converter is required for voltage regulation and adequate energy management [7], [8], [16], [18], [19], [20], [21]. In DC-MGs the DC bus voltage must be regulated and stable. therefore, the Buck converter must avoid DC voltage transients due to sudden changes on loads or DERs [11], [12], [16], [22], [23], [24], [25], [26]. DC-MGs implementations usually require capacitor banks for reducing voltage oscillations in the DC bus. In [9], [10], the authors proposed design and control strategies applied for Buck converters which allow reducing the sizing of capacitors, therefore reducing implementation costs. In [27], a Buck converter was used in a DER application to provide different voltage levels for MG cost reduction. From the bibliographical search, it was found that Buck converters are mainly used in MGs for regulating the DC voltage output; that is to say, Buck converter receives variable voltage and current and must deliver power optimally according to the needs of the specific application.

Due to the aforementioned reasons, this paper details Buck converter applications with variable voltage in its input. It is important to highlight that the technical literature mainly reports models and controllers with a constant input DC voltage, so they do not focus on analyzing the real

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dynamic behavior of the converter in MGs which do not feature a constant input voltage; instead, these applications furnish variable input voltage to the buck converter that must control it [28], [29], [30], [31], [32]. In [33], [34], the authors modeled a PV array through the Thevenin equivalent; however, this model does not use an output capacitor. The Norton equivalent circuit reported in [35], [36] showed a model with a constant current supply and a parallel resistor at the Buck converter input, so dynamics in the output were not considered. In [37], the authors reported a model that includes resistors to describe losses; however, resistors add a higher degree of complexity to the modeling. In [17], two models were developed in Modellica for the buck converter, the average model of the converter was implemented and compared with a more complex model which includes transients. This paper presents several applications of Buck converters in DC MGs and highlights their importance in fields such as stability and coupling for different voltage levels. Also, the Buck converter is shown for compensating DC voltage oscillations and for MPPT systems. The use of Buck converter depends, in most cases, on the control strategy that is implemented. The reviewed applications face with variable voltage at their inputs; nonetheless, most consulted papers consider a constant voltage source at their input, losing part of the dynamic behavior of the converter. The model presented in this paper considers a capacitor at the input and a variable current source for representing a more realistic dynamic behavior of the Buck converter under different operating conditions and applications in DC-MGs. The model proposed in this paper is closer to the implementation in real MG applications, since most applications present fluctuations in the Buck converter input. The simulated DC-MG in this paper includes: 1) photovoltaic (PV) generation with Buck converters for maximum power tracking, 2) DC loads with several profiles, and 3) a Buck converter which main function is DC voltage stabilization when perturbations and changes in generation and load are applied.

This paper is organized as follows: Section II presents the Buck converter applications for DC-MGs. Section III presents the deduction of the Buck converter model for variable input voltage applications. In Section IV, Buck converter simulations are performed for model validation and for showing the applicability of the model in a PI controller. Furthermore, the simulation of a DC-MG is included focusing on the dynamic and transitory performance of the Buck converter for voltage stabilization. Finally, conclusions are discussed in Section V.

II. Buck converter applications in DC-MGs

A Buck converter is a power electronic device composed of switches (generally IGBTs), diodes and energy storage elements (capacitors and inductors). This device is traditionally seen as a DC-DC step down voltage transformer; therefore, for a given input voltage, the output voltage is regulated or controlled. However, the consulted technical review shows that usually the Buck converter input is connected at the output of some MGs devices that furnish a variable voltage (i.e. solar panels). This changes the traditional point of view of the problem since the voltage regulation of the Buck converter is performed at its input instead of its output. Figure 1 depicts different applications of Buck converters in DC-MGs: 1) MPPT for solar generators, 2) MPPT for wind generators, 3) battery chargers for stationary storage, 4) battery chargers for electric vehicles, 5) drivers for electric pumps, and 6) DC coupling between DC-link buses.

A. Maximum power point tracking (MPPT)

Renewable energy sources such as solar and wind are inherently intermittent and configure variable power sources. To deal with this issue, a system that furnishes real-time power control and provides the maximum power in each instant of time is required. The application for obtaining the maximum power in solar and wind applications is the so called MPPT. In this case, the Buck converter is connected at the output of the panel for performing voltage regulation. This configuration requires voltage control at the output of the panel, or in other words, voltage control at the input of the Buck converter. The following are some research works that use Buck converters as hardware for MPPT: [2] proposed a flower pollination algorithm (FPA) and a PI controller for tracking the MPPT. The authors in [3] proposed a MPPT scheme based on the perturbation and observation (P&O) method applied to an isolated solar PV system. Furthermore, In [4], the P&O method was applied on PV and wind systems; nevertheless, these systems were connected to a power network. In [5], the authors proposed a MPPT for a solar system that uses a diffuse Takagi-Sugeno (T-S) control method. In [6] the authors proposed a battery charger that uses a Buck converter as MMPT system for directly coupling solar panels to batteries; operation mode allows the batteries to be charged in both floating mode and high energy demand mode.

B. Voltage regulator

For this application, the Buck converter is in charge of the DC bus voltage regulation. Changes in generation and loads produce variation in the DC voltage, which could significantly affect the system due to rapid changes of environmental variables such as wind or radiation, or also due to fast load changes. A solution for this problem is presented in [8], [18] through a decentralized PI control method that is applied by using a Buck converter in a AC-DC hybrid MG in which the DC-link bus is the main bus. The applied control allowed achieving a plug-and-play system which permits the generation to be disconnected or connected to the system independently, while generation changes do not affect the voltage regulation of the DC bus. Also, in [20], the authors proposed an algorithm based on sliding mode for parallel Buck converters which allows optimal load distribution in the face of arbitrary changes in the topology of the MG, thus achieving an homogeneous voltage profile throughout the DC bus of the MG. In [21], a sliding mode controller was proposed for ensuring voltage regulation for a set of resistive voltage loads and constant power consumption.

Another especial case reported in the technical literature concerning DC bus regulation is a system with multiple sources of wind generation that could cause imbalances in the energy dispatch between generation and loads in isolated DC-MGs which leads to poor voltage regulation at the DC bus [7]. MPPTs may be uncoordinated since the wind flow received by all generators is not the same. This is reflected

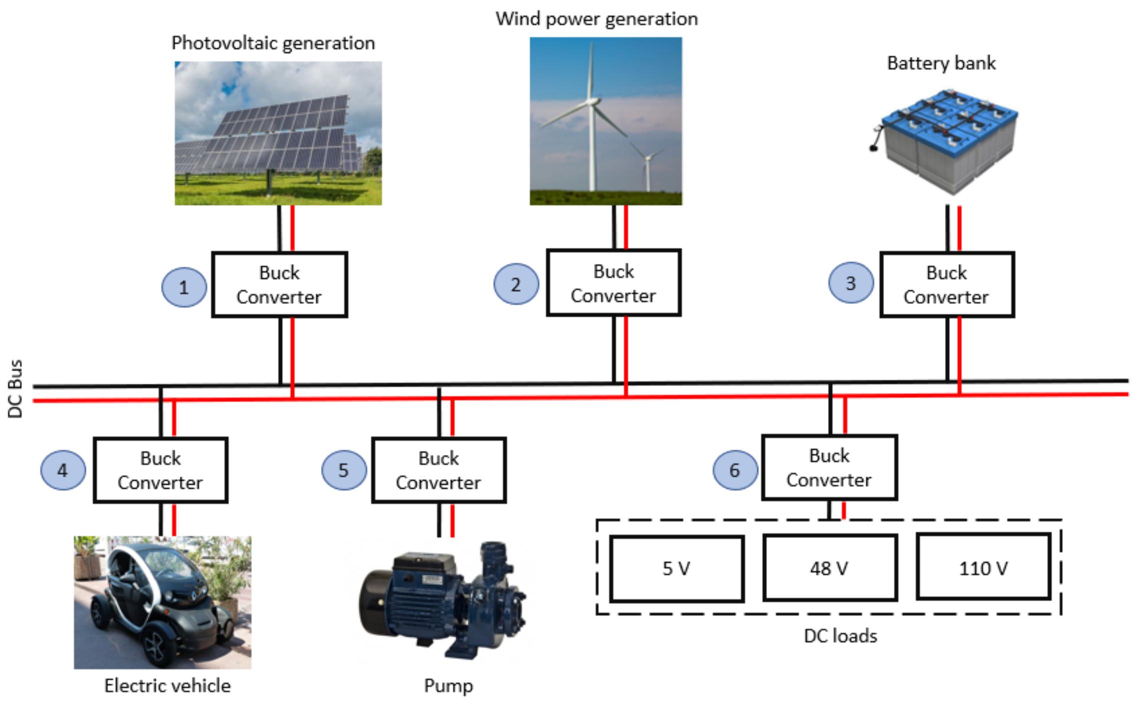

Fig. 1. Buck converter applications in DC microgrids.

in excess of generation which in most cases can not be solved with storage systems. A solution to this imbalance is shown in [7] by means of a load distribution control method that coordinates the operation of permanent magnet wind generators through a two-layer predictive control method; the first layer optimizes the cooperation of parallel Buck converters while the second one sends an optimal power reference to the generator controller.

C. Voltage stability system

DC-MGs have some advantages over AC-MGs since the former present better coupling between DG based on renewable sources. Also, they feature lower losses and require fewer PE elements which results in higher efficiency. Additionally, DC-MGs do not have associated problems related to harmonics, synchronization and reactive power flow. However, DC-MGs may present voltage stability problems; therefore, they require an operation mode where stability is guaranteed and the system can maintain voltage levels within a defined range in all the nodes, even under disturbances [38].

In summary, voltage stability in DC-MGs can be affected due to the following factors: 1) a great quantity of parallel connected DC networks, 2) generation or load variations, and 3) power differences between energy storage systems. For improving voltage stability, the technical literature proposes hierarchical control methodologies (primary and secondary control) and Markov chain modeling for voltage regulation and energy control to achieve a proper energy balance [16], [22].

The authors in [11] proposed a drop control to determine the power of two Buck converters in parallel, so that, it is possible to keep the voltage stable throughout the DC bus of the MG. On the other hand, connection and disconnection of elements in the presence of loads with constant power consumption (Constant Power Load, CPL) such as pumps or other loads may lead to instability problems or voltage collapse [23]. This is due to the negative incremental impedance characteristic related to poor adjustment of the inductance and capacitance of the Buck converter parameters which can exceed certain values or generate resonance.

In [12], a method is presented for adjusting the L-C parameters for parallel Buck converters using Root Locus in Matlab/Simulink. The stability was verified through the eigenvalues methodology and Routh-Hurwitz criterion; adjustments were implemented in a centralized PI controller to generate PWM signals for each Buck converter in parallel. This problem was also studied from another point of view in [24] where it was evident that the stability problem is mostly reflected in the passive elements of the converter such as the capacitor which sometimes is chosen of large size to provide stability on the generation side. However, several control methods can be used for voltage stabilization, so that the size of the capacitor can be reduced by transferring the stability of the passive components to the control loop of the converter, thus reducing the slow dynamics and the high short-circuit current that would imply the use of a larger capacitor.

MPPT algorithms are widely used in PV generation systems as they significantly improve energy production efficiency; however, this system could introduce instabilities in the MG voltage due to changes in irradiation. For overcoming this issue, [25] proposed an array of two converters (Buck and SEPIC), that used a connection of a PV module in series with a SEPIC converter with a MPPT control and a flower pollination algorithm. In this case, a capacitor links both SEPIC and the Buck converter that regulates the voltage for stable coupling with the DC bus while SEPIC works as MPPT.

A way of increasing the reliability of electrical systems is to configure multiple power supplies for a single set of loads;

however, this redundancy may cause imbalances or voltage stability problems when one of the sources must assume the entire load; authors in [26] proposed a drop control with a Buck converter configuration. The implemented proportional control depends on the impact of the gain of statism of the system which is evaluated through the eigenvalues methodology.

D. Oscillation compensation in the DC-link bus

DC-MGs do not experience problems related to reactive power and harmonic content; nonetheless, when inverters or rectifiers are used in applications such as wind power generation or automotive electrical systems, power fluctuations can cause oscillations or large changes in DC bus voltage and produce excessive current ripple which reduces the life of other elements connected to the MG such as batteries or fuel cells. In [9], the authors developed an active compensator based on a PWM-controlled Buck-Boost converter with a repetitive control strategy that seeks to inject the harmonic current or distortion required to eliminate power fluctuations. they also reduced the size of the capacitors that are installed for the compensation. On the other hand, when a DC-MG integrates charging ports for electric vehicles, Buck-Boost converters are often used to acquire an up/down voltage ratio that allows the vehicle's battery to be coupled to the system. When these devices have a very high voltage transformation ratio, parasitic inductances and capacitances limit the voltage conversion which introduces problems such as: noise, voltage and current spikes and off course an increase of losses. In [10], a closed loop PI control was proposed for a poly-phase interpolated bidirectional converter that integrates a Buck converter operating as a voltage divider during charging to achieve a high voltage step conversion that decreases the transformation ratio.

E. Coupling for multiple voltage levels

Islanded DC-MGs with solar generation are a very popular alternative in rural or non-interconnected areas. However, these isolated systems need various voltage levels for satisfying requirements of different applications. Also, when loads are directly connected to the generation output, costs are minimized but the converter is subject to a variable voltage input. In [27], the authors presented the implementation of a Buck converter with one input and two outputs with a single inductor operating in continuous driving mode. Additionally, this topology minimizes the costs and complexity of the control system while increasing adaptability and modularity for solar PV systems.

III. Buck Converter Modeling

Buck converters are PE devices typically used as DC-DC step down voltage transformers. The topology of a Buck converter is depicted in figure 2. In this case, v_{C1} and v_{C2} are the input and output voltages, respectively. The output voltage amplitude depends on PWM switching of the power switch (Q). The gain corresponds to the ratio between the input and output voltage, which is lineal and proportional to the duty cycle.

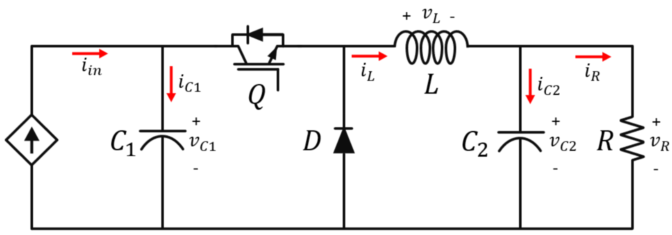

Fig. 2. Buck converter.

A. Switching states

Figure 2 shows the state variables of the Buck converter. References of currents and voltages are depicted using passive sign convention to facilitate the deduction of equations. Voltage polarity has been specified and current directions are indicated through arrows. Power switch and power diode states define the switching states. Q closed corresponds to the first switching state that is shown in Figure 3. Then diode D is inverse polarized. Kirchhoff voltage law allow defining Equation (1) while Kirchhoff current law allow defining Equations (2) and (3).

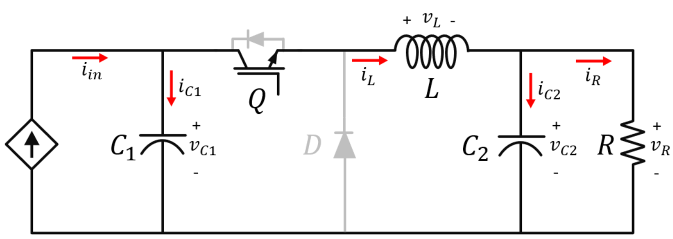

Fig. 3. Equivalent circuit, Q closed.

$$L\frac{di_L}{dt} = v_{C1} - v_{C2} \tag{1}$$

$$C_1\frac{dv_{C1}}{dt} = i_{in} - i_L \tag{2}$$

$$C_2\frac{dv_{C2}}{dt} = i_L - \frac{v_{C2}}{R} \tag{3}$$

Q open corresponds to the second switching state that is shown in Figure 4. The inductor reacts to sudden changes in current, so it changes its polarity $v_L < 0$ then diode D is directly polarized, thus a new equivalent circuit is generated. Kirchhoff laws were used for deducing Equations (4), (5) and (6):

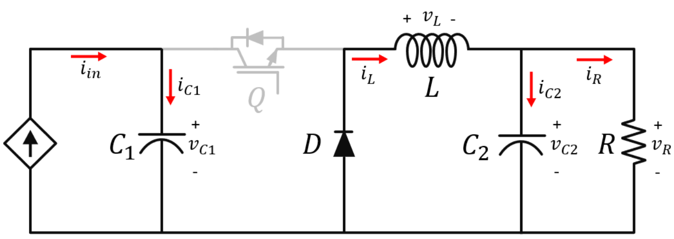

Fig. 4. Equivalent circuit, Q open.

$$L\frac{di_L}{dt} = -v_{C2} \tag{4}$$

$$C_1\frac{dv_{C1}}{dt}=i_{in} \quad (5)$$

$$C_2\frac{dv_{C2}}{dt}=i_L-\frac{v_{C2}}{R} \quad (6)$$

Capacitor C_1 increases its voltage when switch Q is open, since the current that enters (i_{in}) the Buck converter completely circulates by C_1. On the other hand, Capacitor C_1 decreases its voltage when switch Q is closed, since i_{in} is divided between C_1 and L. Consequently, voltage in C_1 is controlled by the operation of the power switch. Furthermore, excess of energy is dissipated in the resistor R.

B. Large-signal model

Large-signal model allows relating both switching states in a single model. The symbol $\widehat{\mu}$ represents the states of Q. $\widehat{\mu}$ is equal to 1 when Q is closed and equal to 0 when it is open. Equation (7) is obtained from Equations (1) and (4),considering the switching states and $\widehat{\mu}$.

$$L\frac{di_L}{dt}=(v_{C1}-v_{C2})\widehat{\mu}+(-v_{C2})(1-\widehat{\mu}) \quad (7)$$

Simplifying, Equation (8) is obtained

$$L\frac{di_L}{dt}=v_{C1}\widehat{\mu}-v_{C2} \quad (8)$$

Current in capacitors C_1 and C_2 is modeled by Equations (9) and (10):

$$C1\frac{dv_{C1}}{dt}=(i_{in}-i_L)\widehat{\mu}+(i_{in})(1-\widehat{\mu}) \quad (9)$$

$$C2\frac{dv_{C2}}{dt}=(i_L-\frac{v_{C2}}{R})\widehat{\mu}+(i_L-\frac{v_{C2}}{R})(1-\widehat{\mu}) \quad (10)$$

Simplifying, Equations (11) and (12) are obtained:

$$C1\frac{dv_{C1}}{dt}=-i_L\widehat{\mu}+i_{in} \quad (11)$$

$$C2\frac{dv_{C2}}{dt}=i_L-\frac{v_{C2}}{R} \quad (12)$$

C. Average Model

The average Buck converter model is obtained assuming that $\widehat{\mu}$ is the duty cycle applied to the power switch Q which is denoted by $\overline{\mu}$. Q is switched at a frequency of the order of kHz since high switching frequencies let the assumption that $\overline{\mu}$ has continuous values between 0 and 1 representing the percentage of active time based on the carrier frequency. Equations (13), (14) and (15) represent the states of the converter.

$$\frac{di_L}{dt}=\frac{v_{C1}\overline{\mu}}{L}-\frac{v_{C2}}{L} \quad (13)$$

$$\frac{dv_{C1}}{dt}=-\frac{i_L\overline{\mu}}{C_1}+\frac{i_{in}}{C_1} \quad (14)$$

$$\frac{dv_{C2}}{dt}=\frac{i_L}{C_2}-\frac{v_{C2}}{RC_2} \quad (15)$$

D. Steady State Equations

Steady state equations define the behavior of the converter when state variables do not change with respect to time, neglecting changes then derivatives become zero. Moreover, state variables are average values. Solving the system of equations given by (13), (14) and (15) the following is obtained:

$$\overline{I_L}=\frac{\overline{I_{in}}}{\overline{\mu}} \quad (16)$$

$$\overline{V_{C1}}=\frac{R\overline{I_{in}}}{\overline{\mu}^2} \quad (17)$$

$$\overline{V_{C2}}=\frac{R\overline{I_{in}}}{\overline{\mu}} \quad (18)$$

Equations (16), (17), and (18) allow inferring that the average voltage of C_1 depends on three parameters: R which is a design parameter, $\overline{\mu}$ that is the control variable and $\overline{I_{in}}$ which is directly related to the DC voltage level. The model proposed in this paper considers the incorporation of capacitor C_1 and a current source in the input; allowing a more accurate representation of the dynamic behavior of the Buck converter and its applications in MGs.

E. Small-signal model

Small-signal models represent the operating points of the system when small disturbances appear, allowing to model the plant and carry out control actions. The following equations show that each variable is made of two terms: an average and a small-signal variable indicated with the subscript δ. For example, the current of the inductor i_L is equal to the average current $\overline{I_L}$ plus a small-signal change $i_{L\delta}$.

$$i_{L\delta}=i_L-\overline{I_L} \quad (19)$$

$$v_{C1\delta}=v_{C1}-\overline{V_{C1}} \quad (20)$$

$$v_{C2\delta}=v_{C2}-\overline{V_{C2}} \quad (21)$$

$$i_{in\delta}=i_{in}-\overline{I_{in}} \quad (22)$$

$$\mu_\delta=\mu-\overline{\mu} \quad (23)$$

The Jacobian linearization process shown in [39] allows obtaining the small signal model. The result of this process is presented in Equations (24), (25) and (26).

$$\frac{di_{L\delta}}{dt}=\frac{\overline{\mu}}{L}v_{C1\delta}-\frac{1}{L}v_{C2\delta}+\frac{\overline{V_{C1}}}{L}\mu_\delta \quad (24)$$

$$\frac{dv_{C1\delta}}{dt}=-\frac{\overline{\mu}}{C1}+\frac{1}{C1}i_{in\delta}-\frac{\overline{I_L}}{C1}\mu_\delta \quad (25)$$

$$\frac{dv_{C2\delta}}{dt}=\frac{1}{C2}i_{L\delta}-\frac{1}{RC2}v_{C2\delta} \quad (26)$$

F. Proposed Transfer Function

Application of the Laplace transform to Equations (24), (25) and (26) yields (27), (28) and (29). Finally, Equation (30) is obtained, which corresponds to the transfer function $v_{C1\delta}/\mu_\delta$.

$$si_{L\delta} = \frac{\overline{\mu}}{L}v_{C1\delta} - \frac{1}{L}v_{C2\delta} + \frac{\overline{V_{C1}}}{L}\mu_\delta \tag{27}$$

$$sv_{C1\delta} = -\frac{\overline{\mu}}{C1} - \frac{\overline{I_L}}{C1}\mu_\delta \tag{28}$$

$$sv_{C2\delta} = \frac{1}{C2}i_{L\delta} - \frac{1}{RC2}v_{C2\delta} \tag{29}$$

$$\frac{-s^2\overline{I_L}RLC_2 - s\overline{\mu}RC_2\overline{v_{C1}} - s\overline{I_L}L - R\overline{I_L} - \overline{\mu}\overline{V_{C1}}}{s^3RLC_1C_2 + s^2C_1L + sC_1R + sC_2R\overline{\mu}^2 + \overline{\mu}^2} \tag{30}$$

IV. Results

A. Model validation

The circuital implementation of a Buck converter was performed by using PSIM software. The Buck converter was simulated using the specifications provided in Table I. The first row shows values of electrical components (parameters). The second one shows the input current and duty cycle value of Q considering a switching frequency of $20kHz$ (these variables are defined by users). Finally, the third row refers to average state variables that were found by using the average model (see section III-D).

TABLE I
PARAMETERS AND VARIABLES VALUES

Parameters	Value	Units
C1	0.0033	F
C2	0.0033	F
L	0.01	H
R	120	Ω
$\overline{I_{in}}$	0.625	A
$\overline{\mu}$	0.5	-
$\overline{I_L}$	1.25	A
$\overline{V_{C1}}$	300	V
$\overline{V_{C2}}$	150	V

The transfer function was validated by running simulations of the electrical circuit depicted in Figure 5. A graphical comparison was performed, concluding that the proposed model represents an accurate approach of the Buck converter behavior.

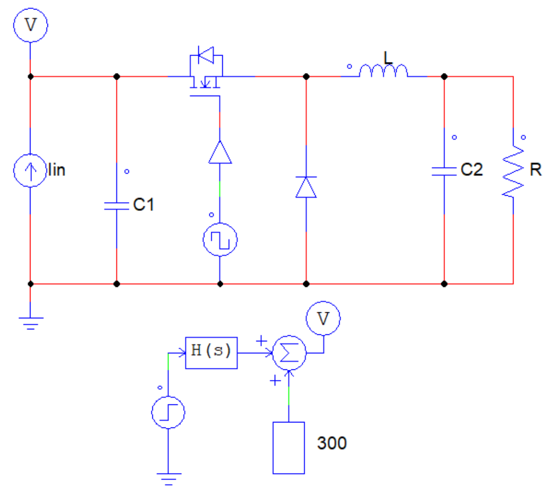

Fig. 5. Buck model simulation.

Figure 6 shows the capacitor voltage (v_{C1}) and transfer function responses of the electrical model shown in Figure 5. The system was disturbed 1% through duty cycle. Note that both waveforms exhibit a similar behavior which validates the accuracy of the proposed model.

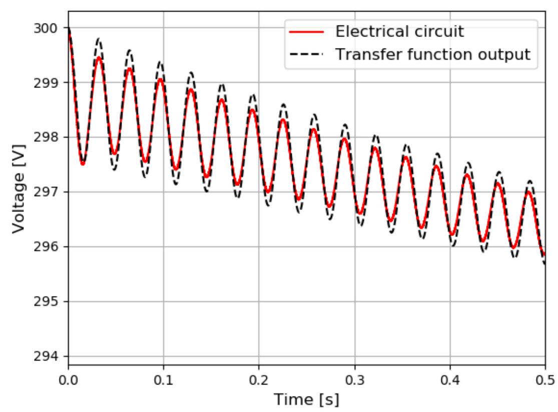

Fig. 6. Electrical model and transfer function responses.

Figure 7 shows the Buck converter bode diagram for comparing frequency responses. The discontinuous line is the proposed mathematical model while continuous line corresponds to the circuital simulation. Note that both mathematical and circuital models are very similar. This means that the mathematical model fits well the circuital implementation.

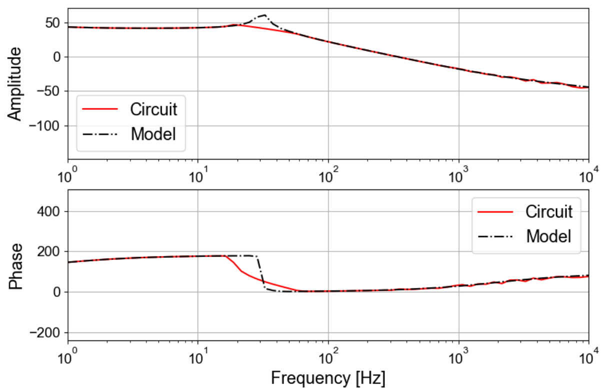

Fig. 7. Buck converter bode validation.

A PI controller was implemented using $68.9779[Hz]$ of cross frequency and $164.706°$ of phase margin. The gain of the PI controller was set to 3.73277 and the time constant to 7.57615 $[ms]$. Figure 8 shows the control response and disturbances. The upper plot shows current i_{in}; note that it starts stable in $0.625[A]$, then two disturbances were applied which correspond to steps of $800[mA]$ at $0.060[s]$ and $0.063[s]$, respectively. A PI controller was implemented for regulating C_1 voltage, setting $300[V]$ as the set point. The lower plot shows C_1 voltage; note that the voltage tends to follow the set point. Moreover, it can be observed the effects of disturbances; it can be seen that the controller successfully returns the voltage to its set point. Note that overshoot is $0.05[V]$ and settling time is less than $0.002[s]$.

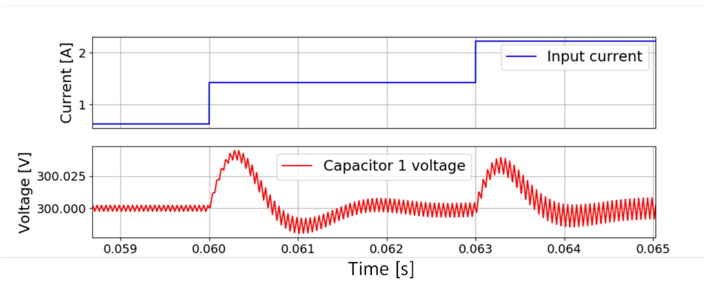

Fig. 8. PI control implementation.

B. DC Microgrid Applications

This section simulates the Buck converter operation in a DC-MG when it is used as a voltage regulator and stabilizer. The simulations consist on the interaction between PV generators, DC-MG loads and the Buck converter that is in charge of establishing the balance of the MG. The developed converter model is used to define the controller for Buck converters. All simulation applications are based on variable voltage input, using the deduced transfer function presented in this paper. The simulations represent one day of operation at scale.

Figure 9 represents the implemented DC-MG. In which three PV generators are incorporated (G1, G2 and G3). G4 represents a generator that injects a constant current, when there is no irradiance on the PV panels. The upper plot depicts the currents of each generator. Loads 1, 2 and 3 are constant impedances that were connected and disconnected from the MG DC bus for generating load perturbation in

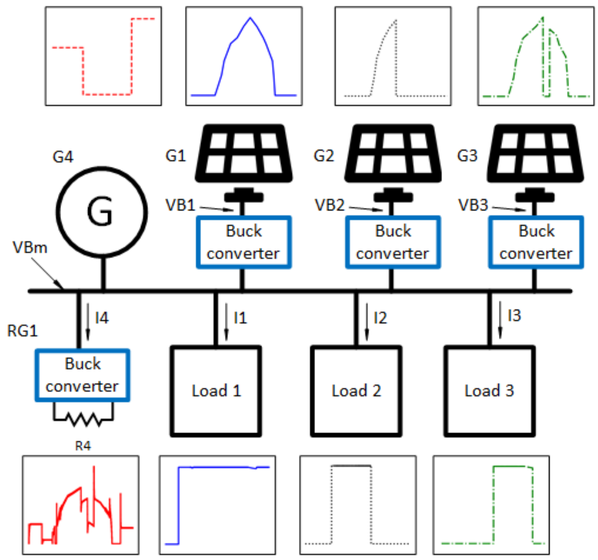

Fig. 9. DC-MG representation.

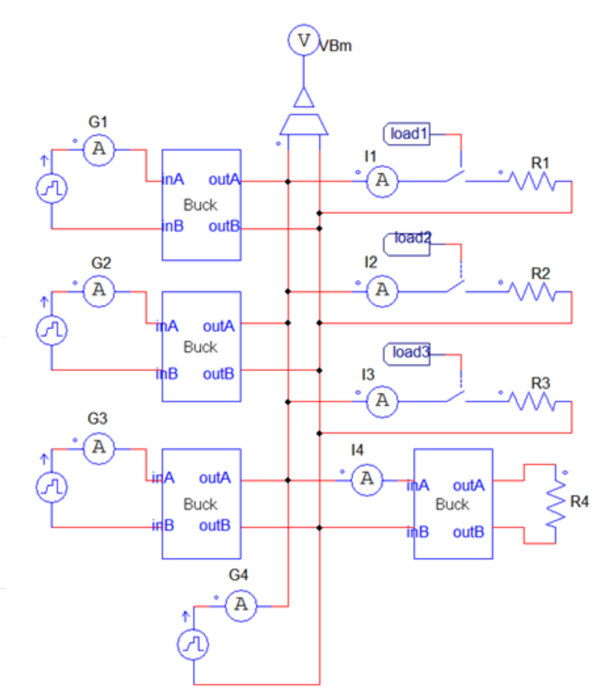

Fig. 10. DC-MG implementation.

the system, the lower plots illustrate their respective current profiles. The RG1 regulator is a Buck converter that represents a battery charger or voltage regulator, which is in charge of extracting power from the DC bus to keep the DC bus voltage constant and stable. Nodes VB1, VB2 and VB3 represent the voltage of the coupling between PV panels and the Buck converters, so they are used to maintain a constant voltage at the input of the converter and inject current to the main DC bus. Similarly, RG1 is in charge of regulating the main DC bus voltage (VBm), rejecting current disturbances at the input of the converter and extracting the excesses of energy to a resistor.

Figure 10 illustrates the DC-MG simulation blocks in PSIM software. Generators are simulated as current sources. Constant impedance loads are simulated by means of re-

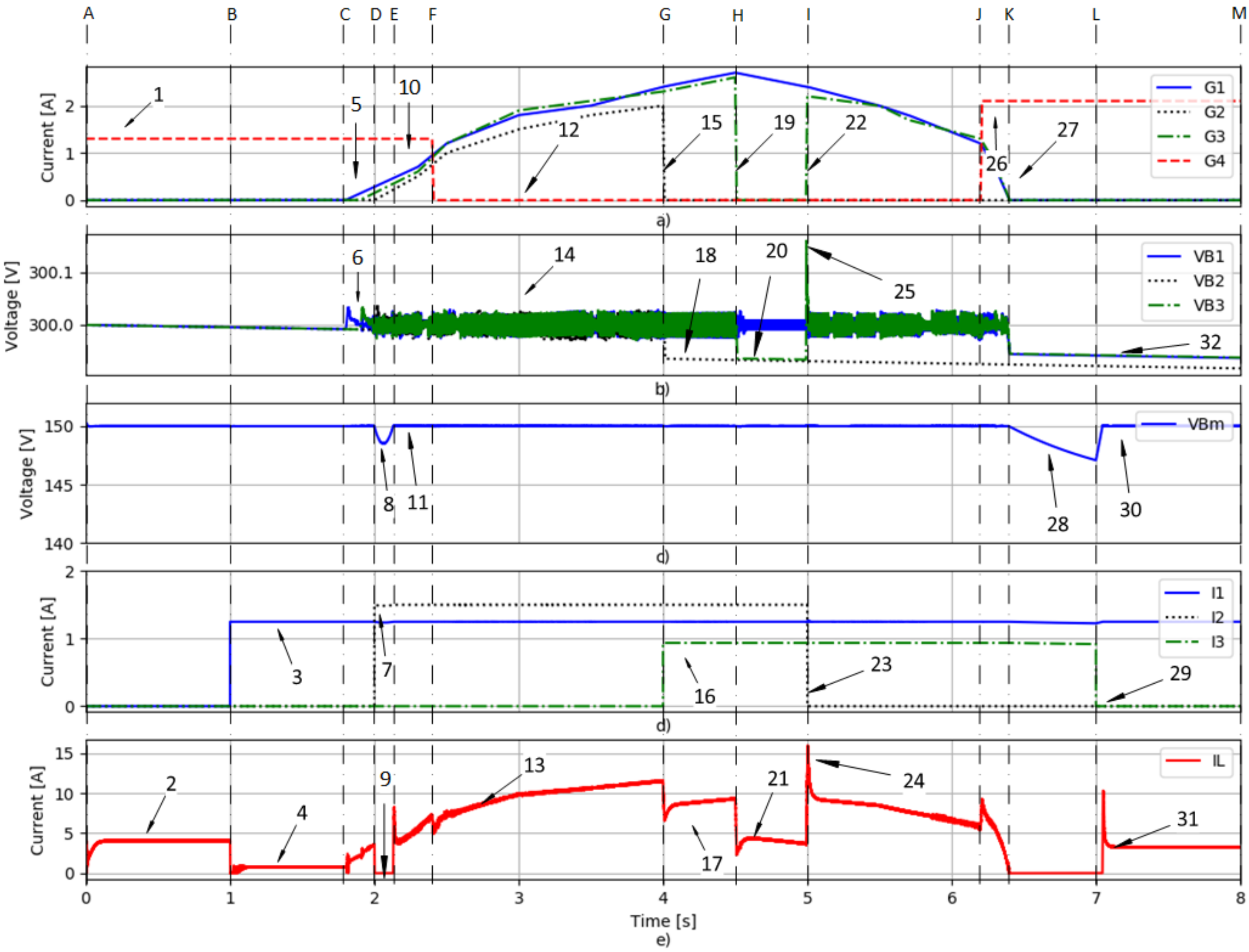

Fig. 11. DC-MG waveforms of MG-DC simulation.

sistors, controlling their connections to the main DC bus. The Buck blocks contain the Buck converters that are used as input voltage regulators. All converters use the same PI parameters for the controllers, only varying the desired voltage value. The output of PV generators was set at 300V while the regulator was set at 150V which is the desired voltage of the main DC bus.

Figure 11 describes the operation of the MG for one day, scaled to eight seconds. The operation of the MG was simulated considering changes in power generation and load, generating disturbances in the injection of distributed resources and demand variation in loads. Buck converters of the MG are in charge of keeping the voltage stable at nodes VB1, VB2, VB3 and VBm against disturbances. Figure 11.a. illustrates the currents of generators G1, G2, G3 and G4. Figure 11.b. depicts voltages at nodes VB1, VB2 and VB3. Figure 11.c. illustrates the voltage of the main bus: node VBm. Figure 11.d. depicts currents I1, I2 and I3 that flow through the loads. Figure 11.e. illustrates the current IL flowing through the inductor of the Buck converter RG1.

Figure 11 is described using periods of time; these are showed above in the upper plot using capital letters. Numbered arrows are used for facilitating the explanation. In period A-B G4 injects 1.3 amps to the main bus (see arrow 1); however, there are no loads connected, then, RG1 regulator consumes the injected power to keep the DC bus VBm constant (see arrow 2). Period B-C load 1 is connected to MG (see arrow 3), then regulator RG1 decreases the power that is extracted to keep the DC bus constant (see arrow 4). In period C-D generators G1, G2 and G3 begin to inject current (see arrow 5); so, voltages in nodes VB1, VB2 and VB3 change (see arrow 6). Under this condition, the Buck converters keep constant voltages, however there are ripples concerning their operation. In period D-E load 2 is connected (see arrow 7); however, the generators do not have enough capacity for supplying the loads, so that the DC voltage (VBm) of the main bus begins to drop (see arrow 8). Under this condition, the RG1 converter does not draw current contributing to the stability of the system (see arrow 9). In period E-F the production of the PV generators increases (see arrow 10), injecting enough power to feed the loads which recovers VBm (see arrow 11); also, the excess of energy is dissipated using RG1. In period F-G G4 is disconnected (see arrow 12) and the system is fed by generators G1, G2 and G3. The generation of G1, G2 and G3 keep increasing; so, RG1 responds stabilizing VBm (see arrow 13). Moreover, note that the voltages of nodes VB1, VB2 and VB3 remain constants at 300V (see arrow 14), despite being disturbed by the current injection of the generators. In period G-H two disturbances are simultaneously applied emulating an extreme condition:

1) a fault that corresponds to an open circuit in the PV panels of G2 (see arrow 15), and 2) the connection of load 3 (see arrow 16). Under this condition, RG1 operates for guarantying balance of power (see arrow 17). Despite these disturbances, all voltages remain within acceptable operating ranges except for VB2 that is in fault (open circuit voltage) (see arrow 18), no ripple is observed since the corresponding Buck converter does not extract power from this node. In period H-I generator G3 suffers lack of irradiance (see arrow 19), then the Buck converter of node VB3 stops extracting power from the node (see arrow 20) while RG1 slightly decreases the current demanded from the bus VBm to keep the voltage constant (see arrow 21). In period I-J the system suffers two disturbances: 1) the reconnection of G3 (see arrow 22), and 2) the disconnection of load 2 (see arrow 23). This produces an excess of generation that is compensated by RG1. Please see arrow 25 to observe the increasing of voltage in VB3 and arrow 26 to observe the rapid reaction of RG1. Period J-K at the end of the day, G1, G2 and G3 begin to reduce their generation; while G4 starts operation again (see arrow 26) for satisfying the demand, G4 injects 2.1 amps. In period K-L the injection of the generators G1 and G3 ceases, but the loads must continue to be supplied (see arrow 27); then, the bus voltage begins to decrease (see arrow 28), since the generation of G4 is not enough to supply loads 1 and 3. In Period L-M load 3 is disconnected (see arrow 29), then the DC bus voltage recovers to 300V (see arrow 30). Note the rapid change of RG1 converter (arrow 31) which indicates the appropriate performance of the system under perturbations. The converters of nodes VB1, VB2 and VB3 cease operation (see arrow32), since there is not enough power to inject into the main DC bus because there is not irradiation applied to the PV panels.

The transitory behavior of DC voltages is shown in Figure 12, period I-J was zoomed, which corresponds to one of the most demanding transients under analysis. Note that Arrow 23 in Figure 11 indicates that load 2 is disconnected while arrow 22 indicates that generator G3 is also disconnected at the same time. Figure 12 shows VB1, VB2, VB3 voltages at 7.3 milliseconds. VB1 and VB2 voltage behave moderately well, VB1 presents small changes during the transitory while VB3 did not changed; however, VB3 voltage increases in a greater proportion since generator G3 started to inject power to the DC bus. However, the Buck controller successfully kept values close to the set point. Voltage overshoot was less than 0.053% and settling time was 0.02 seconds.

To summarize, the applications of the Buck converter that have been simulated are: MPPT, voltage regulator and voltage stability. All applications have voltage disturbances at the input of the Buck converter, as it is reflected in the transfer function reported in this paper. In addition, based on the proposed model, the controllers of the DC-MG applications were tuned. The simulation scenario illustrates several disturbances of the Buck converters and their performance in a DC-MG.

V. Conclusions

Buck converters have a wide variety of applications related to voltage control within microgrid systems: regulation, stability and coupling for different voltage levels. Also, Buck converters are used for compensating DC voltage oscillations

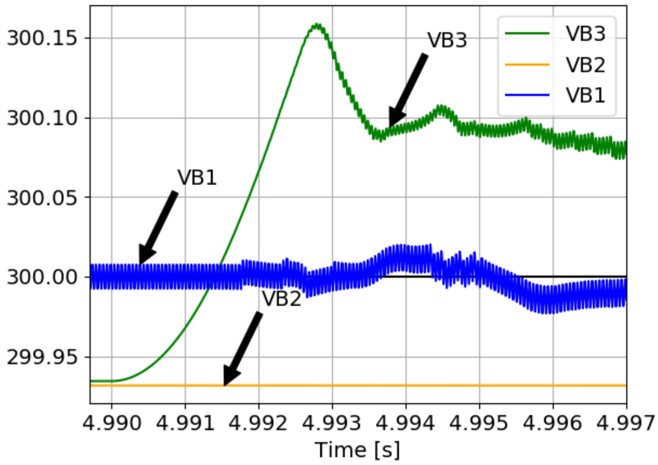

Fig. 12. Transient behavior of DC voltages

and for MPPT systems. Their use depends, in most cases, on the control strategy that is implemented. It is highlighted that all the reviewed applications face with variable voltage at their inputs, however most of papers consulted consider a constant voltage source at the input, losing the dynamic behavior of the converter.

The model presented in this paper considered a capacitor at the input and a variable current source for representing a more realistic dynamic behavior of the Buck converter under different operating conditions and applications in DC-MGs. The model proposed in this paper is closer to the implementation in real MG applications, since most of them present fluctuations in its input.

Simulations allowed the validation and comparison of the proposed mathematical model with the circuital model in terms of time- and frequency-responses. It was found that the mathematical and circuital models fit very well, concluding that the proposed Buck converter model adequately captures its dynamic behavior when a variable source is in its input. Moreover, The implemented PI controller allowed the validation of the proposed transfer function for control purposes, having a good performance in face to disturbances.

A DC-MG was simulated, using a Buck converter in MPPT, voltage regulator and voltage stability applications. The simulated applications were subjected to variable voltage at the Buck converters input; however, the implemented control regulates all voltages to the desired values. The proposed transfer function models the voltage at the input as a function of the duty cycle (with this model the parameters of the PI controller were found). Finally, it can be concluded that the performance of the DC-MG is stable and the operation of the Buck converters contributes to the stability of the system.

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