A Survey on Technologies to Implement Battery Emulators Based on DC/DC Power Converters.

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Abstract*– Currently, many researchers from industry and academic institutions are working on the study of electric vehicles, battery systems and renewable energy sources (solar, wind, geothermal, etc.). In order to carry out research on each of these technologies it is required large capital investment for equipment. Additionally, problems must be faced such as variability of environmental parameters, large space requirements, pollution (in some cases), etc. The use of software and hardware to emulate different types of actual batteries shows to be a low-cost and environmentally friendly option due to some of its features. The battery emulator system has the ability to replicate the behavior of any kind of actual battery using a virtual battery model (also known as battery electric model) and a controllable DC/DC power converter to be used in laboratory environments. Moreover, emulators are not only used for batteries, these can be used to emulate fuel cells, photovoltaic systems, wind generators, thermoelectric generator, etc. This survey aims to present the technologies to implement battery emulators based on DC/DC power converters. This survey is split up into five sections. In the first section, as an introduction, we present the advantages offered by the use of battery emulators to the scientific community and the environment. The second section presents a review about batteries (technologies, models, model parameters, etc.) and also it includes the virtual battery models, which are the main components of battery emulators based on DC/DC power converters. In the third section, we present the main DC/DC power converter types used in these systems and their operation modes. Additionally, in section 4 are presented some case studies where different topologies battery emulators based on DC/DC power converters with battery model are analyzed. These topologies are focused on their use in electric vehicles (EV).

Keywords—battery emulator; model; parameters; software; hardware; power converter

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Keywords—battery emulator; model; parameters; software; hardware; power converter.

I. INTRODUCTION

Currently, the environmental pollution is the major concern of governments around the world because of its harm consequences. The burning of fossil fuels and their derivatives are the main generators of combustion gases. Transportation and power generation are the main sectors that use these fuels [1]. The environmental pollution is the cause of increasing levels of greenhouse gases in the atmosphere [2]. These gases are formed by almost 50% of carbon dioxide [3]. In recent years, the planet has considerably raised its temperature, this has led to an abnormal weather patterns [4]. The emission of greenhouse gases, as well as the reduction of areas covered with forests are the main causes of the increase in level of CO2 in the atmosphere [5].

Every year, either the private or public sectors make efforts to reduce fuel consumption in transportation [6]. EU as an important goal for 2020 intend that 10% of energy consumption in the transportation proceed from renewable energy sources [7]. These efforts are reflected in an increased use of higher efficiency vehicles, and the use of motors that are powered by electricity rather than fuel [5]. This kind of vehicles are known as electric vehicles (EV) and almost all of manufacturers have released commercial EVs models [8]. The widespread use of EVs will contribute to the reduction of pollution in the environment and in this light, the manufacturers have started offering commercial options [9]. In fact, several countries have been using this type of vehicles, as in the case of Seattle City (USA), which has a fleet of 150 buses covering 14 routes with a distance of 115 miles [10]. In Ecuador, as a government initiative, they are betting on the use of 100% electric vehicles in public offices [11]. The main benefits of using electric vehicles include reducing the use of fossil fuels, the fuel imports and environmental pollution as well as, the increasing security in the energy sector [10]. The electrification of transportation sector is changing the way how we generate and use energy.

Generally, the energy required by EVs comes from a battery bank included in their fuselage. The EVs efficiency depends mainly on the performance of their battery bank [12]. This efficiency depends on parameters such as: autonomy, acceleration, energy recovery, etc. [13] [14] [15]. Over the years EVs are becoming more efficient and modern (due to mechanical parts are replaced by electric). Generally, the charging process for EVs is done through the power grid. Effects of this process on these electrical networks are subject of analysis in the scientific community [16] [17] [18]. The battery technology and its cost are the major impediment to the massive use of EVs in our society. Now, there are different types of battery technologies available for EVs such as lead acid, NiMH, Li-Ion etc. [19]. Technology of Li-Ion batteries presents advantages regarding other types, such as fast loading, high energy density, durability, high voltage, low weight, low self-discharge, longer life cycle and others [20], however its major disadvantage is its high cost. Li-Ion battery technology

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allow greater savings and efficiencies, but this technology still remain very costly to produce.

Currently, many researchers from industry and academic institutions are studying about electric vehicles, batteries and renewable energy sources (solar, wind, geothermal, etc.), however, the study of these technologies require big capital investments for equipment and trials [21]. There are also problems in variability of environmental parameters, large space requirements, etc. [22]. In the research of batteries, the analysis focuses on areas such as power density, internal resistance, operating temperature, discharge process and life cycle [23]. In order to carry out experiments with batteries for any equipment or EV, researchers draw upon either real batteries or simulation. The most accurate way to perform an experiment is by using real batteries, loads and generators [24]. Real battery can be rechargeable or non-rechargeable [25], being the second type discarded and replaced in each test during experiments. On the other hand, rechargeable batteries also produce problems since the real battery charge capacity varies after each test, due to: the state of charge (SOC), age and temperature [24]. Other problem presented is the assembly and disassembly of the battery in test vehicle. As a result, the use of real batteries for testing may increase the time to release and become expensive and polluting.

Using virtual battery model and controllable DC power converter to replicate the behavior of different battery types is an alternative option of low-cost and environmentally friendly for laboratory settle, even to demonstrate the effectiveness of complete test systems [26]. The battery emulators provide reproducible experimental settings by using programmable converters [27], which can be used for unlimited number of trials. They can also be used to emulate fuel cells, photovoltaic systems, thermoelectric generators [28] [29], etc. The emulators can replicate scenarios in stable or dynamic state by loading characteristic curves of voltage and current (VI) of different battery types [22]. Using weather data (wind, sun, etc.), any battery behavior can be replicated countless times under laboratory conditions without depending on the variability of these resources. Commonly, emulators are formed by a combination of hardware and software. Handling high voltages and currents are required for hardware because the energy used to emulate a source is taken from the power supply [30]. Thus, to conduct research, primarily for the use of renewable energy sources and battery systems are highly convenient the use of emulators.

This survey aims to present the technologies to implement battery emulators based on DC/DC power converters. This survey is split up into five sections. In the first section, as an introduction, we present the advantages offered by the use of battery emulators to the scientific community and the environment. The second section presents a review about batteries (technologies, models, model parameters, etc.) and also it includes the virtual battery models, which are the main components of battery emulators based on DC/DC power converters. In the third section, we present the main DC/DC power converter types used in these systems and their operation modes. Additionally, in section 4 are presented some case studies where different topologies battery emulators based on DC/DC power converters with battery model are analyzed. These topologies are focused on their use in electric vehicles (EV).

II. BATTERIES

The batteries allow to supply electric power to any device or flexible electronic systems [31], electric vehicles and power distribution network [32] [33]. Additionally, it is able to store energy from any generating source (conventional and renewable) [34]. In [35] a battery is defined as an electrochemical generator that transforms chemical energy into electricity through oxidation reactions - reduction. It is made up of cells, which are connected in series and parallel to obtain desired voltages and currents [36] [37]. Energy is stored at those cells [38]. The battery life depends on the rate of energy consumption [38] so it is important to investigate the behavior of battery at different discharge rates. Similarly, the accuracy of estimating the state of charge (SOC) in battery is one of the biggest challenges for researchers [39] [40], to maximize the battery use efficiency and prevent over discharge and overload [41] [42].

A. Basic theoretical concepts in the electrical behavior of batteries.

In the analysis of a battery is important to have clear the basic theoretical concepts for an understanding of its electrical behavior. These concepts are found in all the papers related to battery emulators. Some of these concepts can be summarized as follows:

- Internal resistance: In the virtual battery models, to be discussed later, the internal resistance is a parameter representing the voltage drop caused by current variation in battery [43].
- State of charge (SOC): Amount of energy that can be taken from the battery in relation to the maximum load that can be stored in the battery [44].
- Depth of discharge (DoD): It measures the fraction of permanent load used, since the average discharge current [45].
- Open circuit voltage: it is the battery voltage without load, when it is fully charged [43].
- Battery capacity: it is measured in amp-hours and represents the amount of energy stored [46].
- Rate of charge / discharge: Velocity of the charge process or delivers its power (discharge current) [46].
- Transient Response: Change of battery voltage caused by an alteration in its load current. The transient response can be characterized by RC networks (resistance - capacitance) [47].

- Lifecycle: Number of times the battery can be charged / discharged [48].

B. Battery types.

Nowadays, there are a variety of battery types available on market. The four most commonly models used include Nickel-Metal Hybrid Lithium-ion, Lead Acid and Lithium Polymer [49]. In Table I can be seen the basic technical parameters of these battery types [50].

TABLE I
TYPES OF BATTERIES.

Battery Type	**Lead acid**	**Ni-Cd**	**Ni-MH**	**Lithium-ion**
Energy density[a] (W/Kg)	30-50	45-80	60-120	110-160
Power density[b]	180	150	250-1000	1800
Nominal voltage	2V	1.25V	1.25V	3.6V
Overcharge tolerance	High	Moderate	Low	Very low
Self-discharge	Low	Moderate	High	Very low
Operating temperature	-20-60ºC	-40-60ºC	-20-60ºC	-20-60ºC
Cycle life[c]	200-300	1500	300-500	500-1000

a: Chargeable electric energy per weight of battery pack.
b: Proportion of dischargeable electric energy to charged energy.
c: The number of charging/discharging cycles in battery's entire life.

Although all batteries handle the same range of operating temperatures, the Li-Ion batteries are those with better benefits than the rest. Among the main advantages are: higher average nominal output voltage, high energy density and power, low energy loss by self-discharge, no memory effect and longer service life [50] [51] [52]. This battery is used in a variety of applications such as power tools, medical equipment, EVs, satellites, etc. Due to its high energy density and storage efficiency (around 90%), the Li-Ion batteries are ideal for use in EVs [12].

In Table II, different types of Li-ion batteries [46] are summarized. Currently, researchers have focused their studies in Lithium iron phosphate (LFP - $LiFePO_4$) as the main chemistry composition for batteries [51] [53] [54] [55]. A great advantage of these batteries is the operating temperature range (ranging from -20 to +60 °C) and its high power density.

TABLE II
TYPES OF LI-ION BATTERIES.

	Lithium Iron Phosphate	**Lithium Manganese Oxide**	**Lithium Titanate**	**Lithium Cobalt Oxide**	**Lithium Nickel Cobalt Aluminum**	**Lithium Nickel Manganese Cobalt**
Cathode chemistry descriptor	LFP	LMO	LTO	LCO	NCA	NMC
Specific energy (Wh/Kg)	80-130	105-120	70	120-150	80-220	140-180
Energy density (Wh/L)	220-250	250-265	130	250-450	210-600	325
Specific power (W/Kg)	1400-2400	1000	750	600	1500-1900	500-3000
Power density (W/L)	4500	2000	1400	1200-3000	4000-5000	6500
Volts (per cell) (V)	3.2-3.3	3.8	2.2-2.3	3.6-3.8	3.6	3.6-3.7
Cycle life Self-discharge (% per month)	1000-2000 <1%	>500 5%	>4000 2-10%	>700 1-5%	>1000 2-10%	1000-4000 1%
Cost (per kWh)	$400-$1200	$400-$900	$600-$2000	$250-$450	$600-$1000	$500-$900
Operating temperature range (°C)	-20 to +60	-20 to +60	-40 to +55	-20 to +60	-20 to +60	-20 to +55

C. Battery models.

The battery model is the key part of an emulator. The model can be used to vary the parameters of actual batteries (next section) and simulate different scenarios of charge and discharge. In these scenarios, we can obtain VI (Voltage-current) characteristic curves corresponding to actual batteries [56]. These results are transferred via software to the emulator, which behaves similar to the actual battery in study. Therefore emulators can behave as an actual battery, additionally the researchers can use them in another test sceneries (i.e. with different charge/discharge rates) [57].

1) Model types: There are different kind of battery models with varying degrees of complexity. According to [47], there are 3 groups of battery models: mathematicians, electrochemical and electrical. Mathematical models are very complex, which can use equations, mathematical methods and stochastic approaches to represent the battery runtime behavior [58], its efficiency and capacity [59] [60]. In another hand, electrochemical models optimize physical aspects of battery design. These models need long time for analysis because they implement complex numerical algorithms and require specific information from batteries (which is difficult to obtain [61]). In [49] it is defined another classification of models: Electrochemical, analytical, stochastic and electric. Analytical and stochastic models are handled on the basis of equations and probability. Electric models use a combination of resistors, capacitors and voltage/current sources to reproduce the behavior of batteries [62]. These models are easy to use for power sector researchers because they can be designed in simulators (Matlab, Plecs, etc.). Battery electric models can be classified into 3 categories: Thevenin based, impedance based and runtime based [63]. In this survey the battery electric models are called virtual battery models.

According to [64], electric models are also classified as ideal model, linear model and Thevenin model (Fig. 1).

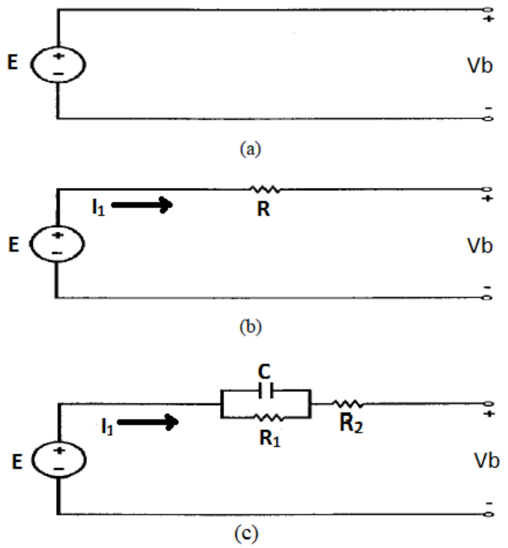

Fig. 1 Electrical models of batteries, a) Ideal, b) Linear and c) Thevenin, [64].

Fig. 1a) shows the ideal battery model, which consists just of a voltage source. In this model all battery internal parameters are ignored. Fig. 1b) represents a linear model. This model takes into account the internal resistance. The battery voltage (E) and the internal resistance (R) can be represented by expressions (1) and (2).

$$E = E_o - k \cdot f \tag{1}$$

$$R = R_o - K_R \cdot f \tag{2}$$

Where E_o is the battery voltage without load when it is fully loaded; f is the state of discharge; R_o is the internal resistance when the battery is fully charged; k, K_R are constants used for experiments. V_b is a voltage close to E measured when the circuit current and the capacitor voltage are zero [53].

Fig. 1c) shows a Thevenin electrical model that uses a resistor in series with a parallel RC network. R_1 represents the contact resistance and C is the behavior of electrodes and electrolyte [65]. This model is used to predict the battery response to load transient events in a particular state of charge (SOC), assuming the open circuit voltage is constant [12] [64]. This model is more accurate compared to the ideal and linear models because it takes into account internal battery parameters. In many publications, the Li-ion batteries are modeled by Thevenin equivalent [66]. As more RC networks are added in series, the complexity increases but greater accuracy for representing battery is achieved [67]. Fig. 2 shows a Thevenin electrical model for a Li-ion battery with 2 network RC [68]. This model also represents the transient response of the battery electrodes.

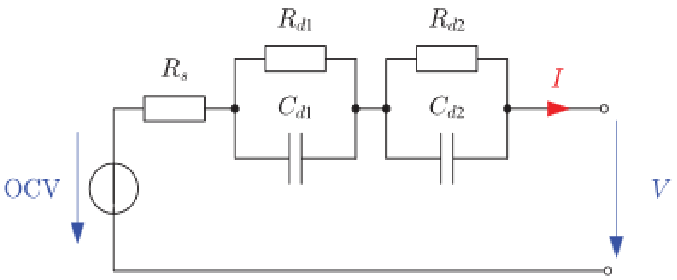

Fig. 2 Thevenin model for Li-Ion battery, [68].

2) Key assumptions in battery models: According to [43], designing battery models requires certain assumptions for analysis and research. Some of them are described as follow:

- Internal resistance is considered constant during the cycles of charge and discharge.
- The load is constant impedance type.
- Internal resistance does not vary with current amplitude.
- Model parameters are obtained from the discharge characteristics and these are assumed equal to the load.
- Battery capacity does not change with the current amplitude.
- Temperature does not affect the model behavior.
- The self-discharge of the battery is not represented.
- Battery has no memory effect.
- Do not take into account the effects of gasification and overload [24].
- Open circuit voltage is constant [12] [64].

D. *Battery model parameters*

The battery model parameters represent the behavior of an actual battery during either charging or discharging processes. In the analysis of a particular battery type is very important to know these parameters. Many times these parameters are deducted from the discharge curve provided by the manufacturer. After getting these parameters, we can build the virtual battery model and replicate the battery behavior inside a simulation platform. A good representation of a battery can implement a Thevenin model together with a Shepherd model. The Shepherd model describes the behavior of the terminal voltage during a change in load current. This type of VI model is discussed in [43] [69] [70] [71]. The combination of models is suitable for a better representation of Li-Ion batteries.

The Shepherd-Thevenin model is shown in Fig. 3, which is governed by the expressions 3, 4 and 5:

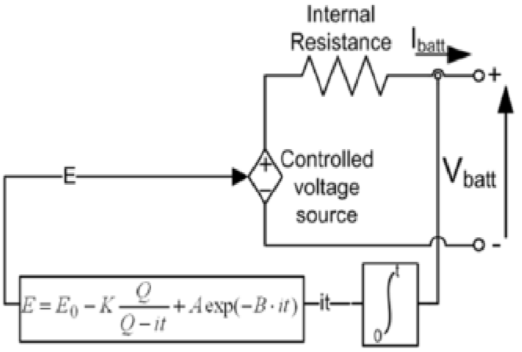

Fig. 3 Shepherd Thevenin battery model, [43].

$$SOC = 100 \cdot \left[1 - \frac{\left(\int i\right)}{Q}\right] \tag{3}$$

$$V_{BAT} = E - R_{int} \cdot I_{bat} \tag{4}$$

$$E = E_o - K \cdot \left(\frac{Q}{\left(Q - \int i\right)}\right) + A \cdot e^{\left(-B \cdot \int i\right)} \tag{5}$$

Where:

- E_o represents the open circuit voltage (OCV) of the battery to full capacity.
- K is the coefficient of polarization resistance (Ω).
- Q is the battery capacity (Ah).
- I is the battery current (A).
- R_{int} is the internal resistance (Ω).
- A is the amplitude of the exponential region (V).
- B is the inverse constant of time of exponential area (Ah^{-1}).

The nonlinear term (Q / (Q - ∫i)) represents the variation of the voltage with the current amplitude and the state of battery charge [69]. The expression 5 has been modified to eliminate the phenomenon of algebraic loop and instability [43]. Therefore, this battery model can replicate the actual battery behavior.

As shown in the above expressions, this model does not take into account the temperature influence on battery behavior and it does not characterize the phenomenon of self-discharge [43]. The temperature influence strongly affects on the battery chemistry. The internal resistance can decrease its value when a battery works at high temperatures [72]. Additionally, continuous exposure to high temperatures can lead to reduce service life and increase the rate of self-discharge [72].

Fig. 4 shows a typical discharge curve of an actual battery. In this curve are highlighted the zones where we can get the parameters *A*, *B*, *K* and E_o, according to the expressions in [43] [71].

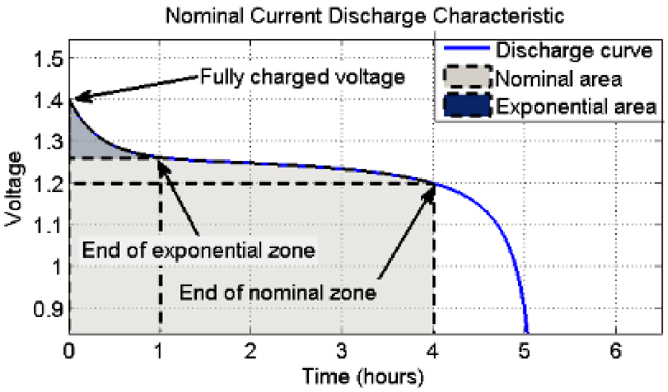

Fig. 4 Typical discharge curve, [43].

A, *B*, *K* and E_o can be calculated for other battery types, as shown in Table III.

TABLE III
BATTERY PARAMETERS, [43].

Type Parameters	Lead-Acid 12V 1.2Ah	Nickel Cadmium 1.2V 1.3Ah	Lithium -Ion 3.6V 1Ah	Nickel Metal-Hydrid 1.2V 6.5Ah
E_o (V)	12.6463	1.2505	3.7348	1.2848
R (Ω)	0.25	0.023	0.09	0.0046
K (V)	0.33	0.00852	0.00876	0.01875
A (V)	0.66	0.144	0.468	0.144
B $(Ah)^{-1}$	2884.61	5.7692	3.5294	2.3077

III. DC/DC POWER CONVERTERS

Power converters have become highly popular in recent years because of their developed efficiency, flexibility and the capability of connecting various sources of energy at time [73]. The design, modeling and control of converters are fields of extensive research by the scientific community. These devices are able to transfer energy between its ports bi-directionally, enduring positive and negative currents [74]. In addition, they are used as interface between power sources and energy storage systems [75]. One of its main features is the constant output voltage despite variations in their input or load [76]. The DC/DC power converters are connected to the load via a DC-link, as shown in Fig. 5. These characteristics make them suitable for use in EVs.

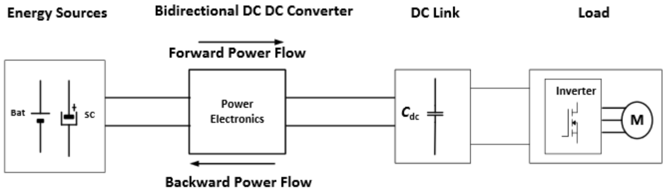

Fig. 5 Diagram of Bidirectional DC/DC converter, [75].

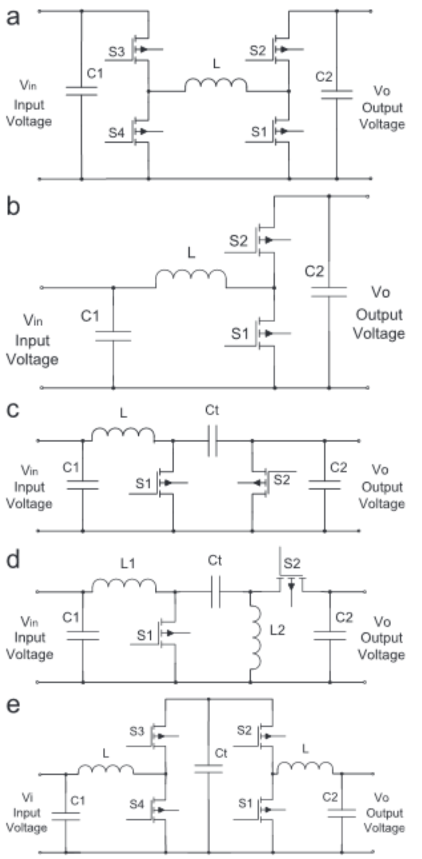

Fig. 6 Bidirectional converters not-isolated a) cascade buck-boost, b) half-bridge, c) cúk, d) sepic y e) split-pi., [79]

Bidirectional converters can be classified into two groups: isolated (galvanic isolation) and not isolated [77]. Distributed generation and storage systems should use isolated converters, when these are connected to the network [78]. Advantage of using galvanic isolation is that it increases the flexibility of the system (meeting required voltage) but also it increase the cost of system. Furthermore, it could be a bit more complicated to design and implement [77]. Not isolated converters are commonly used in battery emulators. Among the most important features we can mention compact size, higher efficiency and use of low voltages. The most used DC/DC power converters in EVs (within the category not isolated) are: buck-boost, half-bridge, cúk, SEPIC and split-pi (Fig. 6) [79]. Despite of the advantages of not insolated converter, some problems can appear, such as pulsating output currents and voltage ripples [76]. In another hand, multiphase converters are formed from buck-boost converter. This survey is focused on buck-boost and multiphase converters.

A. *Bidirectional DC/DC power converter: Buck-boost type*

In [80] [81] [82] [83] the operation of buck-boost power converter is shown. This is a bidirectional converter which can have an output voltage either great or less than its input voltage. In Fig. 7, when the converter works in boost mode, the voltage V_2 (output) is equal to the sum of $V_1 + V_L$ (increasing). In this case V_1 is the power source. But when this works in the buck mode (reducing), the voltage V_1 (output) is equal to V_{C1} and V_L (reducer). In this case V_2 is the power source.

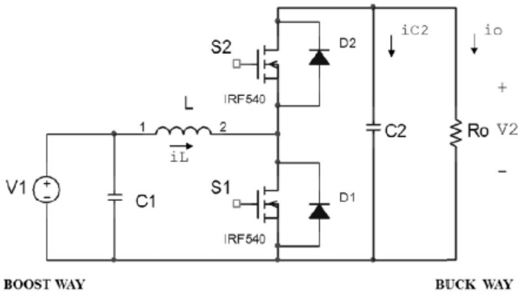

Fig. 7 Buck-boost converter, [74]

C_2 (Fig. 7) is the DC-link capacitor when it works in mode of boots. This capacitor can reduce the current ripple to maintain a constant output voltage, and suppress voltage rises caused by switching operations thus providing reactive power [84] [85]. The ideal sizing of this element is crucial because it can become bulky, heavy and expensive [86]. Similarly, the capacitor C_1 has the same function and characteristics when the converter is working in buck mode. In another hand, inductors configurations allow store energy and deliver power to the load during switching process [75].

B. *Bidirectional DC/DC power converter: Multiphase type*

Multiphase converters are widely used in many applications such as voltage regulator modules, EVs, etc., due to their high efficiency and ability to reduce ripples [87]. In Fig. 8, a multiphase bidirectional voltage converter can be observed (8 phases or 8 legs).

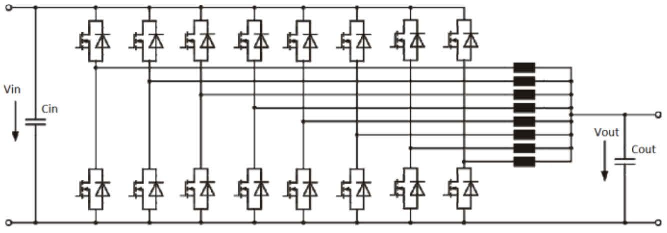

Fig. 8 Bidirectional DC/DC converter: multiphase type, [24].

In the case of buck-boost converter is necessary to increase the switching frequency and to keep low inductance values in order to achieve reduced levels of current ripple, even in small voltage variations between the input and output [24]. Higher switches frequencies can increase energy losses and noise. Thus, to increase the power density, reducing current ripple without increasing the switching frequency, multiphase bidirectional converter are used [88] [89] [90]. These converters are composed of a part that increases the voltage (boost mode) and another that reduces it (buck) [91].

Fig. 9, shows a multiphase converter [92]. As it can be seen in the figure it has three legs. To implement it, firstly the converter operating mode must be selected (boost or buck). In this configuration, the commutation time for every leg is done sequentially and for this case (Fig. 9) it should be one third of the switching period. The control of switching devices can be performed by PI (Proportional-Integral) controllers [91] or another more advanced control techniques.

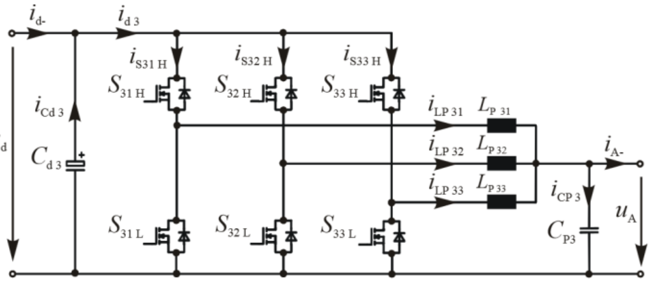

Fig. 9 Multiphase converter, topology 3 legs, [92].

Controlling a larger number of phases can involve the use of specific control schemes. These control techniques should allow synchronization between phases in order to reduce the output voltage ripple and to distribute symmetrically the current between all phases [93] [94].

IV. SOME CASE STUDIES

In this section, we analyze some of topologies of battery emulators that exist in the literature. Initially we expand a little more the concept of battery emulator. Topologies include virtual battery models and power converters that were discussed in the previous sections.

According to [95] the battery emulators can perform automatic and deterministic testing of EVs propulsion systems within a test bench. These devices can emulate different actual battery types without the need of expensive battery systems. In addition, one of the main advantages is that the state of charge (SOC) and state of health (SoH) can be changed at any time. According to [25] [96], a battery emulator is formed by a controllable power source (controlled by a microcontroller) and a server computer. The emulator is capable to collect power profiles through real-time measurements, and it can save data in a file in the emulator profile mode [27].

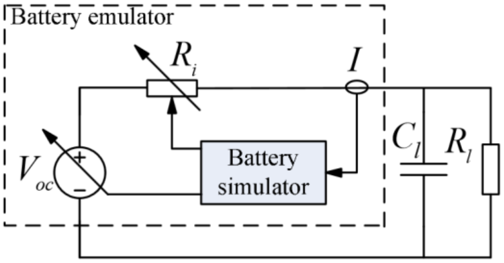

Fig. 10. Circuit model of a battery emulator with load [27].

Fig. 10 shows a battery emulator model circuit [27]. This circuit consists of: a battery linear model, battery simulator, DC-link capacitor and an electrical load. In this study the current and temperature in the battery were measured. Current and temperature measurements determined the set-point of V_{OC} and R_i using DSP (digital signal processor).

In [63], a battery emulator system with a power electronics interface is implemented (Fig. 11). The converter operates with 40V input voltage and is tuned to 20V output voltage with 6A current load.

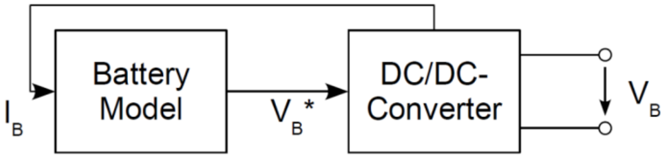

Fig. 11 A circuit model of a battery emulator, [63].

This system consists of an impedance-based battery model. The battery model has as input the emulator current measured (I_B). The battery model, based on I_B calculates the battery voltage V_B, which in turn it is the set point for DC/DC power converter. When the system is in operation, it behaves as an electrochemical storage device which could be integrated into a test bench of electric vehicles or electric traction systems. The power converter is multiphase type (three legs), which can work with voltages and currents up to 400V and 400A, respectively. The multiphase power converter can hold a symmetrical distribution of current load avoiding overloading any leg [93]. In this work, every phase has independent PI control loops. These are part of a decentralized control system. As result, the current is distributed in a symmetrical manner in each leg and the system has a good dynamic behavior according to settings used.

In [24], an emulator with 8 legs multiphase type DC / DC converter is studied. The impedance-based battery model represents a lead-acid battery. This model takes into account the temperature. The control of 8 phases is performed by means of PWM modulation. The modulation frequency is 125 KHz which is generated by an FPGA (Field Programmable Gate Array) board. The controller is based on PID control. This emulator is used for EV testing. The cranking motor was simulated with various types of batteries and with different temperatures.

In Fig. 12, an emulator for Li-Ion battery is shown [12] with a Thevenin-Shepherd battery model. In the power interface a bidirectional buck-boost type DC/DC converter is employed, which is controlled by a PWM generator. In the converter part, a resistance was placed to emulate the battery charging process, as seen in Fig. 13. In charging process, a diode protects the power supply system. To improve the quality of current and voltage ripple, the capacitors C_A and C_D were harnessed. An electric vehicle model run as load (similar to [97]). For the battery emulator test, a speed profile was defined. The simulation was performed using Matlab / Simulink. One of the most important outcomes of this experience was the cost reduction for EV trials.

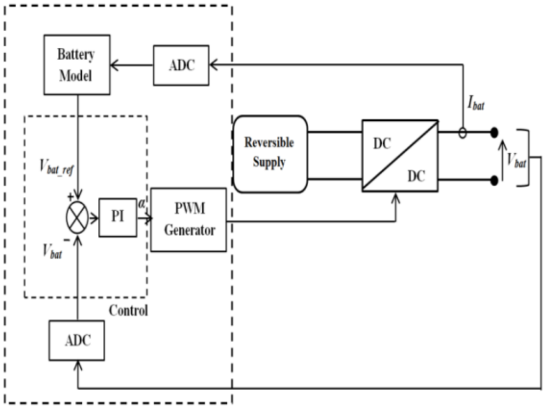

Fig. 12 Battery emulator design, [12].

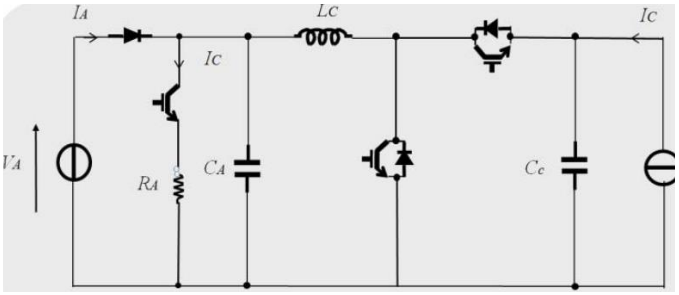

Fig. 13 Buck-boost converter with resistance of charge process, [12].

V. CONCLUSIONS

Battery emulators are technological solutions that allow to study of actual battery behavior in EVs and any other types of electric traction systems. Furthermore, it avoids the risks of working with actual batteries.

The use of battery emulators to replicate either the charge or discharge of any actual battery type in a laboratory setting can be a low-cost alternative and environmentally friendly.

Virtual battery model is the main component of battery emulator based on power electronics. The more precise is the virtual battery model, better results are obtained in the emulation process. It is important to note that the general behavior of the actual battery in analysis can be emulated to countless scenarios with different operating conditions.

The more electrochemical variables are taken into account in models, better dynamic performance characteristics of the battery are captured; characteristics such as non-linear open circuit voltage, charge/discharge current, degradation temperature, number of cycles, storage, etc. The addition of RC networks increase the complexity of virtual models but it increase its accuracy.

The battery model parameters represent the behavior of an actual battery during either charging or discharging processes. With these parameters can be built the virtual battery model for replicating the battery behavior inside a simulation platform. Many times these parameters are deducted from the information provided by the manufacturer discharge curve.

The use of multiphase type DC / DC converters in battery emulators involves specific control schemes. These schemes allow the symmetrical distribution of current load between phases in order to reduce the output current ripple.

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