Control of a Bidirectional Converter to Interface Electrochemical double layer capacitors with Renewable Energy Sources

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Abstract- This paper highlights the controller of a bidirectional converter to interface an ultra-capacitor as storage device to renewable energy systems. Ultra-capacitors are typically used in renewable energy systems to improve the system's reliability and energy conversion efficiency. The controller of the converter system has been designed and simulated based on the integration of both Current Mode Control and Linear Quadratic Regulator methods. The controller performance is tested under different modes of operating conditions in bidirectional converter using MATLAB/Simulink simulation package. The simulation results show that a good DC bus voltage regulation is achieved in the tested conditions. In addition to that, the controller ensures smooth transition between the buck and boost modes of the bidirectional converter operation.

Keywords—bidirectional converter; ultra-capacitor; peak current mode control; linear quadratic regulator.

I.INTRODUCTION

The continual rise in electricity demand, combined with serious environmental problems created by traditional energy systems have been driving societies towards the use of renewable energy sources. Besides being environmentally friendly, renewable energy sources are continually renewed by the cycle of nature and are considered to be practically inexhaustible [1-4]. As a result, the future of these sources as a typical alternative for the traditional sources looks very bright

However, the natural variability of some renewable sources due to their strong dependence on the weather conditions result to a high fluctuated output power, which impacts on the local loads that are sensitive to pulsating power [5-6]. Moreover, the renewable sources generated power does not always match the demanded load power. Hence, there is a need to support these sources by use of energy storage device, where it either injects its stored energy or absorbs the excess energy during the transients in the renewable source; resulting in a smooth output power to the load [7-9].

Amongst storage devices, ultra-capacitor is preferred due to its long life-time, good electrical behavior and to its relatively low initial cost in comparison with modern batteries [10]. In addition, it is positively characterized by its high power density, low losses while charging and discharging, and it's very low equivalent series resistor (ESR) which allows it to deliver and absorb very high currents and to be charged very quickly [11-12]. Furthermore, ultra-capacitor can provide large transient power instantly [13]. Consequently, the use of ultra-capacitor as a storage element increases the effectiveness of the renewable energy source utilization and also improves the capability of dealing with steady-state and transient dynamics.

Connecting the renewable source and the ultra-capacitor requires a power converter and a DC link. The converter must have the capability to allow both directions of power flow between the ultra-capacitor and the DC link, and also the ability to increase or decrease the voltage level in each power flow direction; since the voltage level of the ultra-capacitor and the DC link are different. Therefore, a bidirectional DC-DC converter is used. In bidirectional DC-DC converters, there are two modes of operation. The first mode is the boost mode, where the ultra-capacitor is discharged to a higher voltage level at the DC link; in the second mode, namely the buck mode; here the excess power from the renewable source charges ultra-capacitor.

Various control methods have been proposed in the literature to interface renewable energy sources with a storage device using a bidirectional converter. The authors in reference [13] applied the dynamic evolution control method to interface a fuel cell and the ultra-capacitor. In literature [5], the PI controller was designed for the integration of wind energy conversion system and ultra-capacitor. The current programmed mode (CPM) duty ratio control and linear PI compensator was reported in [14] for controlling a bidirectional converter interfacing wind energy conversion and battery storage system. A combination of both fuzzy and sliding-mode control strategies to interface the wind energy conversion system and the storage device has been proposed in [15]. Different from that available in the literature, the proposed controller in this paper introduces feedback paths that are calculated optimally to minimize an associated cost function, which is expected to improve the dynamic performance of the system.

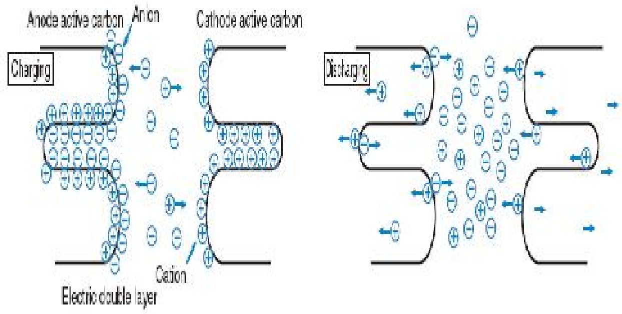
Due to its simplicity, high bandwidth, and low implementation cost, current mode control (CMC) approach is popular in controlling the power electronic converters [16]. Among the different types available for CMC, Peak current mode control (PCMC) is the most common one in which the peak value of the inductor current is sensed and compared with the current reference for the generation of the PWM signal [17]. Another control method that is most cited for controlling the PWM converters is linear quadratic regulator (LQR) control [18]. Since the controller feedback gain-vector is determined optimally in LQR, the designers can guarantee that the converter has good closed-loop behavior, and is relatively insensitive to system parameter variations or external disturbances. In addition, LQR controllers can be applied with independence of the order of the system, and their design can be straightforwardly calculated from the matrices of the system’s small-signal model [19]. Combining the two methods (CMC and LQR) has been done in many studies [3, 19]. The combination indicates that a good response and disturbance rejection were achieved in the tested conditions.

II.ULTRACAPACITOR

Electric double-layer capacitors, also known as supercapacitors, electrochemical double layer capacitors (EDLCs) or ultra-capacitors are electrochemical capacitors that have an unusually high energy density when compared to common capacitors, typically several orders of magnitude greater than a high-capacity electrolytic capacitor.

The electric double-layer capacitor effect was first noticed in 1957 by General Electric engineers experimenting with devices using porous carbon electrode. It was believed that the energy was stored in the carbon pores and it exhibited "exceptionally high capacitance", although the mechanism was unknown at that time.

General Electric did not immediately follow up on this work, and the modern version of the devices was eventually developed by researchers at Standard Oil of Ohio in 1966, after they accidentally re-discovered the effect while working on experimental fuel cell designs. Their cell design used two layers of activated charcoal separated by a thin porous insulator, and this basic mechanical design remains the basis of most electric double-layer capacitors to this day. With advances made on both materials and manufacturing process, today Tecate Group PowerBurst® product show a superior advantage amongst all other ultracapacitors in the market.



a) Charging Model b) Discharging Model

Figure 2: Ultracapacitor Charge Separation

Each application needs to be evaluated based on its requirements. Below are some of the advantages and disadvantages when considering the use of EDLCs:

2.1 Advantages:

- High energy storage. Compared to conventional capacitor technologies, EDLCs possesses orders of magnitude higher energy density. This is a result of using a porous activated carbon electrode to achieve a high surface area.
- Low Equivalent Series Resistance (ESR). Compared to batteries, EDLCs have a low internal resistance, hence providing high power density capability.
- Low Temperature performance. Tecate Group PowerBurst® products, with their use of patented technology, are capable of delivering energy down to -40°C with minimal effect on efficiency.
- Fast charge/discharge. Since EDLCs achieve charging and discharging through the absorption and release of ions and coupled with its low ESR, high current charging and discharging is achievable without any damage to the parts.

The specifics of ultracapacitor construction are dependent on the manufacturer, and the intended application. The materials may also differ slightly between manufacturers or due to specific application requirements. The commonality among all ultracapacitors is that they consist of a positive electrode, a negative electrode, a separator between these two electrodes, and an electrolyte filling the porosities of the two electrodes and separators.

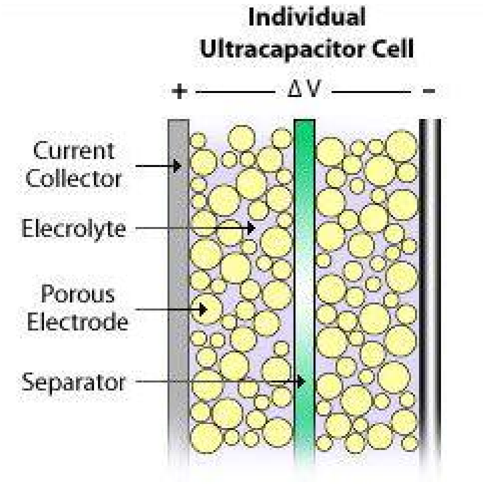


Figure: Internal Cell Construction

III.MODELING OF THE ULTRA CAPACITOR AND BIDIRECTIONAL DC-DC CONVERTER

The equivalent circuit of ultra-capacitor model is applied to simulate the ultra-capacitor. As represented in Fig.3, the model consists of a capacitance Cus ,an equivalent parallel resistance Rp , and an equivalent series resistance Rs .

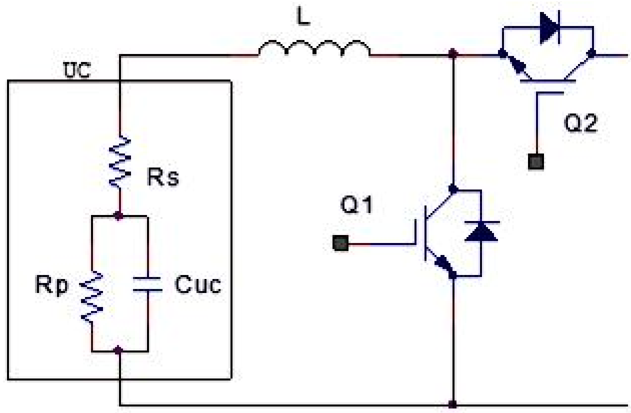


Fig. 3 The electrical circuit of ultra-capacitor-bidirectional DC-DC converter Topology

To realize the reversible direction of power flow in bidirectional DC-DC converters, the switch should ideally carry the current in both directions. Therefore, it is usually implemented with a unidirectional semiconductor power switch connected in parallel to a diode [22]. In the first direction, the converter transfers the energy from the ultra-capacitor to the DC bus when starting up the renewable generation system, and during the transient load conditions. When there is an excess energy at the DC bus, the converter charges the ultra-capacitor in its low-side. The buck charging and boost discharging current modes share the same power plant transfer function, therefore, sharing a unified controller is tolerable. The unified controller concept means one controller can be used for both switches, whereby they are controlled in a complementary fashion [13, 24]. In this work, the boost modeof operation is selected for the purpose of designing the controller. Hence, the small-signal model of the boost converter is derived. The renewable energy source is modelled as a current source connected to the DC bus.

To derive the current-mode controlled model of the boost converter, the new continuous time (NCT) model of the PCMC in [27-28] is used. It is generally accepted due to its simplicity and accuracy [27, 29]. The block diagram of NCT model is represented in Fig. 3.2, where Vin, Vo,Il and dare the perturbations of the input voltage, output voltage, inductor current, and the duly-cycle of the power stage, respectively. The variable v c is the perturbation of the reference voltage of the current loop. In this study, vc is the LQR controller output. Ri is the effective linear gain from the sensed current to the comparator input. kf and kr are the feedforward and feedback gains, and they are different for the different for each different type of converters. Hi is the sampling gain which is used to model the sampling action in the current loop, and for controller design purpose it is taken as a unity.

The modulator gain F_m is the ac gain from the error current signal to the duty-cycle. F_m , k_f and k_r can be expressed as:

$$F_m = \frac{1}{(M_1+M_c)T_s}$$

$$k_f = \frac{-T_s R_i}{2L}$$

$$k_r = \frac{-D'^2 T_s R_i}{2L}$$

where 1 M is the rising slope of the inductor current, Mc is the slope of the artificial ramp signal that is used for slopecompensation.

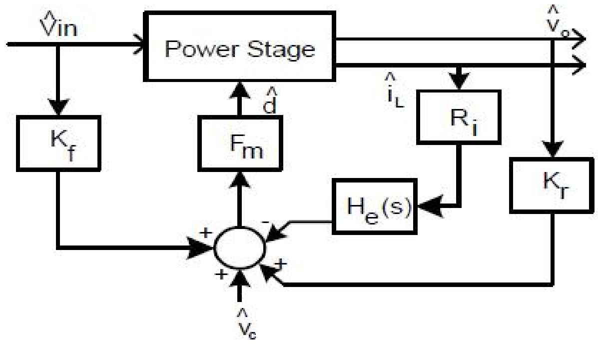


Fig.3. 2. The small-signal model of PCMC converter.

3.1The Linear Quadratic Regulator–CurrentMode Controlled Model

As aforementioned, the objective of the controller in this paper is to ensure a good voltage regulation at the DC bus. Thus, the small signal model of the CMC boost converter is augmented to include the new feedbacks from the state variables of the converter. In addition, a new state variable, the error between the reference and the output voltage, is added, as shown in Fig. 3.3

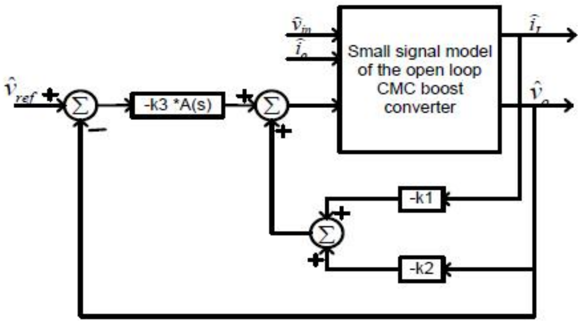


Fig. 3.3 The small signal model of closed-loop CMC PWM boost converter with linear feedback control.

IV.SIMULATION RESULTS

The MATLAB/Simulink simulation results for different operation modes of the bidirectional converter that interfaces the ultra-capacitor to the DC bus are depicted and discussed. The simulated system diagram is shown in Fig.4,

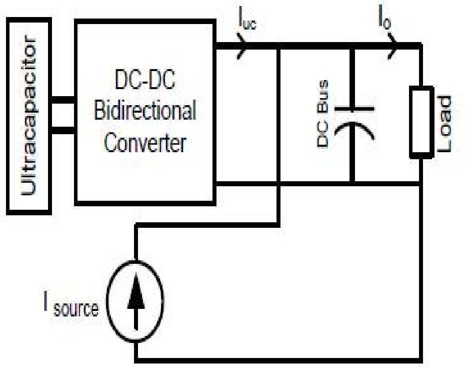
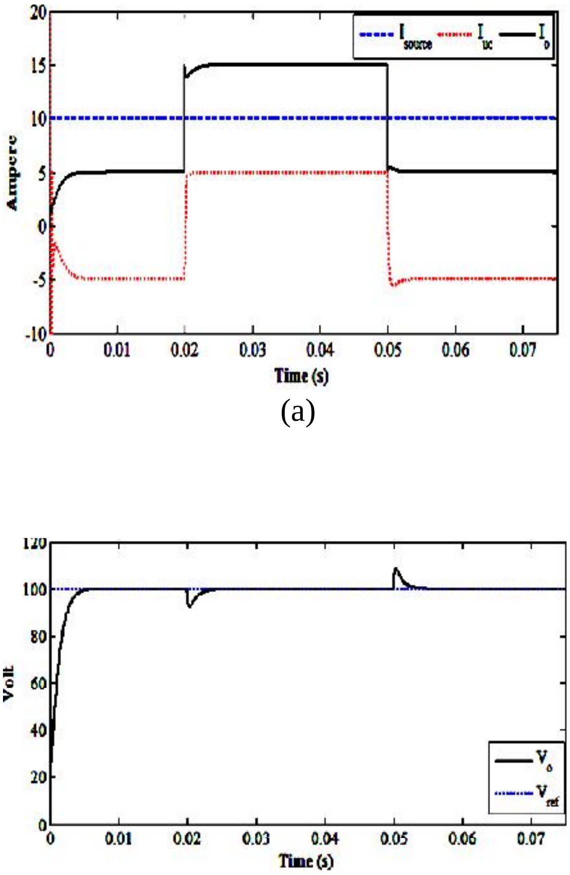


Fig.4. The block diagram of the proposed interfacing system.

The simulation results for the first case system test are shown in Fig. 4.2, where the renewable source current was maintained fixed at 10 A while the load current was changed in steps from 5 A to 15 A and then to 5 A. As illustrated in the Fig. 4.2(a), in the first interval (between t=0 and t=0.02 s) the renewable source covered the load demand and injected its excess current to the ultra-capacitor. In this interval, the bidirectional converter operated in a buck mode. However, when an additional 10 A was required by the load (between =0.02 and t=0.05 s), the renewable source was not able to provide the full load demand. Thus, in this interval, the bidirectional converter switched to a boost mode to discharge the ultra-capacitor and supply the extra load demand (5 A).

When the load current returned to its initial value (between t=0.05 and t=0.08 s), the bidirectional converter softly changed its mode of operation into the buck mode. Fig. 4.2(b) depicts the DC bus voltage. As can be seen, it was regulated at the desired value (100 V) regardless of the changes that happened in the load current. The figure clearly shows that the two modes of the converter operation altered softly.



(a)

(b)

Fig. 4.2. The responses of a step variation in the load current from 5 A to 15 A and then to 5 A of: (a) Load and ultra-capacitor currents (Io, Iuc), (b) Output and reference voltages (Vo, Vref).

V.CONCLUSION

This paper has include the discussion of a new control method based on LQR and CMC control for a bidirectional DC-DC converter that interfaces ultra-capacitor energy storage to a renewable energy system.

The LQR-CMC method has been successfully applied to control the bidirectional converter in the case of boost and buck modes. The objectives of the controller were to regulate the output voltage and to achieve a smooth transition between the two operation modes of the bidirectional converter, namely buck and boost modes. In addition, the proposed controller ensures continuous power supply the load, regardless of the load and renewable energy power changes. In short, the proposed controller is capable of increasing the reliability and energy conversion efficiency of renewable energy systems.

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