FUZZY CONTROL FOR A BIDIRECTIONAL DC-DC CONVERTER THAT INTERFACES ULTRACAPACITOR ENERGY STORAGE TO A RENEWABLE ENERGY SYSTEM

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ABSTRACT - This paper highlights the controller of a bidirectional converter to interface an ultracapacitor as storage device to renewable energy systems. Ultracapacitors 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 fuzzy 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; ultracapacitor; fuzzy control; linearquadratic regulator.

1. INTRODUCTION

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.

Amongst storage devices, ultracapacitor is preferred due to its long life-time, good electrical behaviour and to its relatively low initial cost in comparison with modern batteries.

In addition, it is positively characterized by its high power density, low losses while charging and discharging, and its very low equivalent series resistor (ESR) which allows it to deliver and absorb very high currents and to be charged very quickly. Furthermore, ultracapacitor can provide large transient power instantly. Consequently, the use of ultracapacitor 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 ultracapacitor requires a power converter and a DC link. The converter must have the capability to allow both directions of power flow between the ultracapacitor 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 ultracapacitor 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 ultracapacitor 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 ultracapacitor. 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 applied the dynamic evolution control method to interface a fuel cell and the ultracapacitor.
In literature, a combination of both fuzzy control strategies to interface the wind energy conversion system and the storage device has been proposed. 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 implementation. 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. Another control method that is most cited for controlling the PWM converters is linear quadratic regulator (LQR) control. Since the controller feedback gain-vector is determined optimally in LQR, the designers can guarantee that the converter has good closed-loop behaviour, 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. Combining the two methods (CMC and LQR) has been done in many studies. The combination indicates that a good response and disturbance rejection were achieved in the tested conditions.

This paper describes the design of a controller based on the basis of CMC and LQR control techniques. In the proposed fuzzy controller, the outer loop of the CMC is modified to include the feedback gains of the LQR. The objective of the converter fuzzy controller is to maintain the DC bus voltage at a relatively constant stream, regardless of the load switching and environmental conditions changes.

II. Modeling of the Ultracapacitor and Bidirectional DC-DC Converter

A comparison of ultracapacitor circuit models has previously been made in literature. In this paper, the equivalent circuit of ultracapacitor model as reported in is applied to simulate the ultracapacitor. As represented in Fig. 1, the model consists of a capacitance $C$, an equivalent parallel resistance $R$, and an equivalent series resistance $sR$. 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.

![Fig. 1. The electrical circuit of ultracapacitor bidirectional DC-DC converter topology.](image)

In the first direction, the converter transfers the energy from the ultracapacitor 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 ultracapacitor in its low-side.

According to literature, 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. In this work, the boost mode of operation is selected for the purpose of designing the controller. Hence, the small-signal model of the boost converter is derived. Similar to the study made in, the renewable energy source is modelled as a current source connected to the DC bus. Based on the state space averaging method, the resulted open-loop model of the boost converter is:

$$\frac{d}{dt} \left[ \begin{array}{c} V_L \\ V_0 \end{array} \right] = \left[ \begin{array}{cc} 0 & -(1-D) \\ 1-D & L \end{array} \right] \left[ \begin{array}{c} V_L \\ V_0 \end{array} \right] + \left[ \begin{array}{cc} V_{in} & 1 \\ -V_{in} & 1 \end{array} \right] \left[ \begin{array}{c} \hat{V} \\ \hat{V}_{in} \end{array} \right]$$

(1)

where $C$ is the DC bus capacitance and $sR$ is the load resistance. To derive the current-mode controlled model of the boost converter, the new continuous-time (NCT) model of the PCMC is used. It is generally accepted due to its simplicity and accuracy. The block diagram of NCT model is represented in Fig. 2, where $n$, $c$, $L$, $c'$, and $d'$ are the perturbations of the input voltage, output voltage, inductor current, and the duty-cycle of the power stage, respectively.

The variable $cV'$ is the perturbation of the reference voltage of the current loop. In this study, $cV'$ is the LQR controller output. $iR$ is the effective linear gain from the sensed current to the comparator input. $iK$ and $iK'$ are the feed forward and feedback gains, and they are different for the different for each different type of converters. $iH$ 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 $mF$ is the ac gain from the error current signal to the duty-cycle. $mF$, $iK$ and $iK'$ can be expressed as:

$$F_m = \frac{1}{(M_t + M_e)T_s}$$

(2)

$$k_f = \frac{-T_sR_i}{2L}$$

(3)

$$k_r = \frac{-T_sR_i}{2L}$$

(4)

where $iM$ is the rising slope of the inductor current, $cM$.
is the slope of the artificial ramp signal that is used for slope compensation. It is stated in [30] that there is an inherent stability when \( D > 0.5 \) for all types of converters. In order to guarantee the controller stability for all ranges of the duty-cycle, an artificial ramp with slope \( M \) has to be added (\( \alpha = M T \) is the falling slope of the inductor current). \( T \) is the switching period. As it is very small, the \( rK \) term can be neglected. Based on Fig. 2, when \( rK \) is neglected, the duty ratio law can be expressed as:

\[
\hat{d} = \frac{F_m}{1 - D} \left( -R_1 \hat{v}_L + k_f \hat{v}_m + \hat{v}_c \right) \tag{5}
\]

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

The state-space representation for the small signal analysis can be obtained by replacing the term \( \hat{d} \) in (1) with its value in (5).

The resulted PCMC model of the boost is:

\[
\frac{d}{dt} \begin{bmatrix} \hat{v}_L \\ \hat{v}_0 \end{bmatrix} = \begin{bmatrix} \frac{F_m V_{in} R_1}{1 - D} & \frac{F_m V_{in} R_0}{1 - D} \\ \frac{F_m V_{in} L}{1 - D} \end{bmatrix} \begin{bmatrix} \hat{v}_L \\ \hat{v}_0 \end{bmatrix} + \begin{bmatrix} -F_m V_{in} R_1 \\ 1 - D \end{bmatrix} \hat{a} + \begin{bmatrix} \frac{D}{L} - 1 \\ \frac{D}{L} \end{bmatrix} \begin{bmatrix} \hat{v}_c \\ \hat{v}_m \end{bmatrix} \tag{6}
\]

Fig. 3. The small signal model of closed-loop CMC PWM boost converter with linear feedback control

where the matrices A and B are obtained from the small signal state-space model of the CMC PWM DC-DC boost converter system in (6). \( C = \begin{bmatrix} 0 & 1 \end{bmatrix} \).

In addition, we have

\[
\hat{v}_0 = \begin{bmatrix} C \end{bmatrix} \begin{bmatrix} a_0 \end{bmatrix} \tag{9}
\]

In order to design the LQR system, the formulation of the following cost function is considered

\[
J = \int_0^+ \begin{bmatrix} \alpha \end{bmatrix}^T \begin{bmatrix} K_a \end{bmatrix} \begin{bmatrix} a_0 \end{bmatrix} + \rho \begin{bmatrix} a \end{bmatrix}^2 \end{bmatrix} dt \tag{10}
\]

where \( Q \) is a \( 3 \times 3 \) symmetric positive definite matrix and \( \rho \) is a positive scalar.

Once \( Q \) and \( \rho \) are chosen, the optimal control problem reduces to finding the weights in the vector \( aK \) that minimizes (10). It can be shown that the optimal weight vector \( aK \) is given by [31]:

\[
a_k = \rho^{-1} b_{2a}^T S \ldots (11)
\]

As in [32], the matrix \( Q \) is chosen to be:

\[
Q = \begin{bmatrix} a_{1x2} & a_{1x2} \\ a_{2x2} & q \end{bmatrix} \tag{12}
\]

III. The Linear Quadratic Regulator–Current Mode 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.

\[
\tilde{\xi} = \hat{\xi}_3 = \hat{v}_{ref} - \hat{v}_0 = \hat{v}_{ref} - C \hat{\xi} \tag{7}
\]

With the new state-space vector \( \begin{bmatrix} \xi \end{bmatrix} \)

\[
\begin{bmatrix} \tilde{\xi}_a \end{bmatrix} = \begin{bmatrix} A_{2 \times 2} & 0 \\ \end{bmatrix} \begin{bmatrix} \xi \end{bmatrix} + \begin{bmatrix} b_{12 \times 1} \\ 0_{1 \times 1} \end{bmatrix} \begin{bmatrix} \hat{v}_m \\ \end{bmatrix} + \begin{bmatrix} b_{22 \times 1} \\ 0_{1 \times 1} \end{bmatrix} \begin{bmatrix} \hat{v}_c \\ \end{bmatrix} \tag{8}
\]

\[
\begin{bmatrix} \hat{v}_c \\ \hat{v}_m \\ \end{bmatrix} = \begin{bmatrix} k_0 \end{bmatrix} \begin{bmatrix} \hat{v}_c \\ \hat{v}_m \end{bmatrix} + \begin{bmatrix} 1 \end{bmatrix} \begin{bmatrix} \hat{v}_c \\ \hat{v}_m \end{bmatrix} + \begin{bmatrix} 1 \end{bmatrix} \begin{bmatrix} \hat{v}_c \\ \hat{v}_m \end{bmatrix}
\]

The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as: i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani “s” “min” operator. v. Defuzzification using the „height” method.
Fuzzy Logic Controller

**Fuzzification**
Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). The partition of fuzzy subsets and the shape of membership function adapt the shape up to appropriate system. The value of input error $E(k)$ and change in error $CE(k)$ are normalized by an input scaling factor \[1\] and \[12\].

<table>
<thead>
<tr>
<th>Fuzzy Rules</th>
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<td>$e$</td>
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<tr>
<td>NB</td>
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<td>NM</td>
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In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular input there is only one dominant fuzzy subset. The input error $E(k)$ for the FLC is given as

$$E(K) = \frac{p_{ph(k)} - p_{ph,k-1}}{p_{ph}(K) - p_{ph,K-1}}$$

$$CE(K) = E(K) - E(K - 1)$$

Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

**3.2 Interference Method**

Inference method has been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC

As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, "height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of FC are: error, change in error and output as shown in Figs. (a), (b). In the present work, for fuzzification, non-uniform fuzzifier has been used. If the exact values of error and change in error are small, they are divided conversely and if the values are large, they are divided coarsely.

$$u = -[\alpha E + (1-\alpha) \cdot c]$$

Where $\alpha$ is self-adjustable factor which can regulate the whole operation. $E$ is the error of the system, $C$ is the change in error and $u$ is the control variable. A large value of error $E$ indicates that given system is not in the balanced state. If the system is unbalanced, the controller should enlarge its control variables to balance the system as early as possible. One the other hand, small value of the error $E$ indicates that the system is near to balanced state. Overshoot plays an important role in the system stability. Less overshoot is required for system stability and in restraining oscillations. $C$ in (12) plays an important role, while the role of $E$ is...
IV. Simulation Results and Discussion

In this section, the MATLAB/Simulink simulation results for different operation modes of the bidirectional converter that interfaces the ultracapacitor to the DC bus are depicted and discussed. The simulated system diagram is shown in Fig. 4, and the used parameters for the converter and the ultracapacitor are listed in Table I. The initial voltage of the capacitor is 48V, and the LQR-CMC controller is designed with \( q = 1 \times 10^9 \) and \( \rho = 0.1 \).

The simulation results for the first case system test are shown in Fig. 5, 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. 5(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 ultracapacitor. In this interval, the bidirectional converter operated in a buck mode. However, when an additional 10 A was required by the load (between \( t=0.02 \) 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 ultracapacitor and supply the extra load demand (5A). 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. 5(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.

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

Fig. 5. 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 ultracapacitor currents (I_o, I_{uc}), (b) Output and reference voltages sources(V_o, V_{ref}).

In the second case of simulation test, shown in Fig. 6 (a) and (b), the output voltage reference was changed from 100 V to 110 V and back to 90 V. In addition, \( I \) was changed from 0 A to 10 A at time of 0.04 s. Referring to the figures, it can be seen that before at \( t= 0.04 \) s the load current was completely provided by the ultracapacitor, and the converter was in the boost mode operation. Nevertheless, it was operating in the buck mode, by charging the ultracapacitor, during the remainder of the time. In both modes, the controller ensures good output voltage and current regulations . The output voltage tracked the reference accurately and smoothly. The transient time upon all changes was less than 7 ms, while the peak overshoot resulted from the current change was almost 8%.
V. Conclusion

This paper has included the discussion of a new fuzzy control method based on LQR and CMC control for a bidirectional DC-DC converter that interfaces ultracapacitor energy storage to a renewable energy system. The LQR-CMC method has been successfully applied to fuzzy 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.

REFERENCES


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