Dynamic Evolution Control of Bidirectional DC-DC Converter for Interfacing Ultracapacitor Energy Storage to Fuel Cell Electric Vehicle System

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Abstract—Fuel Cell Electric Vehicles (FCEV) has higher efficiency and lower emissions compared with the internal combustion engine vehicles. But, the fuel cell has a slow dynamic response. Therefore, a secondary power source is needed during start up and transient conditions. Ultracapacitor can be used as secondary power source. By using ultracapacitor as the secondary power source of the FCEV, the performance and efficiency of the overall system can be improved. In this system, there is a boost converter, which steps up the fuel cell voltage, and a bidirectional DC-DC converter, that couples the ultracapacitor to the dc bus. This paper proposes a new control method based on dynamic evolution control bidirectional dc-dc converter for interfacing ultracapacitor energy storage to a fuel cell system. The whole system with fuel cell model was simulated in SIMULINK for step change in load current.

Keywords—Dynamic Evolution Control, bidirectional dc-dc converter, ultracapacitor energy storage, Fuel Cell.

I. INTRODUCTION

The application of fuel cells in electric vehicles has been getting more awareness. An electric vehicle powered by fuel cells gives far more promising performance. Fuel cell has higher energy storage capability thus enhancing the range of operation for automobile and is a cleaner source of energy [1]. Fuel cells also have the added advantage of using hydrogen as fuel which will reduce world's dependence on non-renewable hydrocarbon sources. Automobiles have changing load requirements during different modes of travel. Further there are braking and acceleration requirements for control of automobile. These demands require that the source of energy should be able to respond to fast changing loads. Fuel cells do not have the capacity to respond to fast changing loads with response time of 10's of second.

Therefore, secondary energy storage is needed for responding the increased load instantly. Among several energy storage devices, ultracapacitor is a good option due to several advantages like high power density, long lifecycle and very good charge/discharge efficiency [2]. Ultracapacitor also have more cycles of charging and discharging during its lifetime. They can also provide large transient power instantly thus capable of providing energy for increased load for automobile requirements like acceleration, or sudden slope. Hence ultracapacitor is a suitable choice for secondary source of energy in electric vehicles applications.

Fig. 1. General approach of Connecting Energy Buffer

Several methods have been devised to connect energy storage device to the fuel cell. Fig.1 shows a typical way of doing this [3]. In this paper, a converter system for connecting ultracapacitor as secondary energy storage, to fuel cell electric vehicle systems is presented. The ultracapacitor is connected to dc bus of the fuel cell electric vehicle system through a bidirectional DC-DC converter. This bidirectional converter discharges the ultracapacitor when there is an increase in the load current and charges it back after the fuel cell reaches its new steady state. As shown in Fig. 2, Load and Inverter stage is represented as an equivalent dc load. Controller for interface converter, based on dynamic evolution control, has been designed. This controller controls ultracapacitor...
current such that the dc bus voltage droop is minimized even after a sudden change in load current.

II. POWER MANAGEMENT SYSTEM

The fuel cell, which is considered in this research, has a 42V nominal voltage. The bus voltage should be 100V and remain constant. So the fuel cell voltage should be stepped up through a boost converter. The ultracapacitor is connected to the bus through a bidirectional converter. During the start up and transient conditions, the ultracapacitor will supply the load. In this case the converter will act as a boost converter. When the power generated by the fuel cell is more than the power needed for the load, and also during the regenerative braking, the converters can act as a buck converter and charge the ultracapacitor. The ultracapacitor has 165 F capacity, and it can be charged up to 48V.

The schematic of the whole system, which produces the required DC voltage, is shown in Fig. 2.

![Fig. 2. Interface Converter Topology](image)

III. DYNAMIC EVOLUTION CONTROL THEORY [4]

A. Basic Idea

Feedback control refers to an operation that, in the presence of disturbances, tends to reduce the difference between the output of a system and the reference input and that it does so on the basis of the difference. [5]

In order to generalize this definition, we can assume that, “The difference between the output system and the reference input, which is denoted by error state, must be reduced to zero all the time, regardless, whether the disturbance is present or not.” This assumption is the fundamental of Dynamic Evolution Control.

The basic idea of the dynamic evolution control is to reduce the error state by forcing the error state to follow the specific path, that ensure the error state goes to zero in increase of time.

B. Evolution Path and Dynamic Evolution Function

The objective of the dynamic evolution controller is to control the dynamic characteristic of the system to operate on the target equation, \( Y = 0 \). In dynamic evolution controller, the dynamic characteristic of converter system is forced to make evolution by following an evolution path. The selected evolution path is an exponential function as shown in Fig. 3. The equation of this exponential function can be written as:

\[
Y = C \cdot e^{-mt} \tag{1}
\]

Where \( C \) is the initial value of \( Y \), and \( m \) is proportional to the initial decrease rate of \( Y \).

In this exponential function, the value of \( Y \) is decrease exponentially to zero as a function of time. The decrease speed of \( Y \) is proportional to the decrease rate \( m \).

Let \( Y \) represents the state error function of the converter. Then, \( Y \) is forced to follow the evolution path as show in fig.1, so the dynamic evolution of the state error function \( (Y) \), with initial value \( Yo \), can be represented as

\[
Y = Yo \cdot e^{-mt} \tag{2}
\]

It means that the state error function \( (Y) \) is driven decrease to zero exponentially with decrease rate \( m \).

![Fig. 3. Dynamic Evolution path](image)
\[ \frac{dY}{dt} = -mY \]

As a result, the dynamic evolution function can be written as equation (3).

\[ \frac{dY}{dt} + mY = 0, \quad m > 0 \]  \hspace{1cm} (3)

where, \( m \) is a design parameter specifying the rate of evolution.

C. Synthesis Process

The main objective of the synthesis process is to obtain the control law that guarantees the state error function \( Y \) of converter decrease to zero by following the evolution path. For dc-dc power converter, this control law represents the duty cycle equation of the converter. This duty cycle equation \( a(V_o, V_g, i_L) \), represents \( a \) as a function of the state \( V_o, V_g, \) and \( i_L \).

In order to obtain the duty cycle equation \( a(V_o, V_g, i_L) \), the dynamic equation of the converter system is analyzed and substituted into the dynamic evolution function (3).

The duty cycle equation is used to calculate the desired value of signal level control \( v_{control} \). The \( \text{PWM signal} \) is generated by comparing a signal level control \( v_{control} \) with a repetitive waveform as shown in Fig. 4. The frequency of the repetitive waveform with a constant peak, which is a sawtooth \( v_{st} \), establishes the switching frequency. This frequency is kept constant. Therefore, the dynamic evolution control is operated at constant switching frequency.

IV. SYNTHESIS OF THE BIDIRECTIONAL DC-DC CONVERTER CONTROLLER

The bidirectional dc-dc converter, which is interfacing ultracapacitor to the bus, is shown as Fig. 5. The converter can be operated in two modes of operation, namely boost operation and buck operation. During the boost operation, the converter acts as a boost converter and the power flows from ultracapacitor to dc bus. During buck operation, the converter acts as a buck converter and the power flows from dc bus to the ultracapacitor.

Due to this converter power switches are operated in complementary way, it is sufficient to find out the control law in boost mode of operation only. In fact, the duty cycle of the upper switch, which is responsible for the buck operation, is always \( 1 - \alpha \).

Synthesis of Dynamic Evolution Controller is begun with analyzing and substituting the dynamic equation of the converter system into the Dynamic Evolution Function (3).

Based on the average model of the PWM switch [6], the dynamic equation of boost mode of operation is obtained as follows:

\[ V_{uc} = L \frac{di_l}{dt} + V_o(1 - \alpha), \quad 0 < \alpha < 1 \]  \hspace{1cm} (4)

Where \( V_{uc} \) is input voltage, \( i_l \) is the inductor current, \( V_o \) is output voltage, \( \alpha \) is the duty cycle and \( L \) is inductor inductance.

Rearranging (4), the output voltage of converter can be written as:

\[ V_o = V_{uc} + V_o \cdot \alpha - L \frac{di_l}{dt} \]  \hspace{1cm} (5)

The dynamic evolution synthesis of the controller begins by defining the state error function \( Y \) as follows

\[ Y = k \cdot V_{err} \]  \hspace{1cm} (6)

Where \( k \) is a positive coefficient and \( V_{err} \) is error voltage \( (V_{err} = V_{ref} - V_o) \).

The derivative of \( Y \) is given by:
\[
\frac{dY}{dt} = k \frac{dV_{err}}{dt} \tag{7}
\]

Substitution (6) and (7) into (3), yields

\[
k \frac{dV_{err}}{dt} + m.k.V_{err} = 0
\]

\[
k \frac{dV_{err}}{dt} + (mk - 1)V_{err} + V_{ref} = V_o \tag{8}
\]

Directly substituting the converter voltage output \(V_o\) from (5) into (8) we can get:

\[
k \frac{dV_{err}}{dt} + (mk - 1)V_{err} + V_{ref} = V_{uc} + V_o \cdot \alpha - L \frac{di_L}{dt} \tag{9}
\]

Solving for \(\alpha\), the obtained duty cycle \(\alpha\) is given by:

\[
\alpha = \frac{k \frac{dV_{err}}{dt} + (mk - 1)V_{err} + L \frac{di_L}{dt} + V_{ref} - V_{uc}}{V_o} \tag{10}
\]

The expression for duty cycle \(\alpha\) is the control action for the converter controller.

Duty cycle equation (10) forces the state error function \(Y\) to satisfy the dynamic evolution function (3). Consequently, the state error function \(Y\) is forced to make evolution by following equation (2) and decrease to zero \((Y = 0)\) with a decrease rate \(m\). so, the state error function \(Y\) satisfy the equation

\[
Y = k.V_{err} = 0
\]

Thus the state error of the converter will converge to zero.

\[
V_{err} = 0 \tag{11}
\]

Substituting \(V_{err} = V_{ref} - V_o\) into (11), we can see that the voltage output of converter converges to the converters steady state:

\[
V_o = V_{ref} \tag{12}
\]

From the synthesis procedure, it is clear that the dynamic evolution controller works on the full nonlinear system and does not need any linearization or simplification on the system model at all as is necessary for application of traditional control theory.

Rearranging the duty cycle equation (10), the duty cycle \(\alpha\) can be written as:

\[
\alpha = \frac{V_{ref} - V_{uc}}{V_o} + \frac{(mk - 1)V_{err}}{V_o} + \frac{k \frac{dV_{err}}{dt} + L \frac{di_L}{dt}}{V_o} \tag{13}
\]

It is interesting to note that the control law in (13) consists of four distinct parts. The first part is the feedforward term \((V_{ref} - V_{uc})/V_o\), which is calculated based on the duty cycle at the previous sampling instant. This term compensates for variations in the input voltages. The second and third terms consist of proportional and derivative terms of the perturbations in the output voltage respectively. The last term consists of the derivative terms of the inductor current.

From (13), it is also seen that the input voltage, output voltage and inductor current are involved in control output. The advantage is the dynamic evolution control can compensate all of variation in the input and output voltages also the change of inductor current. It contributes to the better dynamic performance of the controlled system.

The dynamic evolution control law theoretically does not require precise knowledge of the model parameters. The parameter required is the inductor inductance \((L)\). This requirement sounds become a small limitation on the control system for a reason: sometimes it is difficult to get the fixed value of \(L\). From investigation, the change in inductor inductance value is not affect significant to simulation result. Hence, ones can use the nominal or average value of inductor inductance as value of \(L\) in control law equation.

V. SIMULATION RESULT

The performance of the whole system was simulated in MATLAB SIMULINK. The control target is to regulate dc bus voltage, \(V_o = 100V\). The reference of the dc bus voltage is fixed 100V during the operation. Fig. 6 shows the demanded power for a period of time. The bus voltage and fuel cell voltage is represented in fig. 7, and the simulation result of \(i_{uc}, i_{fc},\) and \(i_o\) are shown in Fig. 8. Demanded power during T1 and T2 is 500W. During T3
the vehicle is braking, and during T4 demanded power is 500 W.

The results show that during the first time span, T1, the fuel cell power is less than the required power, therefore the ultracapacitor will supply the load. In the second time span, T2, fuel cell power has reached the required level, so it will supply the load. Fuel cell starts to supply current. The current of fuel cell increase to nominal current, along with the ultracapacitor current is decrease. During the third time span, T3, the vehicle is braking. The ultracapacitor will charge during the regenerative braking. In the fourth time span, T4, fuel cell supply power to the load and ultra capacitor backup the difference power between the supplied power from fuel cell and the load demand power.

Fig. 7 shows that in all time spans the dc bus voltage does not droop. The ultracapacitor accomplish to stabilizing the dc bus during the low power of fuel cell and during the transient time. The power generated by fuel cell shown in Fig. 9, and the power generated by ultracapacitor is shown in Fig. 10.
VI. CONCLUSION

The paper discusses a new control method based on dynamic evolution control for bidirectional dc-dc converter that interfacing ultracapacitor energy storage to a fuel cell system. Ultracapacitor and converter improve the dynamic response of fuel cell system, hence enabling fuel cell powered automobile to accelerate rapidly and also respond to sudden changes in load conditions in an improved manner. The paper shows that using a bidirectional converter as an interface between fuel cell and ultracapacitor gives better control over fuel cell voltage during transients. The controller designed allows the ultracapacitor to respond to fast changing loads and then get charged back to its nominal voltage when the fuel cell power is bigger than the demanded load or when vehicle is braking.

VII. ACKNOWLEDGMENT

The authors would like to thank the Ministry of Science, Technology and Innovation (MOSTI) of the Malaysian government for providing the funding for this research.

Reference: