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Modelling and Simulation of Predictive Voltage Control for a Multi-Port DC/DC Converter

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Abstract: Nowadays DC/DC converters with multiple ports are continuously evolving with new ventures in control methodologies. A Four Port Converter with an input port, two storage ports and a load port is chosen for the implementation of Predictive Voltage Control. The Four Port Converter has five different operating modes and separate event controller is employed for mode selection. The idea of predictive control is to predict the control variable of the upcoming switching cycle based on the status of the system parameters in the present switching period. The universal law for prediction of the duty cycle of the converter is derived. The controller is implemented with PSIM simulation software to ascertain the feasibility of the controller. The simulation results reveal that the proposed controller could reduce steady state voltage ripple and improve the dynamic performance of the converter.

Key words: Energy footprint · Hybrid Electric Vehicles · Research interest

INTRODUCTION

The promising acceptance of Hybrid Electric Vehicles (HEV) and the availability of the technology have renewed the research interest towards electric propulsion. Hybrid Electric Vehicles on its course of evolution has included different sources and storage units into its architecture. While the clean energy footprint of an HEV is still debated [1], hybrid electric vehicles have found increased acceptance [2]. Different architectures of electric vehicles [3] and power converter topologies are reported in past literature [4, 5]. Due to the presence of multiple sources and storage units, the power topologies have evolved into multi-port converters. Multi-port topologies could be either isolated [6] or non-isolated. Due to the less weight and simple control, non-isolated topologies are preferred over isolated topologies [7-10]. The control of power converter is a hot research area for which different control algorithms were proposed. Although the classical control techniques are still in use, new methods of digital control [11–13] are experimented for better performance. The idea of predictive control is to predict the duty cycle of the upcoming switching period based on the parameters measured in the current switching period [11]. This concept reduces the tuning difficulties of classical control and provides a straightforward control.

The concept of predictive current control of inductor current in a power converter could also be extended to the predictive voltage control of output capacitor.Compared to the work done on Predictive Current Control[14–16], the concept of predictive voltage control is less explored for control of DC/DC converters[17–19].This research work explores the idea of predictive voltage control to regulate the output voltage.

The rest of the paper is organised as follows: Section II presents the topology of power converter chosen for predictive voltage control, Section III elaborates the derivation of control law for duty cycle prediction, Section IV presents the simulation results and Section V concludes the paper.

Topology: A Four Port DC/DC converter with an input port (V_i), two storage ports (V_b, V_{uc}) and a load port is considered for the implementation for the Predictive Voltage Control. The Power circuit of the Four Port Converter (FPC) is adopted from [10] as shown in Fig. 1 and it has five operating modes. Each operating mode

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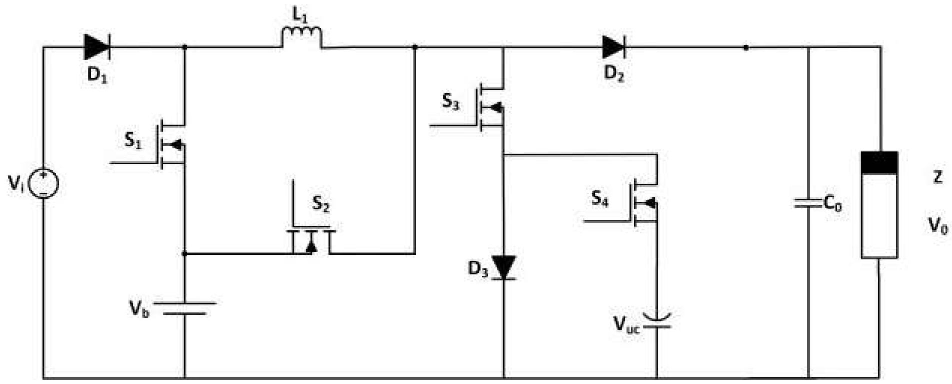

Fig. 1: Power Circuit of Four Port DC/DC Converter Suitable for HEV [10]

consists of two switching states and works in a way similar to a boost converter. A summary of operating modes is presented in Fig. 2 where, the first switching state is denoted by the darkened line in the circuit and the second switching state is denoted by discrete red lines.

Operating Modes

Mode I: In the first switching state S_3, D_1 and D_3 are ON and during the second switching state D_1 and D_2 are turned ON to transfer energy from the input port (V_i) to the load port (V_o). The circuit with the first switching state denoted by darkened lines and the second switching state denoted by discrete red lines are shown in Fig. 2(a).

Mode II: When the voltage of (V_i) drops below (V_b), this mode is activated as the cathode of the diode is more positive with respect to cathode. The switching devices S_1, S_3 and D_3 are turned ON during first switching state and S_1 and D_2 are ON during the second switching state as shown in Fig. 2(b).

Mode III: In this hybrid mode energy from input port (V_i) and the secondary storage port (V_{uc}) are transferred to the load port. Inductor L_1 charges when S_3, S_4 and D_1 (Refer Fig. 2(c)) are ON and discharges when switching devices D_1 and D_2 are ON.

Mode IV: In this hybrid mode energy from primary storage port (V_b) and the secondary storage port (V_{uc}) are transferred to the load port.Inductor L_1 charges when S_1, S_3 and S_4 are ON and discharges when switching devices S_1 and D_2 are ON as shown in Fig. 2(d).

Mode V: This mode isan energy recovery mode that facilitate the excess energy produced by the input source. Switching devices S_3, D_1 and D_3(Refer Fig. 2(e)) are active during the first switching state and the second switching state S_2 and D_1 are ON to transfer energy from the input port (V_i) to the primary storage port (V_b).

Predictive Voltage Control

Derivation of Control Law: Applying the charge-second balance [20] on the output capacitor C_0, the charging during the period dT_s and discharging slope during the period $d'T_s$ could be found. The output voltage during the n^{th} switching cycle is given by,

$$V_0(n) = V_0(n-1) - \frac{V_0 \times d[n] \times T_s}{ZC} + \frac{\left\{i_L - \frac{V_0}{R}\right\} \times d'[n] \times T_s}{C} \quad (1)$$

Grouping variables yields,

$$V_0(n) = V_0(n-1) - \frac{V_0 \times T_s\{d[n] + d'[n]\}}{ZC} + \frac{i_L \times d'[n] \times T_s}{C} \quad (2)$$

Since the sum of on and off periods in a duty cycle,

$$d[n] + d'[n] = 1 \quad (3)$$

Substituting Eq.3 in Eq.2 yields,

$$V_0(n) = V_0(n-1) - \frac{V_0 \times T_s}{ZC} + \frac{i_L \times d'[n] \times T_s}{C} \quad (4)$$

Using the relation in Eq.3, Eq.4 could be rewritten as,

$$V_0(n) = V_0(n-1) - \frac{V_0 \times T_s}{ZC} + \frac{i_L \times \{1 - d[n]\} \times T_s}{C} \quad (5)$$

Taking the inductor current term $i_L$to the LHS,

$$\frac{-i_L \times \{1 - d[n]\} \times T_s}{C} = \{V_0(n-1) - V_0(n)\} - \frac{V_0 \times T_s}{ZC} \quad (6)$$

Rearranging for computation of duty cycle yields,

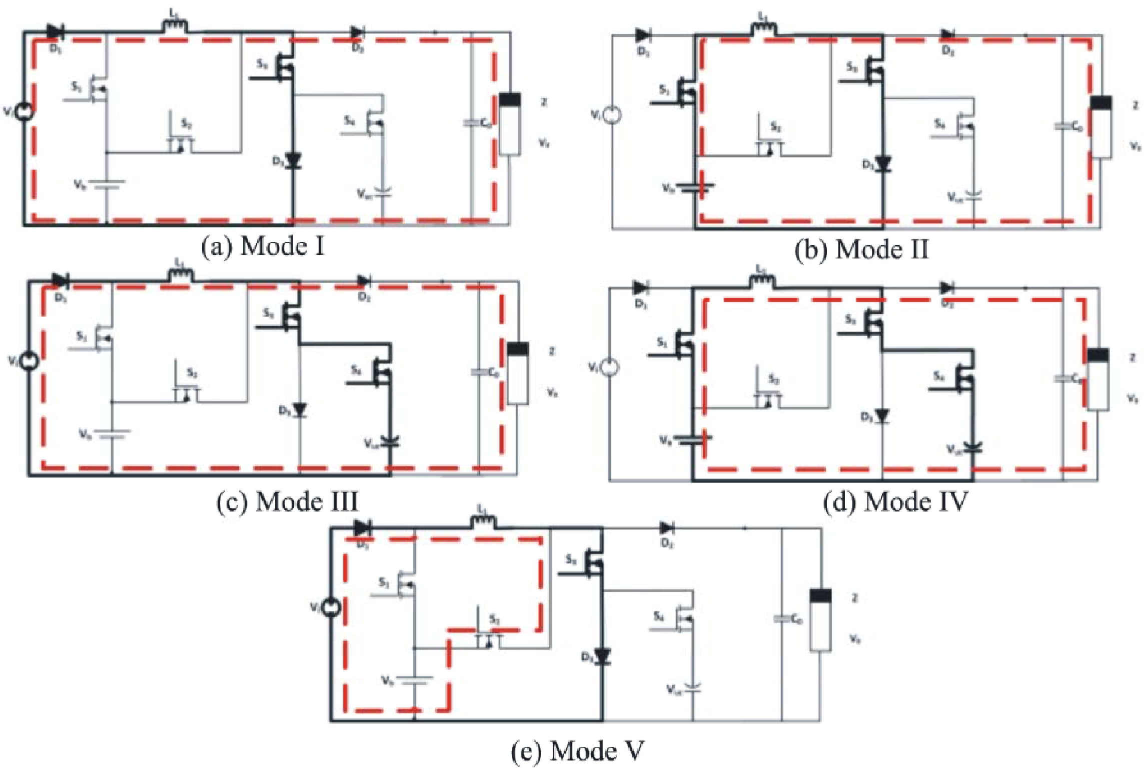

Fig. 2: Switching State in each Operating Mode

$$d[n] = 1 + \{V_0(n-1) - V_0(n)\}\frac{C}{i_L \times T_s} - \frac{V_0}{i_L \times Z} \quad (7)$$

Now by making the voltage in the upcoming period equivalent to the reference value, $V_o(n) = V_{ref}$, Eq.7 becomes,

$$d[n] = 1 + \{V_0(n-1) - V_{ref}\}\frac{C}{i_L \times T_s} - \frac{V_0}{i_L \times Z} \quad (8)$$

Using Eq. 7, the duty cycle for the n^{th} switching cycle could be predicted if the output voltage ($V_o(n-1)$) and inductor current (i_L) are measured. The actual idea of predictive control is to predict the duty cycle for the upcoming duty cycle. The output voltage of the $(n+1)^{th}$ switching cycle is given by,

$$V_0(n+1) = V_0(n) - \frac{V_0 \times T_s}{ZC} + \frac{i_L \times d'[n] \times T_s}{C} - \frac{V_0 \times d[n+1] \times T_s}{ZC} + \frac{\left\{i_L - \frac{V_0}{R}\right\} \times d'[n+1] \times T_s}{C} \quad (9)$$

Grouping $[n+1]$ duty cycles with respect to V_o yields,

$$V_0(n+1) = V_0(n) - \frac{V_0 \times T_s}{ZC} + \frac{i_L \times d'[n] \times T_s}{C} - \frac{V_0 \times T_s\{d[n+1] + d'[n+1]\}}{ZC} + \frac{i_L \times d'[n+1] \times T_s}{C} \quad (10)$$

Using Eq.3 with respect to $(n+1)^{th}$ switching cycle in Eq.10 yields,

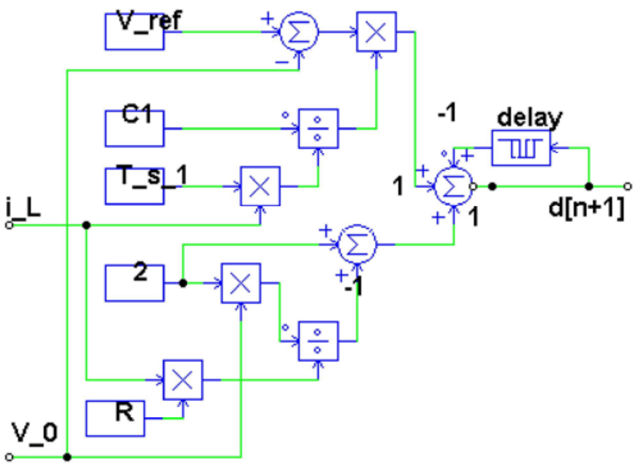

Fig. 3: Controller Structure for Predictive Voltage Control

$$V_0(n+1) = V_0(n) - \frac{V_0 \times T_s}{ZC} + \frac{i_L \times d'[n] \times T_s}{C} - \frac{V_0 \times T_s}{ZC} + \frac{i_L \times d'[n+1] \times T_s}{C} \quad (11)$$

Rearranging,

$$V_0(n+1) = V_0(n) - \frac{2V_0 \times T_s}{ZC} + \frac{i_L \times T_s\{d'[n] + d'[n+1]\}}{C} \quad (12)$$

Substituting $d = 1 - d$, corresponding to each duty cycle yields,

$$V_0(n+1) = V_0(n) - \frac{2V_0 \times T_s}{ZC} + \frac{i_L \times T_s\{2 - d[n] - d[n+1]\}}{C} \quad (13)$$

Taking the inductor current term (i_L) yields to LHS,

$$\frac{-i_L \times T_s\{2 - d[n] - d[n+1]\}}{C} = V_0(n) - V_0(n+1) - \frac{2V_0 \times T_s}{ZC} \quad (14)$$

Dividing the Eq.14 by $\frac{C}{-i_L \times T_s}$ throughout,

$$2 - d[n] - d[n+1] = \frac{C}{-i_L \times T_s}\{V_0(n) - V_0(n+1)\} - \frac{2V_0}{-i_L \times Z} \quad (15)$$

Our objective is to predict the duty cycle for the $(n+1)^{th}$ switching cycle $d[n+1]$ based on the measured parameters at the n^{th} switching cycle.Solving for $d[n+1]$ yields,

$$d[n+1] = 2 - d[n] + \frac{C}{i_L \times T_s}\{V_0(n) - V_0(n+1)\} - \frac{2V_0}{i_L \times Z} \quad (16)$$

Looking from $(n+1)^{th}$ switching cycle, $V_o(n)$ becomes the measured voltage at the previous cycle and for prediction is assumed to be the reference voltage.

$$V_0(n) = V_{0(m)}$$

$$V_0(n+1) = V_{ref} \quad (17)$$

By substituting Eq.17 in Eq.16 the final equation for prediction of duty cycle at $(n + 1)^{th}$ switching cycle becomes,

$$d[n+1] = 2 - d[n] + \frac{C}{i_L \times T_s}\{V_{0(m)} - V_{ref}\} - \frac{2V_{0(m)}}{i_L \times Z} \quad (18)$$

Simulation: The simulation of the Predictive Voltage Control for the Multi-Port DC/DC converter is implemented using PSIM software. The control objective of this technique is to regulate the output voltage within the specified limits. The final equation for the prediction of duty cycle as shown in Eq.18 could be built as a mathematical structure where the inductor current (i_L) and output voltage ($V_{o(m)}$) are measured parameters. All other parameters in the equation such as the capacitor value (C), switching period (T_s) and load impedance (Z) could be implemented using constant blocks with duty cycle of the previous period ($d[n]$) feedback from the previous computation. The structure of the Predictive Voltage Controller used in PSIM is shown in Fig. 3.

RESULTS AND DISCUSSION

This section presents the simulation results of the Predictive Voltage Control of the Four Port Converter. The simulation utilises a physical model of the Photo Voltaic panel at the input port (V_i), a battery at the primary storage port (V_b) and picewise- linear model of an Ultracapacitor at the secondary storage port (V_{uc}). Since the converter is capable of operating in five different operating modes, an event control is utilised for mode selection based on the statusof themeasured system parameters. This event controller initiates mode transition at appropriate tervals. The default starting state is always set to Mode I. Since the control structure is independent of the input sources used in each operating mode, a common controller structure is implemented for all the operating modes. In fact the procedure used in the previous section could be implemented for control law derivation in each operating mode and all those laws will be exactly identical to Eq.18. The steady state output voltage is mode I is shown in Fig. 4. To test the dynamic feasibility of the Predictive Voltage Controller, a step variation is applied at the load port. The step variation is applied at time t=5seconds and then turned off at t=6seconds of the simulation time as shown in Fig. 5. The controller responds to the dynamics of the pretty quickly and a strict regulation of the output is maintained beside a surge as shown in Fig. 6.

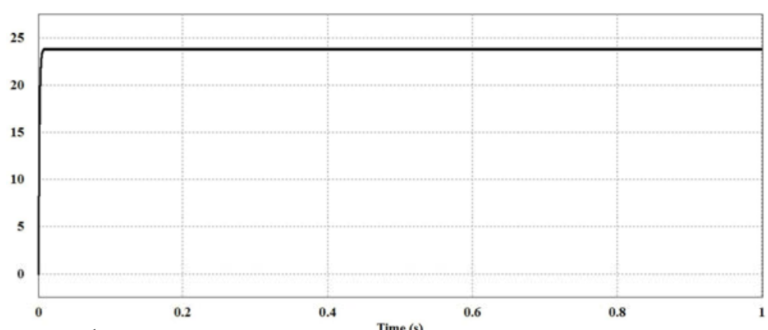

Fig. 4: Steady State Output Voltage.

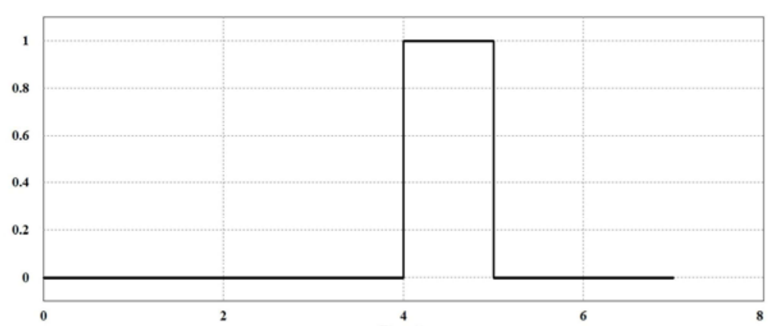

Fig. 5: Step Actuation Signal

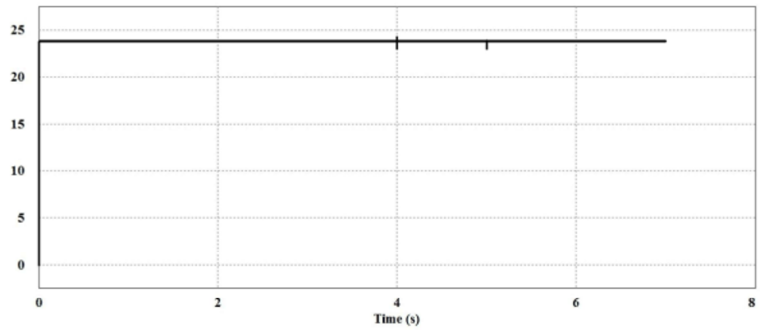

Fig. 6: Output Voltage Response to Load Step Variation

CONCLUSION

This paper proposes a predictive voltage controller for a Four Port DC/DC converter applicable for a Hybrid Electric Vehicle. The predictive control applies to all the applications in which control objective has to be exactly achieved. The universal control law applicable for all five operating modes for the prediction of the duty cycle of the Four Port Converter is derived out. The controller is implemented in PSIM in conjunction with an event control algorithm for mode selection. The feasibility of the controller in steady state and dynamic conditions are studied using simulation. The results show that there is ripple reduction in steady state and fast response to load dynamics. The control objectives are exactly achieved which makes this controller ideal for a converter with strict constraints on system parameters.

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