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Investigation on transient response of fuel cell power conditioning unit during rapid load changes

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***Abstract*—Fuel cell is one of the renewable energy sources used extensively in stand-alone as well as grid tied applications. Fuel cell provides a low voltage and high current DC output which has to be properly conditioned according to the demand of load. Therefore, a power conditioning unit (PCU) is essential for processing the unregulated DC voltage. The PCU posses different dynamics from the fuel cell, so proper modeling of fuel cell as well as PCU is essential. Tight voltage regulation of the power converters used in PCU is also necessary, so that regulated power can be provided to sophisticated load. The transient state performance and recovery time during load changes has to be very small. This paper focusses on the application of synchronous buck converter which provides low voltage output for different appliance of electric vehicle. Synchronous buck converter is used because of its low losses. A digital compensator is used to control the voltage during sudden changes in load profile. Simulation studies are performed to study the transient state performance of the converter.**

Keywords*—Fuel cell, power conditioning unit, synchronous buck converter

I. Introduction

Civilian, military and space transport vehicle require reliable, compact and highly efficient power supplies. The normal lead-acid battery can't provide the requisite power in an efficient manner. Therefore, hydrogen energy is used to provide reliable and efficient power to different stationary as well as transportation applications [1]. In space applications, fuel cell is used as an reliable energy sources in space craft and space shuttle [2]. In military applications, fuel cell is used as a power source in autonomous underwater vehicles (AUV) [3], [4]. In civilian transport, fuel cell is used in auxiliary power unit of trucks [5]. Among different types of fuel cells categorized according to the electrolyte used, Proton Exchange Membrane Fuel Cell (PEMFC) is widely used for transportation applications [6]. For the first time in August 21, 1962, fuel cells were successfully used in Gemini space craft. Apollo space craft used alkaline fuel cells [2]. The fuel cell based power system not only provides power supply, but the by-products of fuel cell such as water and heat are also used in space craft.

The transport vehicle consists of one or more than one power source, an energy saving device. A power conditioning unit (PCU) is required to process the power. PCU consists of converter and inverter topology, which are used to step-up, step-down or transfer power. DC-DC power converters are the key unit of PCU which are used to step-up or step down power and deliver power to different loads. Proper selection of PCU topology and proper control of PCU is very much necessary for smooth functioning of the power system. Unidirectional converter and bidirectional converters are used in transport vehicle as the power needs to flow from source to load and vice versa. The most important aspect of converter is tight load voltage regulation in steady state and low recovery time in transient state. Due to its inherent thermodynamic mechanism, fuel cell can't respond to sudden load changes adequately, so an energy storing device is required for the same.

This paper presents the electro chemical modeling and simulation of proton exchange membrane fuel cell which is widely used as battery source in transport vehicle. A power conditioning unit consists of synchronous DC-DC converter is used to regulate and step down the fuel cell voltage and provide low power to critical load in vehicle. Digital PI controller is implemented to control the converter. The steady state response and transient state response of the converter is studied with the help of simulation studies.

This paper is organized as follows. Section II provides the electrochemical model of the fuel cell. Section III discusses the importance of power conditioning unit, different topology and control strategies of DC-DC converter. Section IV provides the simulation results of the integrated system (fuel cell with synchronous buck converter). Transient changes in load profile is considered and the performance of the controller during the said period is analyzed. Section V provides the concluding remarks.

II. Modeling of Fuel Cell

In fuel cell, fuel is supplied to the anode and air is supplied to the cathode. The chemical reaction between the cathode and anode produce electricity. Fuel cells are highly efficient and has high power density. To increase the amount of power, number of cells are connected in series or parallel configuration and this particular configuration is called fuel cell stack. The electrical modeling of fuel cell is well documented in [7]–[9]. The output voltage of a single fuel cell can be represented as,

$$V_{cell} = E_{Nernst} - V_{act} - V_{ohm} - V_{con} \tag{1}$$

The thermodynamic potential E_{Nernst} can be expressed as

$$E_{Nernst} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}(T - T_o) + \frac{RT}{2F}\left[\ln\left(P_{H_2}\sqrt{P_{O_2}}\right)\right] \tag{2}$$

where ΔG is the change in free Gibb's energy of the reaction, ΔS is the change in entropy of reaction, R is the universal gas

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constant and F is the faraday's constant.

$$E_{Nernst} = a - b(T - 298.15) + c\ln\left(\frac{P_{H_2}}{101325}\right) + \frac{c}{2}\ln\left(\frac{P_{O_2}}{101325}\right) \tag{3}$$

Here a = 1.229, b = 0.85×10^{-3} and c = 4.3085×10^{-5}. Partial pressure of oxygen, hydrogen and water is represented as P_{H_2}, P_{O_2} and P_{H_2O} respectively and can be obtained from the following differential equations.

$$\dot{P}_{H_2} = -\frac{1}{t_{H_2}}\left(P_{H_2} + \frac{1}{K_{H_2}}\left(q_{H_2}^{in} - 2K_r I_{fc}\right)\right) \tag{4}$$

$$\dot{P}_{O_2} = -\frac{1}{t_{O_2}}\left(P_{O_2} + \frac{1}{K_{O_2}}\left(q_{O_2}^{in} - 2K_r I_{fc}\right)\right) \tag{5}$$

$$\dot{P}_{H_2O} = -\frac{1}{t_{H_2O}}\left(P_{H_2O} + \frac{2}{K_{H_2O}}K_r I_{fc}\right) \tag{6}$$

Here $q_{H_2}^{in}$ is the molar flow of hydrogen, K_r is a constant and I_{fc} is current of fuel cell stack.
Activation over potential which can be derived from Butler-Volmer equation can be represented as,

$$V_{act} = -\left[\xi_1 + \xi_2 T + \xi_3 T \ln\left(C_{O_2}\right) + \xi_4 T \ln\left(i_{FC}\right)\right] \tag{7}$$

where ξ_1, ξ_2, ξ_3 and ξ_4 are cell parameter coefficients.
Oxygen concentration C_{O_2} in the interface can be represented as

$$C_{O_2} = \frac{\frac{P_{O_2}}{101325}}{5.08 \times 10^{-6}\exp\left(\frac{-498}{T}\right)} \tag{8}$$

The voltage drop due to transfer of electrons through electrodes and to the transfer of protons through the membrane is called the ohmic loss which can be represented as

$$V_{ohm} = i_{FC}\left(R_M + R_C\right) \tag{9}$$

where R_C is the constant.
Resistance of the membrane R_M can be represented as

$$R_M = \frac{\rho_M l}{A} \tag{10}$$

Here, ρ_M is the membrane specific resistivity and can be calculated as,

$$\rho_M = \frac{181.6\left[1 + 0.03\left(\frac{i_{FC}}{A}\right) + 0.062\left(\frac{T}{303}\right)^2\left(\frac{i_{FC}}{A}\right)^{2.5}\right]}{\left[\lambda_m - 0.634 - 3\left(\frac{i_{FC}}{A}\right)\right]\exp\left[4.18\left(T - \frac{303}{T}\right)\right]} \tag{11}$$

λ_m is the average water content in membrane which varies from 0 to 100%. The value of λ_m varies from 0 to 14.
The concentration loss is due to the reactive excess concentration near the catalyst surface. The concentration drop can be represented as,

$$V_{con} = -\frac{RT}{2F}\ln\left(1 - \frac{j}{j_{\max}}\right) \tag{12}$$

Here, j is the current density and j_{max} is the maximum current density.
The electrical performance of a fuel cell can be evaluated through the polarization curve which is nothing but the V-I characteristics (cell potential v/s cell current density) of a fuel cell shown in Fig. 1. The fuel cell voltage drops with increase in load current density. The voltage loss can be attributed to various losses such as ohmic loss, concentration loss and activation loss. The efficiency of fuel cell is directly proportional to the cell potential and is illustrated in Fig. 2. The ohmic loss of fuel cell is shown in Fig. 3 and the activation loss of fuel cell is shown in Fig. 4.

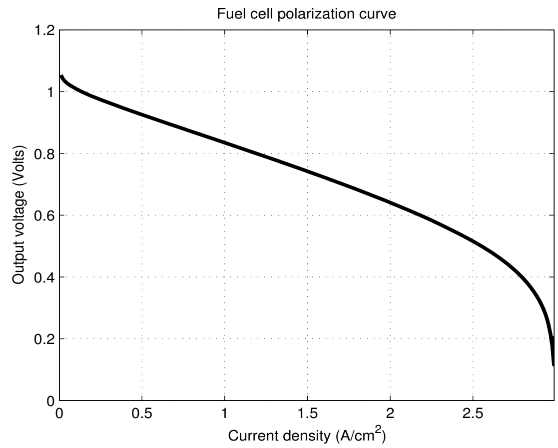

Fig. 1: Polarization curve of fuel cell

III. Power Conditioning Unit

A single unit of fuel cell provides a very low unregulated DC output (1.2 V). Therefore, a number of fuel cells are connected either in series or parallel to get a higher voltage. To use it in different applications a power conditioning system is used. The PCU can either step up the voltage or step down the voltage according to the type of application and specification. The major limitation of fuel cell is that it is slow to respond the sudden change in load profile, so the selection of topology of PCU and control of PCU is one of the challenging tasks. Different topologies of PCU for

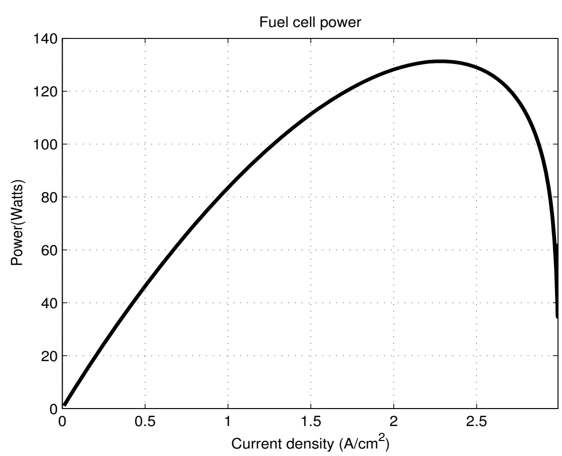

Fig. 2: Efficiency of fuel cell

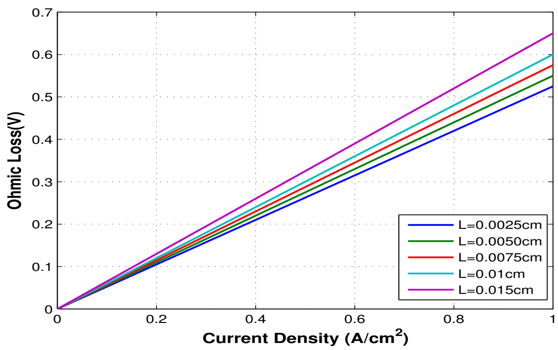

Fig. 3: Ohmic Loss as a function of electrolyte thickness

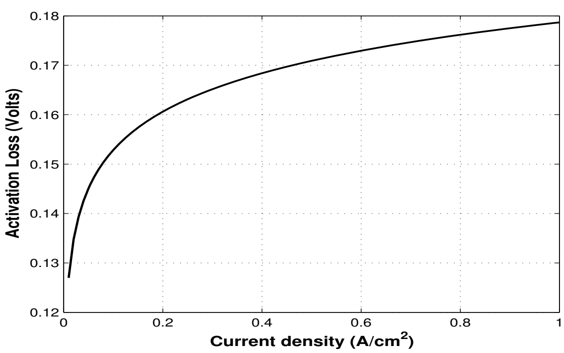

Fig. 4: Activation Loss

fuel cell are reviewed in [10]–[13]. In terms of control, there are numerous type of control available in literature starting from simple PI controller to complicated nonlinear and adaptive controller. But as a standard practice, voltage mode control and current mode control are widely used for control of converter because of its simplicity and robustness. This paper implements a synchronous buck converter to regulate the output voltage of PEMFC. Digital voltage mode control of synchronous buck converter is used. Set point tracking and load disturbance rejection of the controller is studied. Conventionally the controller implementation is analog in nature but there the analog controller is not reconfigurable in nature. Due to variation in ambient conditions and component aging there can be degradation of control action. Therefore, digital controller is widely used in controller implementation [14]. There are three different approaches of designing a digital controller but the most common method is to design an analog controller and then digitize it [15]. The control algorithm is implemented in low cost computing device. Digital controller is reconfigurable in nature and it has no effect on ambient condition or component aging etc. Fig. 5 shows the intersection of the fuel cell polarization when the duty cycle of DC-DC converter is varied.

A. Modeling of Synchronous Buck Converter

To design a controller, model of the converter is of utmost importance. Power converter is a time variant system and

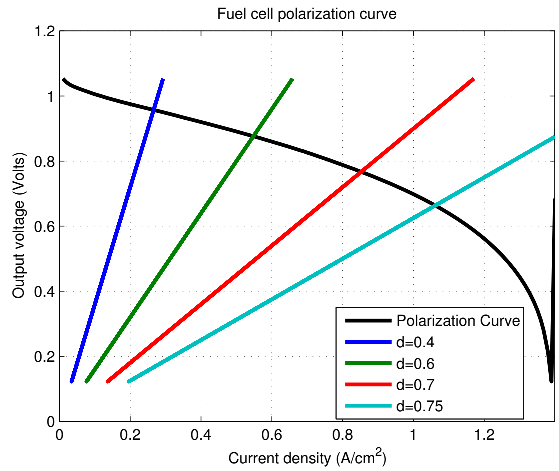

Fig. 5: Intersection of polarization curve with straight line of load when duty cycle changes

the dynamics changes w.r.t the change of orientation of the switch (ON/OFF). For each state of the switch a separate state space model has to be obtained and the complete model of the converter can be obtained using state space averaging technique which is considered as one of the most useful modelling technique in power converter domain [16]. The state space averaging technique can be represented as

$$\begin{aligned}\dot{x}(t) &= (d(t)A_1 + (1-d(t))A_2)\,x(t)\\ &\quad + (d(t)B_1 + (1-d(t))B_2)\,u(t)\end{aligned} \tag{13}$$

$$\begin{aligned}y(t) &= (d(t)C_1 + (1-d(t))C_2)\,x(t)\\ &\quad + (d(t)E_1 + (1-d(t))E_2)\,u(t)\end{aligned} \tag{14}$$

During ON and OFF state, the state space representation of the synchronous buck converter is represented as

$$\begin{aligned}\dot{x} &= \begin{bmatrix} -\left(\frac{R_L}{L} + \frac{R_cR}{L(R+R_c)}\right) & -\left(\frac{1}{L} - \frac{R_c}{L(R+R_c)}\right) \\ \frac{R}{C(R+R_c)} & \frac{-1}{C(R+R_c)} \end{bmatrix} x \\ &\quad + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in}\end{aligned} \tag{15}$$

$$y = \begin{bmatrix} \frac{R_c}{1+\frac{R_c}{R}} & 1 - \frac{R_c}{R\left(1+\frac{R_c}{R}\right)} \end{bmatrix} \begin{bmatrix} I_L \\ V_c \end{bmatrix} \tag{16}$$

From the above variables, average state space model can be obtained. Small signal discrete time modeling has gain a lot of interest in recent years because of the wide implementation of digital controller [17]. The discrete time modeling of the converter can be found using the following expression.

$$G_{dv}(z) = \frac{b_1z^{-1} + b_2z^{-2} + - - - - + b_Nz^{-N}}{1 + a_1z^{-1} + a_2z^{-2} + - - + a_Mz^{-M}} \tag{17}$$

B. Digital Control of Synchronous Buck Converter

Digital control of synchronous buck converter has been widely reported in the literature. Alejandro R. Oliva et.al [18], implemented pole placement using complete state feedback control of synchronous buck converter of rating (input:

7V, output 3.3V/1A). The proposed control law has been implemented using TI320F240 DSP. Dae Woon Kang et.al [19], reported digital adaptive high efficient converter which provides voltage between 0.7V to 1.2V with a maximum peak ripple of 5mV.

The block diagram of digital control of synchronous buck converter which acts as a PCU for a fuel cell source is represented in Fig. 6.

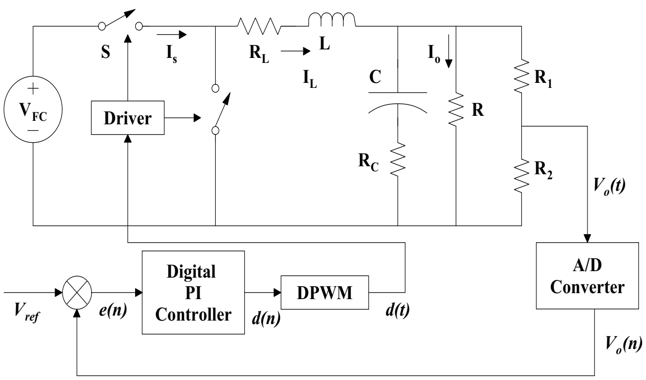

Fig. 6: Digital controller for PCU of fuel cell

The output voltage of the power converter is measured using a voltage divider circuit. The analog voltage is converted to digital form using analog to digital converter (ADC). The ADC is chosen keeping in mind the resolution and conversion time. The windowed ADC technique which works on asynchronous sampling is widely used because of its high resolution [20]. The reference signal is compared with the ADC output to get the error signal. The error signal is processed by the digital controller. Digital PID controller is one of the most common controller used in power converter circuits. The parallel form of discrete PID can be represented as

$$G_c(z) = K_p + \frac{K_i}{1 - z^{-1}} + K_d\left(1 - z^{-1}\right) \tag{18}$$

$$d(n) = d(n-1) + Ae(n) + Be(n-1) + Ce(n-2) \tag{19}$$

The desired duty cycle for the switch is calculated using the digital logic of digital pulse width modulation (DPWM) technique. For an accurate voltage regulation, DPWM should have a high resolution. The high resolution also avoids limit cycle oscillations during the steady state of the converter. According to the thumb rule of design of digital controller for switched mode power supply the resolution of DPWM is one bit higher than the resolution of ADC. Developing DPWM architecture is one of the critical part of digital controller design. A review of reported architecture of DPWM with emphasis on ASIC and FPGA implementation can be found in [21]. The gate pulses generated by DPWM are provided to the switch through appropriate driver and isolation circuits.

IV. Simulation Results and Discussions

In order to evaluate the performance of PCU in a fuel cell stack for a automotive application, simulation are performed using MATLAB-Simulink. Commercial fuel cell stack comes in different ratings, in this simulation setup fuel cell provides unregulated 12V DC output. A synchronous buck converter is considered which regulates the fuel cell stack voltage and steps down the input voltage to provide 3.3V DC (low power) to dedicated electronic appliances and processor load. The parameters of the converter are summarized in the following table.

TABLE I: Simulation Parameters

Number of fuel cell units	N	10
Voltage of fuel cell stack	V_{FC}	12 V
Input voltage to synchronous buck converter	V_{DC}	12 V
Reference voltage	V_o	3.3 V
Inductor	L	4.1 μH
Inductor Resistance	R_L	80 mΩ
Capacitor	C	376 μF
ESR	R_C	5 mΩ
Load Resistance	R	1 Ω
Switching Frequency	f_{sw}	100 KHz
Sampling Time	f_s	1μs

Fig. 7 illustrates the output voltage of synchronous buck converter controlled using digital PI controller. As seen in the graph there is perfect load regulation. The corresponding load current and inductor current is also seen.

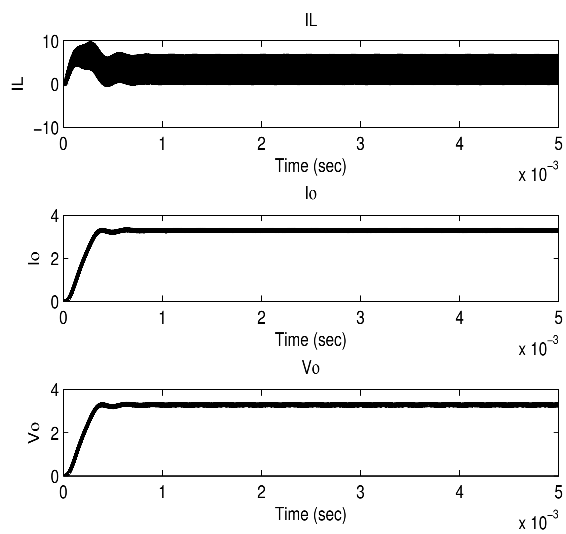

Fig. 7: Output voltage of synchronous buck converter (Set-point tracking)

To investigate the effect of step change in load to the output voltage, a step change in load current is simulated. The step change in load current occurs at 3ms. The corresponding output voltage and inductor current is shown in Fig. 8. It is seen from the graph that despite the variation in load current, the output voltage has very little effect in the range of ±1%. To investigate the effects of pulse or periodic change of load current in the converter output voltage, a periodically varying load current is simulated. The load current varies periodically at 0.5ms. From the simulation results it is shown that the load voltage has some transients (in the range of 0.7V). The corresponding output voltage and inductor current is shown in Fig. 9.

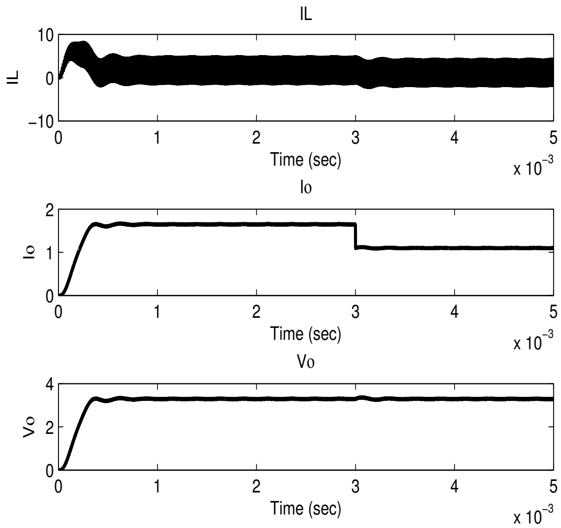

Fig. 8: Output voltage of synchronous buck converter during step change in load (Load disturbance rejection)

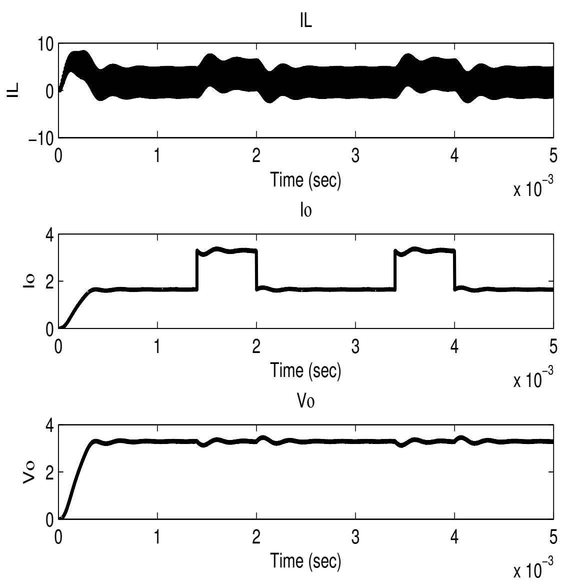

Fig. 9: Output voltage of synchronous buck converter during periodic step change in load (Load disturbance rejection)

There are basically two kinds of disturbances in the converter, i.e disturbance due to load current and disturbance due to source voltage. The effect of load current disturbance on the output voltage is discussed above. The input voltage disturbance is simulated and the effect of the disturbance on the output voltage is studied. Fig. 10 shows the sudden change of 2V for a period of 1ms in the input voltage. The corresponding output voltage has some transients (overshoot and undershoot in the range of 0.7V) in the output voltage.

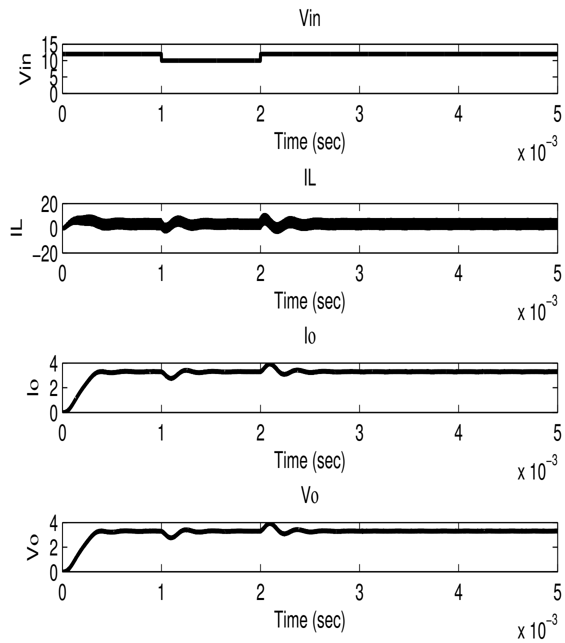

Fig. 10: Output voltage of synchronous buck converter during step change in input (disturbance rejection)

V. Conclusion

In this paper, a synchronous buck converter based PCU is developed for a PEMFC. The PCU regulates the unregulated voltage of fuel cell and steps down the voltage of fuel cell to 3.3V which is further used to provide power to low power applications of a transport vehicle. The fuel cell is an inherently slow system because of its thermodynamic equations. So power electronics engineers faces a real challenge to develop PCU for the fuel cell. This paper investigates the effect of rapid change of load on the output voltage of the converter. Different load changes (change in input voltage, step change in load and pulsating change in load) are simulated and the subsequent transient response of the output voltage are studied. From the simulation results, it is found out that the digital PI controller

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