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Robust Boost Converter for Fuel Cell Application using Model Adapative Reference Control Design

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Abstract—ICT engine uses hydrocarbon oil as a fuel for its propulsion. This petroleum product is going to be finished within next few decades, as well as they emits greenhouse gasses and air pollutant which are responsible for global warming. Efficiency of petroleum based automobiles is also low. The issues of the conventional automobiles can be overcome by replacing it with hybrid electric vehicle. A hybrid electric vehicle uses fuel cell as primary source of energy. For this application there is requirement of high power dc-dc boost converter, which step-up load voltage as per as vehicle requirements. This paper introduces a model adaptive reference control design for dc-dc boost converter for fuel cell system. The stability of the proposed controller is always guaranteed. The testing of the designed controller verified by simulating whole system in MATLAB/Simulink 2013a.

Keywords— fuel cell; boost converter; pi controller ; model adaptive reference control design(MRAC).

Internal combustion engine uses petroleum product like petrol and diesel for its rotation system which produces greenhouse gasses as well as high emission resulting in global warming. Electric vehicle is a vehicle that uses electrical energy for rotation system. Use of electrical energy makes automobile industry pollution free.

Electric vehicle uses energy source such as battery, ultra-capacitor, Fuel cell (FC) for propulsion system. FC is unable to respond alone in sudden change in load that is why an ultra-capacitor is required for propulsion system during transient condition. Ultra-capacitor also charges during regenerative braking of motor. As FC is conventionally used as primary source of energy for hybrid electric vehicle so it is required to handle FC management for electric vehicle [1]-[3].

FC is a pollution free source of electrical energy as it never produces any harmful gases. Normally application of FC in electric vehicle as primary source, which can supply uninterrupted power to propulsion system. FC will continuously provide energy on change in demand continuously until the fuel and oxidants are provided [4].

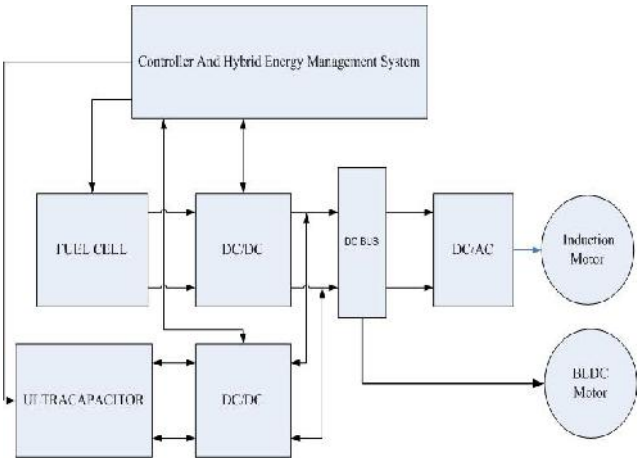

Fig. 1. Block diagram of FC based hybrid electric vehicle.

Some different types of FC are already in market like Alkaline Electrolyte FC (AEFC), Molten Carbonate FC (MCFC) Direct methanol FC (DMFC), Phosphoric Acid FC (PAFC), solid oxide FC (SOFC) and Proton Exchange Membrane FC (PEMFC). Out of all these fuel cell PEMFC is best and effective FC for conversion of energy in electric vehicle. PEMFC's has better efficiency, low

operating temperature (50^o-100^o) and it never produces any dangerous gasses so it is eco-friendly in nature. PEMFC never offer fast response due to slow electrodynamics and chemical reaction in it, therefore it cannot reply to unforeseen modification in load [4]-[6]. Another disadvantage is Starvation development. Lack of Fuel or oxygen cell can cause voltage drop during unforeseen energy demand. [7]-[9].

As fuel cell is primary energy source; so it have to provide regular power to propulsion system that is why it is necessary to regulate the output voltage of FC. As voltage profile of FC is low, a quadratic boost converter is interfaced with the FC and dc bus. A control technique is designed for boost converter to maintain or regulate dc bus voltage in proportion to load change. This paper introduces a model adaptive reference control design for boost converter which maintain constant voltage at dc bus during transient condition or during load variation. The stability of the closed loop system is always guaranteed. The typical block diagram of hybrid electric vehicle is shown in fig. 1.

I. ELECTRIC POWER MANAGEMENT SYSTEM

The hybrid electric vehicle consists of FC having efficient and less emission of dangerous gasses comparatively to different supply of oil energy. Generally hydrogen and air are used as fuel for FC; it will help to decrease the utilization of typical (non-renewable) source of energy. A boost converter is interfaced with FC and dc bus. Input control management for FC is extremely required as load changes [10]-[11]. Input of FC is controlled with the help of a PI controller as shown in Fig.2.

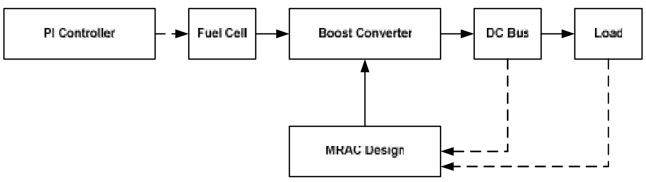

Fig. 2. Power management for fuel cell

The control technique is simulated in MATLAB/Simulink 2013a.The desired value of the fuel cell current is regulating the input of the fuel cell (hydrogen and air) with the help of PI controller. This PI controller control the amount of hydrogen and air accordingly desired fuel cell current. The model reference adaptive control design controls the output voltage of the boost converter at dc bus (100 V) during transient condition or variation in load demand.

II. MODELLING OF QUADRATIC BOOST CONVERTER

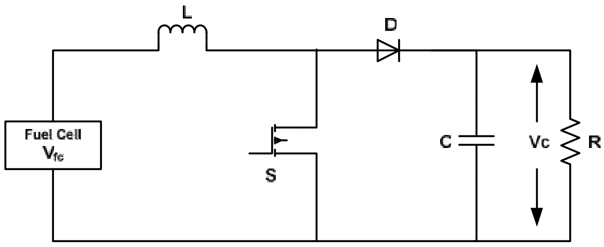

Fig. 3. Model of boost converter

The typical diagram of boost converter is shown in figure 3, converter uses a diode, an inductor and an IGBT switch (S) which is controlled by an input signal (u). In this boost converter the controlled signal (u) is given to the switch in a way that when u=0 then IGBT is OFF and when u=1 then IGBT is ON.

$$\frac{di_L}{dt} = -(1-u)\frac{V_c}{L} + \frac{V_{fc}}{L} \quad (1)$$

$$\frac{dv_c}{dt} = (1-u)\frac{i_L}{C} - \frac{V_c}{RC} \quad (2)$$

Let $I_L=X_1$ and $V_c=X_2$, the state equation becomes as

$$\dot{x}_1 = -(1-u)\frac{1}{L}x_2 + \frac{V_{fc}}{L} \quad (3)$$

$$\dot{x}_2 = (1-u)\frac{1}{C}x_1 - \frac{1}{RC}x_2 \quad (4)$$

Now we know that

$$X = AX + BU \quad (5)$$

$$\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{x_2}{L} \\ \frac{-x_1}{C} \end{bmatrix} u \quad (6)$$

Where I_L is the inductor current, V_c is output voltage and V_{fc} is the fuel cell voltage. The average value of the inductor current never drops to zero, due to the load variation. When load is change during transient condition voltage drop occurs at the dc bus of system so it is necessary to regulate dc bus voltage with the help of close loop system.

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III. CONTROLLER FOR CIRCUIT(MODEL REFENCE ADAPTIVE CONTROL DESIGN)

The transfer function of the converter is given as[12]-[13]-[14]:

$$G_p(s) = \frac{G_{pdo}(1 - \frac{1}{\mu_z}s)}{(1 + \frac{1}{p_1}s)(1 + \frac{1}{p_2}s)}$$

(7)

Where

$$G_{pdo} = \frac{\mu_0^2 G_{do}}{\mu_z}, \qquad G_{do} = \frac{V_o}{DD'},$$

$$D' = (1 - D)$$

$$V_o = -\frac{D}{D'}V_1, \qquad \mu_o = \frac{D'}{\sqrt{L_2 C_{dc}}},$$

$$\mu_z = \frac{R_2 D'^2}{L_{dc} D}$$

$$Q = R_L D' \sqrt{\frac{C_{dc}}{L_2}},$$

$$p_1, p_2 = \frac{\mu_0 \pm j\mu_0\sqrt{4Q^2 - 1}}{2Q}$$

Converter has two pole and one zero in transfer function located in the left half of s-plane and right half of s-plane. A digital control methodology is proposed where converter transfer and ZOH of the circuit is combined.

$$G_{hop}(s) \sqcup G_{ho}(s)G_p(s) \qquad (8)$$

Taking z- transform and we have

$$G_{hop}(z) = (1 - z^{-1})Z\left\{\frac{G_{pdo}(1 - \frac{1}{\mu_z}s)}{(1 + \frac{1}{p_1}s)(1 + \frac{1}{p_2}s)}\right\} \qquad (10)$$

The above combination has the following form with Q>0.5, as follow

$$G_{hop}(z) = \frac{b_1 z + b_2}{z^2 + a_0 z + a_1} \qquad (11)$$

Above equation can also be written as

$$G_{hop}(d) = \frac{dB(d)}{A(d)} = \frac{d(b_1 + b_2 d)}{1 + a_0 d + a_1 d^2} \qquad (12)$$

Where $d=z^{-1}$. In figure 4 control scheme is proposed for the converter, where *dG(d)/F(d)* is the reference model.

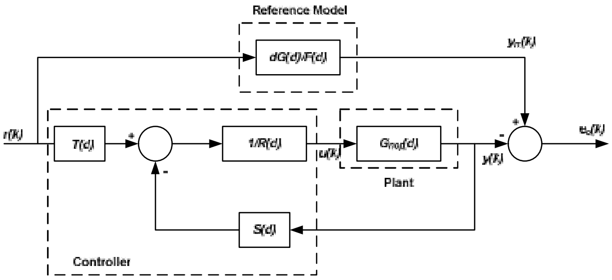

Fig. 4. The proposed control scheme for the converter

The relationship between input and output can be written as

$$A(d)y(k) = dB(d)u(k) \qquad (13)$$

A(d) and *B(d)* can be factorize as

$$A(d) = A_+(d)A_-(d) \qquad (14)$$

$$B(d) = B_+(d)B_-(d) \qquad (15)$$

$$G_{hop}(d) = \frac{dB(d)}{A(d)} = \frac{dB_-(d)}{A_+(d)} \qquad (16)$$

The linear controller for the step up converter can be proposed as

$$R(d)u(k) = -S(d)y(k) + T(d)r(k) \qquad (17)$$

R(d), *T(d)* and *S(d)* are the polynomials. *r(k)* is the reference input, relation between r(k) and u(k) can be derived from equation (13) and (17) as

$$y(k) = dB_-(d)L(d)r(k) \qquad (18)$$

Where

$$L(d) = \frac{T(d)}{[R(d)A(d) + dS(d)B(d)]} \qquad (19)$$

For the reference model input output relationship for stable system can be written

$$y_m(k) = \frac{dG(d)}{F(d)}r(k) \qquad (20)$$

G(d) and *F(d)* are coprime at F(0)=1. *G(d)* and *F(d)* can be assumed as because of the second order system.

$$F(d) = 1 + f_1 d + f_2 d^2 \qquad (21)$$

$$G(d) = g_1 + g_2 d + g_3 d^2 \qquad (22)$$

We have to design *R(d)*, *S(d)* and *T(d)* such that the following cost function is minimized for model adaptive reference controller

$$J = \left\| E(d) + \sim dU(d) \right\|_2 \qquad (23)$$

Where α≥0 is weighting scalar, *E(d)* is the transfer function of $e_o(k)$, *U(d)* is the transfer function of *u(k)*.

From figure 4

$$E(d) = d\left[\frac{G(d)}{F(d)} - B\_(d)L(d)\right] \times \frac{N(d)}{D(d)} \qquad (24)$$

$$U(d) = \left[A(d)L(d)\right] \times \frac{N(d)}{D(d)} \qquad (25)$$

Where $\frac{N(d)}{D(d)} = \frac{r_m}{(1-d)}$ is the transfer function of step input *r(k)*, r_m is the amplitude of input.

Put the value of (24) and (25) in (23)

$$J = \left\| d\left[\frac{G(d)}{F(d)} - B\_(d)L(d) + \sim A(d)L(d) \times \frac{r_m}{1-d}\right] \right\|_2$$

(26)

$$J = r_m \left\| \left\{ \frac{G(d)}{F(d)} - \left[B\_(d) - \sim A(d)\right] L(d) \right\} \times \frac{1}{1-d} \right\|_2$$

(27)

Let $C(d) = B\_(d) - \sim A(d)$ (28)

and *C(d)* can be factorized as

$C(d) = C_+(d) C\_(d)$ also $\bar{C}(d) = \bar{C}_+(d)\bar{C}\_(d)$

Put (28) into (27)

$$J = r_m \left\| \left[\frac{G(d)}{F(d)} - C(d)L(d)\right] \times \frac{1}{1-d} \right\|_2 \qquad (29)$$

$$J = r_m \left\| \left[\frac{G(d)\bar{C}\_(d)}{F(d)(1-d)C\_(d)} - \frac{C_+(d)\bar{C}\_(d)L(d)}{(1-d)}\right] \right\|_2$$

(30)

$$\frac{G(d)\bar{C}\_(d)}{F(d)(1-d)C\_(d)} = \frac{F_c(d)}{C\_(d)} + \frac{F_o(d)}{F(d)(1-d)}$$

(31)

Multiplying both sides of equation (31) by, we get $F(d)(1-d)C\_(d)$

$$G(d)\bar{C}\_(d) = F_c(d)F(d)(1-d) + F_o(d)C\_(d)$$

(32)

Du to *F(d)(1-d)* and *C_(d)* are coprime so there is a unique polynomials $F_c(d)$ and $F_o(d)$

$$F_c(d) = f_{c,0} \qquad (33)$$

$$F_o(d) = f_{o,0} + f_{o,1}d + f_{o,2}d^2 \qquad (34)$$

Fo(d) can be calculated as

$$F_o(z_i)C\_(z_i) - G(z_i)C\_(z_i) = 0 \quad i=1,2,3.. \qquad (35)$$

Above can also be written as

$$\begin{bmatrix} 1 & z_1 & z_1^2 \\ 1 & z_2 & z_2^2 \\ 1 & z_3 & z_3^2 \end{bmatrix} \begin{bmatrix} f_{o,0} \\ f_{o,1} \\ f_{o,2} \end{bmatrix} = \begin{bmatrix} W(z_1) \\ W(z_2) \\ W(z_3) \end{bmatrix} \qquad (36)$$

From the above calculation we get

$$J^2 = r_m^2 \left\| \frac{F_c(d)}{C\_(d)} + \frac{F_o(d)}{F(d)(1-d)} - \frac{\bar{C}\_(d)C_+(d)L(d)}{(1-d)} \right\|_2^2$$

(37)

By orthogonally

$$J^2 = r_m^2 \left\| \frac{F_c(d)}{C\_(d)} \right\| + r_m^2 \left\| \frac{F_o(d)}{F(d)(1-d)} - \frac{L(d)\bar{C}\_(d)C_+(d)}{(1-d)} \right\|_2^2 \geq r_m^2 \left\| \frac{F_c(d)}{C\_(d)} \right\|_2^2$$

(38)

By solving above equation $L_o(d)$ can be determined as

$$L_o(d) = \frac{F_o(d)}{F(d)C_+(d)\bar{C}\_(d)} \qquad (39)$$

By comparing (39) and (19)

$$T(d) = F_o(d) \qquad (40)$$

R(d) and *S(d)* can be determined by following equation

$$R(d)A(d) + dS(d)B(d) = F(d)C_+(d)\bar{C}\_(d) \qquad (41)$$

$$R(d) = r_o + r_1 d + r_2 d^2 \qquad (42)$$

$$S(d) = s_o + s_1 d \qquad (43)$$

$$(r_o + r_1 d + r_2 d^2)(1 + a_o d + a_1 d^2) + (s_o + s_1 d)(b_1 d + b_2 d^2)$$
$$= (1 + f_1 d + f_2 d^2)(1 + c_1 d)(c_2 + c_3 d)$$

(44)

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$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ a_o & 1 & 0 & b_1 & 0 \\ a_1 & a_o & 1 & b_2 & b_1 \\ 0 & a_1 & a_o & 0 & b_2 \\ 0 & 0 & a_1 & 0 & 0 \end{bmatrix} \begin{bmatrix} r_o \\ r_1 \\ r_2 \\ s_o \\ s_1 \end{bmatrix} = \begin{bmatrix} c_2 \\ c_2(f_1+c_1)+c_3 \\ c_2(f_1c_1+f_2)+c_3(f_1+c_{1)} \\ c_2 f_2 c_1 + c_3(f_1c_1+f_2) \\ c_3 f_2 c_1 \end{bmatrix} \quad (45)$$

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ a_o & 1 & 0 & b_1 & 0 \\ a_1 & a_o & 1 & b_2 & b_1 \\ 0 & a_1 & a_o & 0 & b_2 \\ 0 & 0 & a_1 & 0 & 0 \end{bmatrix} \qquad H = \begin{bmatrix} r_o \\ r_1 \\ r_2 \\ s_o \\ s_1 \end{bmatrix}$$

$$K = \begin{bmatrix} c_2 \\ c_2(f_1+c_1)+c_3 \\ c_2(f_1c_1+f_2)+c_3(f_1+c_{1)} \\ c_2 f_2 c_1 + c_3(f_1c_1+f_2) \\ c_3 f_2 c_1 \end{bmatrix}$$

Matrix (45) can be rewritten as

$$EH = K \quad (46)$$

$$H = E^{-1}K \quad (47)$$

Coefficient of polynomial *R(d)* & *S(d)* & i.e. r_o, r_1, r_2 & s_o, s_1 respectively can be calculated by solving the vector H.

TABLE I

FC PARMETERS

Parameter	Rating
FC power	6 KW
Nominal operating voltage	45 V
Nominal operating current	134 A
Number of cell	65
Nominal stack efficiency	55%
Operating temperature	65 Celsius
Nominal air flow rate	300
Nominal fuel supply pressure	1.5 bar
Nominal air supply pressure	1.0 bar
Nominal composition of H_2	99.50%
Nominal composition O_2	21%
Nominal H_2O	1%

TABLE II

MRAC PARMETERS

Parameter	Rating
r_o	18.169
r_1	.314
r_2	$2.18*10^{-3}$
s_o	-0.616
s_1	-5986.98
F(d)	1, 0.175, -0.075

IV. RESULTS AND SIMULATION

The FC system with quadratic boost converter is simulated and performance verified in MATLAB/Simulink 2013a. The goal of the controller is to maintain constant 100 volt at dc bus during transient or load variation conditions.

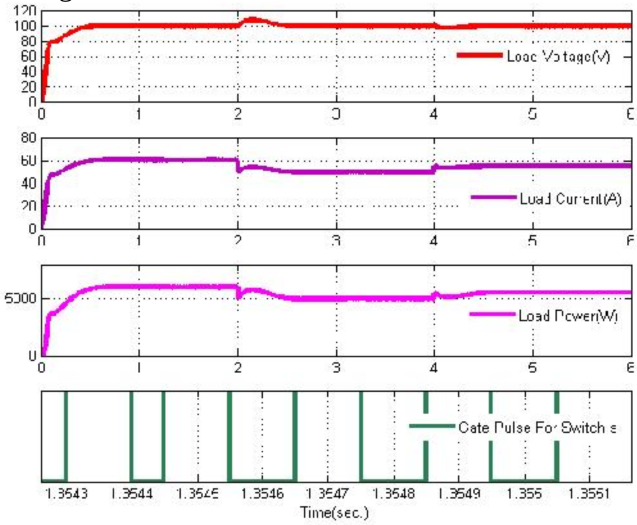

Fig. 4. Load voltage, current, power, gate pulse for switch S

The load voltage or dc bus voltage, load current, load power and gate pulse for switch S are shown fig. 4. In the first interval of time from 0-2 sec load demand is 6 KW. During this interval fuel start to supply power to the dc bus through quadratic boost converter. At the time of 1 sec fuel cell is capable to supply required power of 6 KW to dc bus or load. The voltage level at dc bus is 100 V which is remaining constant up to 2 sec. The corresponding current is 60 A.

In the second time interval of 2-4 sec the load demand at dc bus changes from 6 KW to 5 KW. Due

to change in load there is a fluctuation in voltage at dc bus. At the time of 2.49 sec oscillation are damped out and dc bus maintaining constant 100 V at dc bus. The fuel cell supply 5 KW power to dc bus and corresponding current through load is 50 A.

Similarly in the third time interval of 4-6 sec load demand changes from 5 KW to 5.5 KW. Again there is a fluctuation occurs in voltage at dc bus; these fluctuation are damped out at the time of 4.49 sec and the voltage level at dc is 100 V. The demanded power of 5.5 KW supplies by the fuel cell and corresponding current is 55 A.

The fuel cell voltage, fuel cell or current through inductance L1, fuel cell power and stack efficiency of fuel cell are shown in fig. 5.

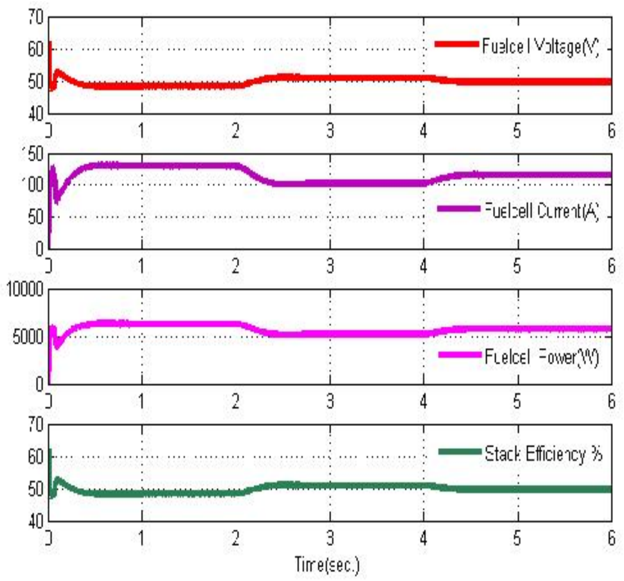

Fig. 5. Fuel cell voltage, current, power and stack efficiency

V. CONCLUSION

FC is pollution free supply of energy as it utilizes hydrogen and air for its fuel. Output power of FC depends upon input fuel (air and hydrogen) supplied. The fuel of the FC is controlled by using PI controller and model reference adaptive control design for boost converter designed to regulate the load voltage. System will remains in stable region always. It is clear from the results that fuel cell current is regulating by PI controller and during load variation the dc bus voltage fluctuate but after some time oscillation are damped out and voltage at dc bus remaining constant of 100 V. It can be concluded that dynamic performance of the system improves, resulting better performance and stability during transient conditions as required for automobile application.

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