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Adaptive Control of Interleaved Boost Converter for Fuel Cell Energy

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***Abstract*—The problem of controlling interleaved dc-dc boost converters (IBC) is addressed for fuel cell (FC) energy generation system. The aim is to ensure output voltage regulation and perfect current sharing, between different branches, despite changes of the converter power load. The problem is dealt with using an adaptive control strategy, based on large-signal nonlinear model of the whole FC-IBC system, involving online estimation of the uncertain load. The difficulty of the present adaptive control problem lies in the fact that the uncertain load comes not only in the model but also in the current reference signal. Therefore, the perfect current sharing requirement cannot be met unless the online load estimate converges to its true value. It is formally shown that the estimate actually converges to its true value ensuring the achievement of all desired control performances.**

I. INTRODUCTION

The world's demand for electrical energy has been increasing steadily and is expected to continue growing, while the enormous part of electrical energy in most countries is generated by conventional sources of energy. The ongoing global climate change and the diminishing fossil fuel resources make the global energy trends more complex. Therefore, the penetration of distributed generation (DG) (see Fig.1) at medium and low voltages is expected to play a key role in future power systems. Implementing distributed energy resources (DER), e.g. wind turbines, photovoltaic panels, gas turbines and fuel cells, into interconnected grids could be part of the solution to meet the rising electricity demand ([1], [14]). DG technologies are currently being improved through several research projects toward the development of smart grids. Mini-grids, including DG, are being installed in rural areas of industrial as well as developing countries. As the rural settlements of these countries are scattered, power systems in these areas depend on the available energy sources. Among all renewable energies, hydrogen and fuel-cell are seen as the most promising, thanks to the very high efficiency in converting the chemical energy into electrical energy and low emissions production ([2], [3],[4]).

DERs need interfacing units to provide the necessary crossing point to the grid. The core of these interfacing units is a power electronic converter that is resorted not only for complying with interfacing principle requirements but also for ensuring various useful functions. In this paper, the interconnection of fuel-cell generators to a DC bus via boost converters is investigated (Fig.1). Fuel cells have been resorted in various industry applications ranging from low power (50W) to high power (250kW). It is clear that high efficiency fuel cell systems must involve high performance dc-dc converters. Interleaved dc-dc boost converters (IBC) do meet this requirement [9]. Specifically, an IBC consists of *N*-paralleled boost converters that generate power according to the interleaving technique [7]. The benefit of interleaving is to reduce the inductor current in the different phases making possible the reduction of inductor size ([10], [8]). The larger the number of phases is, the more important the inductor size reduction. The number of phases is also crucial because the ripples (in the converter input current and output voltage) are inversely proportional to that number, while the converter manufacturing cost is proportional to it. Therefore, the phase number is a compromise of the above considerations [11]. The IBC has recently been studied within various applications, e.g. power factor correction circuits, photovoltaic arrays, fuel cell systems and others ([5], [6]).

The present paper is focusing on the problem of controlling IBCs within FC based power generation systems (Fig. 1). The control objective is twofold (Fig. 2): (i) ensuring a tight regulation of the converter output voltage; (ii) guaranteeing a perfect current sharing between the converter phases. These objectives must be achieved despite the uncertain and changing converter power load. Given the uncertain nature of the load, an adaptive control solution is developed using the Lyapunov design technique, based on large-signal nonlinear model of the whole FC-IBC system. But, unlike usual adaptive controllers, the present one involves reference signals (namely, those of the phase currents) that are functions of the online load estimate. Therefore, the requirement of perfect current sharing cannot be met unless the online load estimate converges to its true value. It is formally shown that the load estimate actually converges to its true value and, consequently, all desired control performances are asymptotically achieved.

The paper is organized as follows: in Section 2, the IBC for fuel cell generators is described and modeled; Sections 3 is

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devoted to controller design and closed-loop analysis; the controller tracking performances are illustrated by numerical simulation in Section 4.

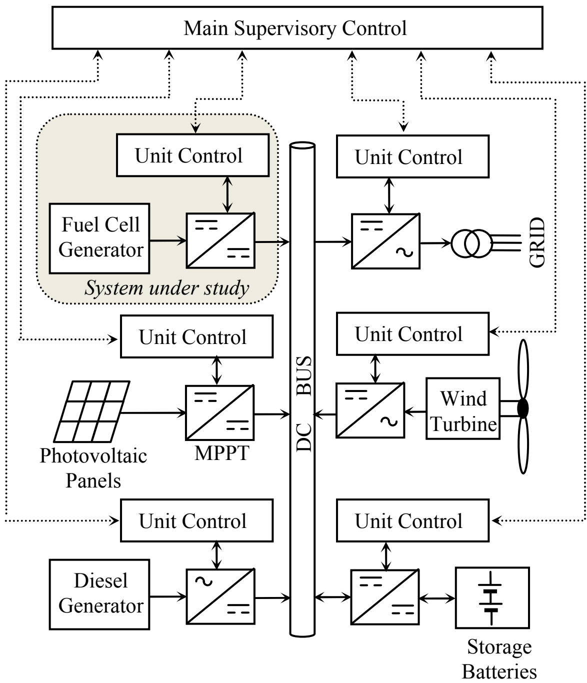

Fig.1: Control architecture in distributed energy resources

II. Presentation And Modeling Of Fuel Cell IBC System

Figure 2 shows the fuel cell interleaved boost converter (FC-IBC) system. It consists of an FC generator, N interleaved boost converters connected in parallel, sharing a common load represented by a pure resistance R representing the power in DC bus load. This resistance is unknown as it depends on the load power demand. This uncertainty constitutes a major aspect of the control problem.

A. Operational principles of interleaved boost converter principles

The number of inductors and switches in the IBC is the same as the number of phase. But, there is only one common capacitor (Fig. 2). The current supplied by the fuel cell goes through N separate paths reducing the stress on IBC. Each path is controlled using interleaved PWM. The total current ripple is therefore reduced compared to the current ripple of each converter, reducing the stress on fuel cell. For a given current ripple, the interleaved channels allow much smaller and lighter inductances.

B. Fuel cell V-I polarization curve

A real-life fuel-cell $V-I$ polarization curve is shown in Fig. 3. It is seen that the fuel-cell voltage is a decreasing function of load current density. This voltage decrease is caused by three major losses [12]: the activation loss, the Ohmic losses, the gas transport losses.

The $V-I$ polarization curve of Fig.3 is presently used for simulation purpose.

Fig. 3 shows a large difference between the minimal and maximal voltage of the FC generator. Then, the nonlinearity of this characteristic must be accounted for in control design. To this end, the $V-I$ curve of Fig.3 is given a polynomial approximation using MATLAB *polyfit* function. The obtained approximation is:

$$v_{in} = \sum_{n=0}^{7} p_n (i_T)^n \overset{def}{=} \varphi(i_T) \qquad (1)$$

where coefficients p_n $(n = 0,...,7)$ are gathered in Table 1.

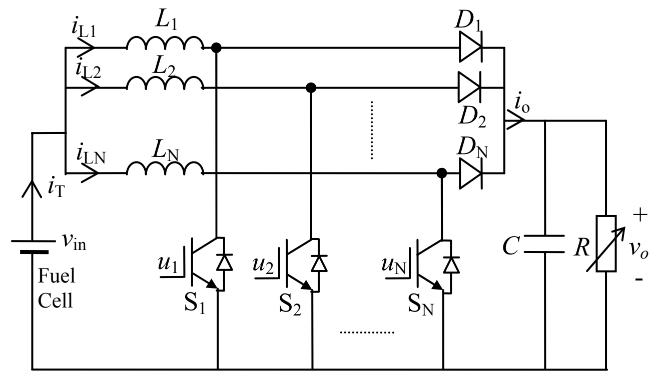

Fig.2: FC-IBC system

TABLE 1: POLYNOMIAL COEFFICIENTS

p_0	p_1	p_2	p_3
10^3	−35,9	2.45	−0.09
p_4	p_5	p_6	p_7
$1.8\text{x}10^{-3}$	$-2\text{x}10^{-5}$	$1.14\text{x}10^{-7}$	$-2.64\text{x}10^{-10}$

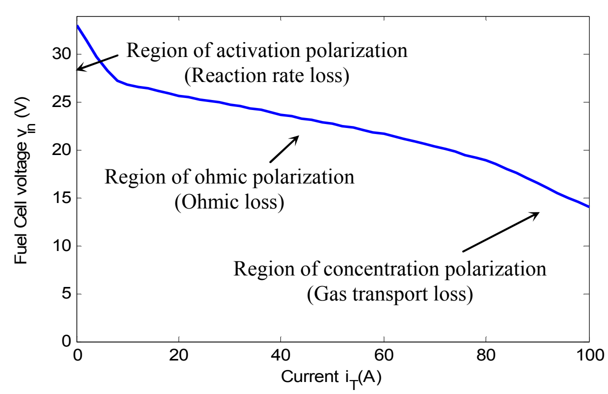

Fig. 3. A real-life fuel-cell $V-I$ polarization curve, which is used in the present study

C. Interleaved Boost Converter Modeling

In the IBC of Fig. 2, each inductance L_k $(k = 1 \ldots N)$ presents an equivalent series resistance (ESR) r_{Lk}. The control input u_k of the k^{th} boost converter is an interleaved PWM signal taking values in the set $\{0,1\}$. The inductances are supposed to be identical:

$$\begin{cases} L_1 = L_2 = ... = L_N = L \\ r_{L1} = r_{L2} = ... = r_{LN} = r_L \end{cases} \quad (2)$$

Applying the Kirchoff's laws, successively with $u_k = 1$ and $u_k = 0$, to the circuit of Fig. 2 one obtains the following instantaneous model of the k^{th} boost converter:

$$\frac{di_{Lk}}{dt} = -(1-u_k)\frac{v_o}{L} - \frac{r_L}{L} i_{Lk} + \frac{\varphi(i_T)}{L} \quad (3a)$$

$$\frac{dv_o}{dt} = \frac{1}{C} i_T - \frac{1}{RC} v_0 - \frac{1}{C}\sum_{j=1}^{N} u_j i_{Lj} \quad (3b)$$

with N the number of parallel paths and

$$i_T = \sum_{k=1}^{N} i_{Lk} \quad (3c)$$

where equation (1) was used to get (3a). This model is useful for building a simulator of the circuit. But, it is not convenient not for control design, because it involves a binary control inputs i.e. u_k. For control design purpose, it is more convenient to consider the following averaged model [13]

$$\dot{x}_{1k} = -(1-\mu_k)\frac{1}{L} x_2 - \frac{r_L}{L} x_{1k} + \frac{\varphi(x_T)}{L} \quad (4a)$$

$$\dot{x}_2 = \frac{1}{C} x_T - \frac{1}{RC} x_2 - \frac{1}{C}\sum_{j=1}^{N} \mu_j x_{1j} \quad (4b)$$

$$x_T = \sum_{k=1}^{N} x_{1k} \quad (4c)$$

where x_{1k} denotes the average value of the current i_{Lk}; x_2 is the average value of the output voltage v_o; x_T is the average value of the input current i_T; μ_k is the average value of the binary control input u_k. All variables averaging are performed over switching periods. Consequently, the quantity μ_k, commonly called duty ratio, varies continuously in the interval $[0\,1]$ and acts as the input control signal for the k^{th} PWM IBC module.

III. Adaptive Controller Design and Analysis

A. Adaptive Control Design

In this study, the load resistance R in model (4) is unknown and subject to infrequent jumps. The load jumps result from the changes of the (active power of the) loads connected to the grid. To cope with such model uncertainty the controller will be given a learning capacity. Specifically, the controller includes an on-line estimator of the unknown parameter:

$$\frac{1}{R} = \theta \quad (5)$$

Another feature of the controller is to account for the nonlinearity of the fuel cell characteristic represented by (1). The control objectives of the controller to be designed are: (i) asymptotic stability of the closed loop system; (ii) perfect regulation of the voltage v_o in presence of load variations; (iii) proper current sharing between the IBC paths; (iv) good estimation of load resistance, this requirement will be justified later in this subsection.

The second control objective amounts to enforce the output voltage x_2 to track a given constant reference signal $V_d > \min(\varphi(i_T)$ despite the system parameter uncertainties. It shown in many places [15] that boost converter dynamics are non-minimum phase. Consequently, the output voltage regulation objective is not achievable for arbitrary shape reference signals. This issue is commonly coped with by reformulating the voltage tracking objective as a current tracking problem. Accordingly, the current i_T will be enforced to track a reference signal x_{Td} that is chosen so that if (in steady state) $i_T = x_{Td}$ then $v_o = V_d$. Power conservation implies that x_{Td} is related to V_d by the relation:

$$x_{Td} = \frac{V_d^2}{R\varphi(x_{Td})} \overset{def}{=} \frac{V_d^2}{\varphi(x_{Td})}\theta \quad (6)$$

The last equation shows that the reference current signal x_{Td} *depends on the uncertain parameter* θ. This dependence makes the present adaptive control problem a not standard one [16]. As the true value of θ is unknown and time-varying, it is logical to substitute to that value an (online) estimate $\hat{\theta}$; the adaptive law providing this estimate has yet to be determined. Accordingly, the current i_T will have to track the estimated reference signal $\hat{x}_{Td}$ defined as follows:

$$\hat{x}_{Td} = \frac{V_d^2}{\varphi(x_T)}\hat{\theta} \quad (7)$$

But, it is clear that for the initial output voltage tracking objective to be achieved, the parameter estimation error,

$$\tilde{\theta} = \theta - \hat{\theta} \quad (8)$$

must converge to zero.

Let us first focus on the current tracking objective. Keeping in mind the requirement of proper current sharing, the following tracking error is introduced:

$$z_{1k} = x_{1k} - \frac{\hat{x}_{Td}}{N} = x_{1k} - \frac{V_d^2}{N\varphi(x_T)}\hat{\theta}; \quad (k=1\ldots N) \quad (9)$$

It is clear that if these errors vanish asymptotically then i_T will converge (in average) to x_{Td}. To this end, the dynamics of z_{1k} have to be clearly defined. Deriving (9), it follows from (4a-b) that:

$$\dot{z}_{1k} = -(1-\mu_k)\frac{x_2}{L} - \frac{r_L}{L}x_{1k} + \frac{\varphi(x_T)}{L} - \frac{V_d^2}{N\varphi(x_T)}\dot{\hat{\theta}}$$

$$+\frac{V_d^2}{N\varphi(x_T)^2}\hat{\theta}\phi_1(x_T)\left[-\frac{Nx_2}{L} - \frac{r_L}{L}x_T + \frac{N\varphi(x_T)}{L} + \frac{x_2}{L}\sum_{k=1}^{N}\mu_k\right] \quad (10)$$

with

$$\phi_1(x_T) = \frac{d\varphi(x_T)}{dx_T} \quad (11)$$

To obtain control laws for the signals μ_K (that make the errors $\{z_{1k}, k = 1,...,N\}$ vanish asymptotically), we consider the following Lyapunov function candidate:

$$V_1 = \frac{1}{2}\sum_{k=1}^{N} z_{1k}^2 \quad (12)$$

It is readily seen that the time derivative of this function is:

$$\dot{V}_1 = \sum_{k=1}^{N} z_{1k}\dot{z}_{1k} \quad (13)$$

Equation (13) shows that the equilibrium $\{z_{1k} = 0,\ k = 1,...,N\}$ is globally asymptotically stable provided that:

$$\dot{z}_{1k} = -c_1 z_{1k} \quad (14)$$

where $c_1 > 0$ is a design parameter. Then, combining (10) and (14) one gets the following control law μ_K for the k^{th} module:

$$\mu_k = \frac{1}{x_2}\left\{-Lc_1 z_{1k} + x_2 + r_L x_{1k} - \varphi(x_T) + \frac{LV_d^2}{N\varphi(x_T)}\dot{\hat{\theta}}\right.$$

$$\left. +\frac{V_d^2}{N\varphi(x_T)^2}\hat{\theta}\phi_1(x_T)\left(Nx_2 + r_L x_T - N\varphi(x_T) - x_2\sum_{k=1}^{N}\mu_k\right)\right\} \quad (15)$$

The control law (15) involves the adaptation law $\dot{\hat{\theta}}$ and the estimated parameter $\hat{\theta}$. The second step of regulator design is then to elaborate an appropriate adaptation law for $\hat{\theta}$, so that the estimator error $\tilde{\theta}$ converges to zero. Presently, it is crucial that the estimated parameter $\hat{\theta}$ converge to its (unknown) true value θ because this is necessary for $\hat{x}_{Td}$ to converge to its desired reference x_{Td} and this in turn is necessary for the output voltage v_o to converge to its desired reference value V_d. To determine an adaptive law for $\hat{\theta}$, let equation (4b) be rewritten as follows

$$x_2 = \alpha_1 - \theta\psi \quad (16a)$$

where

$$\alpha_1 = \frac{1}{s+c_2}\left\{\frac{x_T}{C} + c_2 x_2 - \frac{1}{C}\sum_{j=1}^{N}\mu_j x_{1j}\right\} \quad (16b)$$

$$\psi = \frac{1}{s+c_2}\left(\frac{x_2}{C}\right) \quad (16c)$$

where $c_2 > 0$ is a design parameter and s refers to the time-derivative operator. Since the unknown parameter θ comes linearly in (16a), the following gradient adaptive law can be used to get online estimate of that parameter:

$$\dot{\hat{\theta}} = -\gamma\psi e \quad (17)$$

where $\gamma > 0$ is any positive real gain and e is the estimation error defined by:

$$e = x_2 - \alpha_1 + \hat{\theta}\psi \quad (18)$$

In view of (8) and (16a), this can be rewritten as follows (whenever θ is constant):

$$e = -\tilde{\theta}\psi \quad (19)$$

The adaptive controller thus designed includes the nonlinear control law (15) and the adaptive law (17).

B. *Stability analysis*

Let us first analyze the adaptive law (17).

Proposition 1. Consider the adaptive estimation algorithm (17) applied to the subsystem (4b), also rewritten in the form of (16a).

1) If the unknown parameter θ is constant then, one has:

$\hat{\theta} \in L_\infty$; $e \in L_2$

2) Suppose further that the (average) output signal x_2 is persistently exciting in the sense that there are some real constants $\beta_0, T_0 > 0$ such that, $\forall t \geq 0$:

$$\int_t^{t+T_0} \psi^2(\tau)d\tau \geq \beta_0 T_0 \quad (20)$$

Then, the parameter estimation error $\tilde{\theta}$ vanishes exponentially fast □

Proof. 1) From (8) one has $\dot{\tilde{\theta}} = -\dot{\hat{\theta}}$ because θ is constant. Then, (17) and (19) give:

$$\dot{\tilde{\theta}} = -\gamma\psi^2\tilde{\theta} \quad (21)$$

The analysis of (21) is carried out considering the Lyapunov function candidate:

$$V_2 = \frac{\tilde{\theta}^2}{2\gamma} \quad (22)$$

The time-derivative V_2 along the solution of (21) is:

$$\dot{V}_2 = -\psi^2\tilde{\theta}^2 = -e^2 \leq 0 \quad (23)$$

It readily follows from (23) that V_2 is nonincreasing which implies that $\hat{\theta} \in L_\infty$, due to (22). Furthermore, one gets integrating both sides of (23):

$$\int_0^\infty e(t)^2\, dt = V_2(0) - V_2(\infty) \le V_2(0)$$

This shows that $e \in L_2$.

2) Integrating the first order differential equation (21), one gets:

$$\tilde{\theta}(t) = e^{-\gamma \int_0^t \psi^2(\tau) d\tau}\, \tilde{\theta}(0) \qquad (24)$$

The persistent excitation property (20) ensures that, for any integer k and any $t \in [kT_0 \ (k+1)T_0)$:

$$\int_0^t \psi^2(\tau) d\tau \ge \int_0^{kT_0} \psi^2(\tau) d\tau \ge \beta_0 k T_0 \ge \beta_0 (t - T_0)$$

which together with (24) implies that:

$$\left|\tilde{\theta}(t)\right| \le \left|\tilde{\theta}(0)\right| e^{\gamma \beta_0 T_0} e^{-\gamma \beta_0 t}$$

This establishes Part 2 of Proposition 1 ■

The main result of the paper is now summarized in the following theorem.

Theorem 1. Consider the closed-loop system consisting of a the fuel cell interleaved boost converter system represented by (4a-b), where the load resistor R is constant but unknown, and the controller composed of the adaptive control law (15) and the parameter update law (17). Then, in the same conditions as Proposition 1, one has:

1) The errors $z_{1k} = x_{1k} - \dfrac{x_{Td}}{N}$ converge to zero implying perfect asymptotic current sharing

2) The output voltage tracking error $\varepsilon = x_2 - V_d$ converges to zero, implying perfect asymptotic voltage regulation □

Proof. It has already been noticed that the control law (15), together with (10), implies (14). Substituting the right side of (14) to $\dot{z}_{1k}$ in (13) yields $\dot{V}_1 = -c_1 \sum_{k=1}^{N} z_{1k}^2 = -2c_1 V_1$. Hence, $V_1 = \frac{1}{2}\sum_{k=1}^{N} z_{1k}^2$ vanishes exponentially fast. This proves Part 1. Then, from (4c) and (9) it follows that $\hat{x}_{Td} - x_T$ vanishes exponentially fast which in turn implies the convergence of the steady-state error $x_2 - V_d$ to zero. This proves Part 2 of Theorem 1 ■

IV. Simulation Results

The performances of the proposed adaptive controller are now illustrated by simulation. The controlled system is a three phase interleaved boost converter with the characteristics of Table 2.

Fig. 5 describes the controller performances in presence of a constant reference $V_d = 48V$ (which represents the DC bus voltage) and successive load resistance jumps. The jumps vary between 2.5Ω and 5Ω, corresponding power changes of 50% in the DC bus. It is seen that the control performances are satisfactory, despite the load resistor uncertainty. It is worth noting that such a good behavior is preserved when facing different variations of the load resistance. This result confirms a tight regulation under uncertainties. Fig. 6 shows that current sharing, between the interleaved inductor currents, is properly also well accomplished. Fig. 7 confirms the exact identification of the changing unknown parameter. Finally, Fig.8 shows a perfect interleaving between inductor currents.

TABLE 2: PARAMETERS OF THE INTERLEAVED BOOST CONVERTER

Parameter	Symbol	Value
Number of phases	N	3
Inductance value	L	$2.2mH$
Inductance ESR	r_L	$20m\Omega$
Output Capacitor	C	$1200\mu F$
Switching frequency	f_s	$10kHz$

The experimental bench is described by Fig 6 and is simulated using the MATLAB software. The design control parameters are chosen as follows: $c_1 = 1\text{x}10^3$, $c_2 = 2\text{x}10^3$ and $\gamma = 2$. The resulting control performances are shown by Figs 7 to 10.

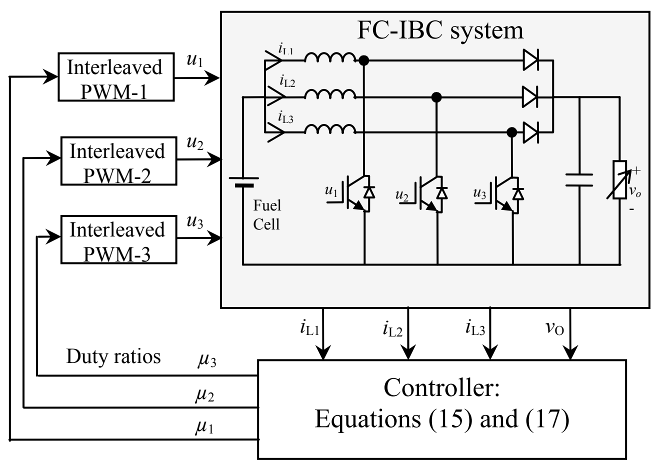

Fig.4: Experimental bench for FC-IBC control

V. Conclusion

The problem of controlling multiphase interleaved boost converters for fuel cell energy generation system has been considered. The regulator is obtained from the nonlinear average model (4) using adaptive controller. Using both formal analysis and simulation, it has been proven that the obtained adaptive regulator achieves the performances for which it was designed, namely:

(i) Perfect asymptotic output voltage regulation,

(ii) Excellent current sharing among modules, and
(iii) Good estimation of unknown parameter.

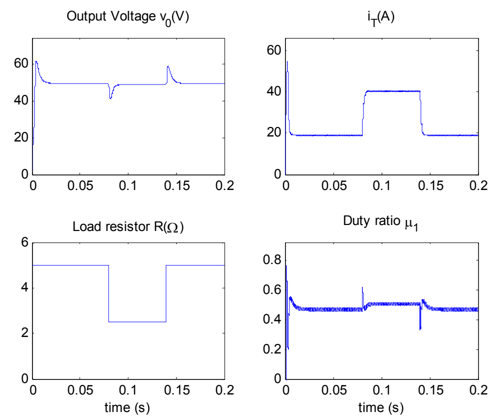

Fig.5: Controller behavior in response to a step reference $V_d = 48V$ and changes in the load resistance

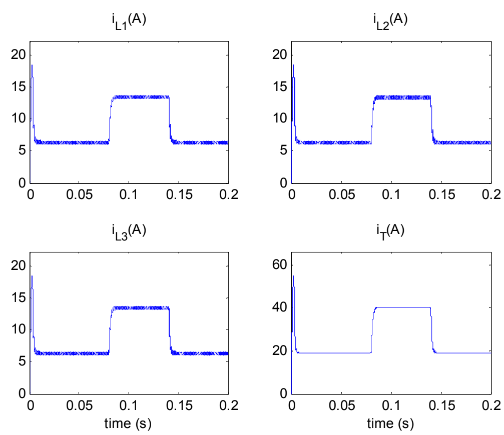

Fig.6: Inductor currents in response to a step reference $V_d = 48V$ and changes in the load resistance

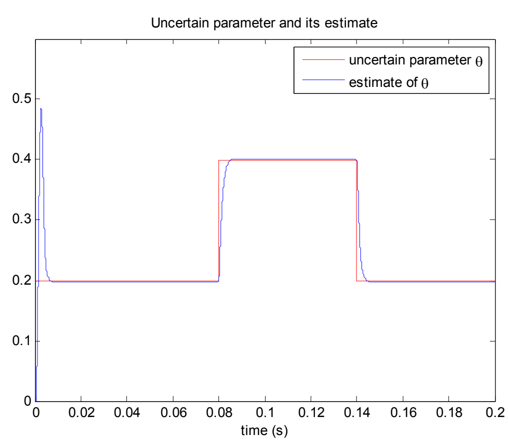

Fig.7: Uncertain parameter and its estimate

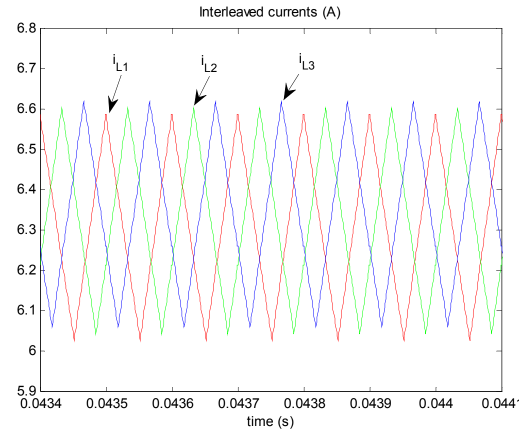

Fig.8: Interleaved currents

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