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Decentralized Control of a Fuel Cell Ultra-capacitor Hybrid Network

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***Abstract*— This paper addresses decentralized control of a simple hybrid power system consisting of a single fuel cell and an ultra-capacitor. This work develops separate controllers for the fuel cell and the ultra-capacitor, rather than a centralized controller. With a goal developing a control paradigm that is scalable to many energy resources connected to a network, the controllers are designed primarily to use locally sensed information. Explicit communication between controllers, such as exchange of locally sensed information, is absent. An energy conservation based approach, combined with a current regulation method developed by the authors in their earlier work [1], is used for transient control of the fuel cell. The control of state-of-charge of the ultra-capacitor is also principally governed by energy conservation, but implemented using two different approaches. One is based on dissipation, and the other is based on voltage modulation. The former is a conservative approach, while the latter is potentially more energy efficient. Simulation results are presented to demonstrate these concepts. Further research is ongoing to develop a detailed analytical base for this work.**

I. INTRODUCTION

Solid Oxide Fuel Cell (SOFC) is an attractive technology for energy conversion due to advantages such as fuel flexibility, high temperature operation, tolerance to impurities, high efficiency, and potential for co-generation using heat as a byproduct [1]. Nevertheless, among issues such as mechanical integrity, thermal stresses, their load following capability is also a limiting factor hindering their widespread use [2]. This issue can be addressed by hybridization of SOFCs with a energy storage device [3]. But it necessitates the design of algorithms for transient control and stability in the presence of uncertainties. Several approaches have been proposed to achieve the aforementioned goal.

A considerable proportion of work is done on the transient control of Polymer Electrolyte Membrane (PEM) fuel cells where air delivery is a limiting factor(see [4], [1] and references therein). In [5], the authors have introduced the concept of hybrid power sources using PEM fuel cell as main source, batteries on the DC link, and super-capacitors as transient power source. In [6] the authors presented an adaptive control strategy for active power sharing in the hybrid power source i.e. fuel cell and batteries. Their control strategy adjusts the output current setpoint of the fuel cell according to the state-of-charge (or voltage) of the battery. Similar works can be found at [7], [8]. Relatively fewer researchers have focused on SOFC hybridization to compensate intrinsic limitations on load following. A novel control strategy for active power flow in a hybrid SOFC/battery distributed generation system was introduced in [9]. The method introduces an on-line power management by a hierarchical hybrid controller between dual energy sources that consist of a battery bank and an SOFC. Additionally, an adaptive controller was proposed for a hybrid SOFC system in [3].

However, the works discussed above are in the realm of centralized control where all the information is transmitted into a central unit to be processed. There are practical limitations to such centralized designs. As the number of energy resources in the network increases, the size of the optimization problem can easily exceed the real-time computational capability of current micro-controllers [10]. Hence, this approach cannot be scaled-up as the network size increases. Therefore, the idea of decentralized control was introduced in which each component will process information locally and has a local controller. But the system-level goal will nevertheless be achieved by seemingly disconnected actions of the distributed controllers.

Even though the idea of decentralized control is relatively new in the area of power grids and complex systems, some previous works can be found in the literature. In [10], the authors developed a model predictive decentralized control approach for a PEM fuel cell/ultra-capacitor hybrid which controls fuel cell and ultra-capacitor current, and enforces point-wise-in-time constraints of each subsystem independent of each other. Another work by [11] uses non-linear dynamic model of SOFC involving selection of controlled variables, input-output pairing selection, and PID controller tuning. An application of nonlinear decentralized robust control to large-scale power systems appears in [12]. In [13], the authors considered the problem of decentralized control of interconnected power systems under large changes in real and reactive loads causing large structural changes in the system model.

In this paper, first a brief description of the fuel cell system and its hybridization with ultra-capacitor is presented. Then, the decentralized approach and the use of energy conservation in this context are explained. Thereafter, the principal idea of the proposed decentralized control is demonstrated in the absence of uncertainties. Next, the idea is extended to incorporate the uncertainties using two methods. The first method is conservative, leading to gradual over-charging of the ultra-capacitor and necessitates energy dissipation to regulate the capacitor's stored energy. The second uses voltage modulation for regulating the capacitor's stored energy. In the latter approach, the fuel cell uses the regulated voltage in conjunction with power fluctuations to gradually lower

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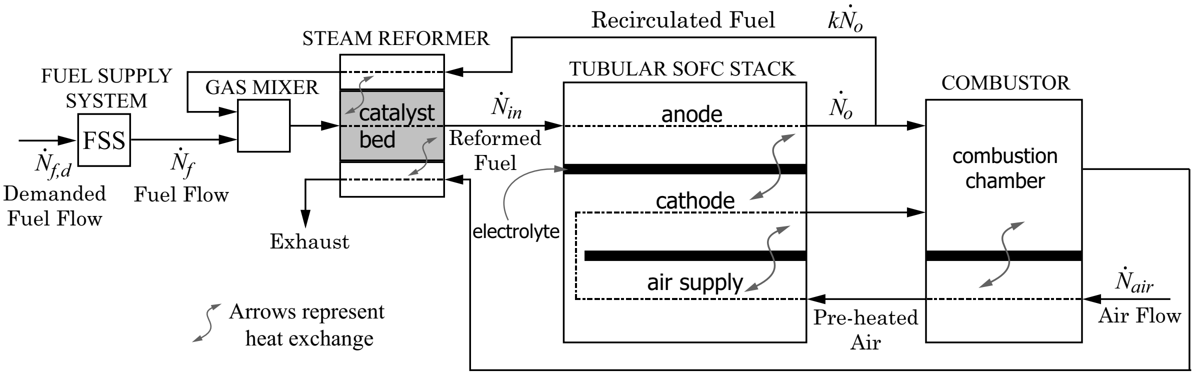

Fig. 1. Schematic of SOFC System

uncertainty bounds over time. Finally, concluding remarks are made and references are provided.

II. SYSTEM DESCRIPTION

A. SOFC

The SOFC considered is a tubular steam reformer based system which employs methane as fuel, Fig.1. The reformer breaks the methane molecules into a hydrogen-rich mixture feeding the anode of the fuel cell stack where electrochemical reactions occurs. The anode exhaust contains a steam-rich gas mixture which a known fraction k of it is recirculated back to the reformer into a mixing chamber where fuel $\dot{N}_f$ is added. The fuel supply system (FSS) consists of a fuel pump and/or valves and a fuel flow controller. Steam reforming in endothermic and the heat required is supplied from two sources, namely, the recirculated anode exhaust flow and the combustor exhaust that is passed through the reformer. The combustor also reheats the cathode air $\dot{N}_{air}$. The mathematical model presented in detail in [14], and has been validated against results in literature [15], [16].

B. Hybrid Network and Control Objectives

Fig. 2 is a schematic of the hybrid system with a decentralized control scheme. Other approaches for building a fuel cell ultra-capacitor/battery are presented in [17], [4]. In our approach, the fuel cell and the ultra-capacitor are connected in parallel. The fuel cell supplies power to the load through a uni-directional DC/DC converter C_1. The ultra-capacitor is connected to the load through a bi-directional DC/DC converter C_2 allowing charge and discharge. Converter C_1 has an efficiency η_1 and C_2 has discharge and charge efficiencies of η_2 and $\bar{\eta}_2$ respectively [18].

Referring to Fig.2, the control objectives are:

1) The hybrid system will satisfy the power demand $V_L i_L$ (see Fig.2) at every instant.
2) The fuel utilization of the SOFC will achieve a target value of 80% at steady-state, i.e. $U_{ss} = 0.8$.
3) The control strategy will simultaneously maintain the SOC (State-Of-Charge) of the ultra-capacitor at a target value of $S_t = 0.8$.
4) Design decentralized controllers K_1 and K_2 for the fuel cell and ultra-capacitor respectively to achieve the objectives.

Next, we make the following observations regarding the hybrid interface:

- Based on the schematic in Fig.2, since the fuel cell and the ultra-capacitor are connected in parallel,

$$V_L i_L = \eta_1 V_{fc} i_{fc} + \left[\frac{\eta_2 + \bar{\eta}_2}{2} + \frac{\eta_2 - \bar{\eta}_2}{2}\mathrm{sgn}(i_{uc})\right] V_{uc} i_{uc}, \quad (1)$$

  is true at any instant.
- Due to their fast responses, C_1 and C_2 can be modeled as static energy conversion devices, as in Eq.(1).
- The bus voltage (V_L) is held constant. This is possible by operating either C_1 or C_2 in voltage control mode while the other operates in current control mode, [18]. In this work we will consider C_1 to be in current control mode, while C_2 maintains voltage $V_L = 24$V.

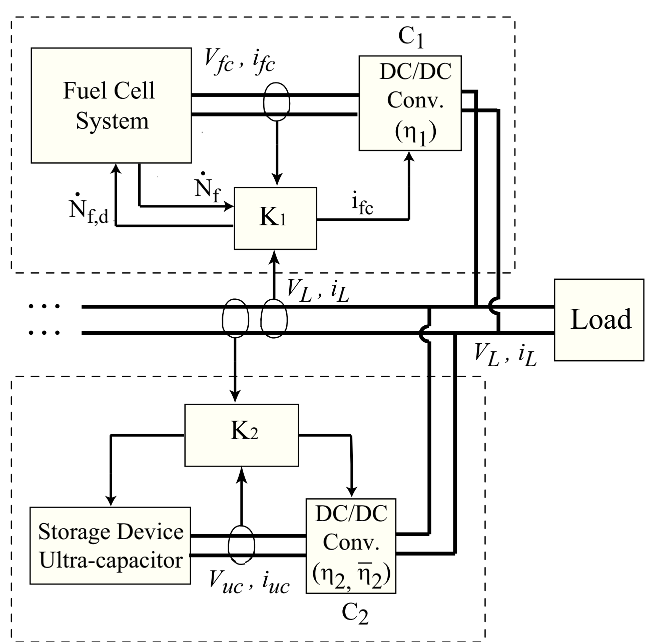

Fig. 2. Schematic of Hybrid Fuel Cell System with Decentralized Control

III. ENERGY CONSERVATION BASED CONTROL

A. Approach

This work applies conservation of energy to develop decentralized control of the hybrid system in Fig.2. Conceptually, the approach is illustrated in Fig. 3. The figure shows

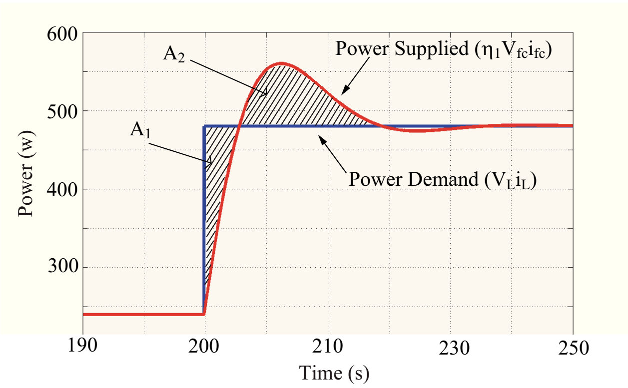

Fig. 3. Conservation of Energy Approach

a sudden increase in power demand and the corresponding load-following response of the source (fuel cell). The area A_1 represents the energy supplied by the storage device (ultra-capacitor in this case) to make up for the fuel cell's deficiency for load following. Therefore, if the area A_2, which represents the extra energy supplied by the source, is same as A_1, then it would ideally charge the capacitor to its original SOC. Extending this idea, we note that if $\sum_i A_{1,i} = \sum_k A_{2,k}$, i.e. if

$$\lim_{t\to\infty} E_A = \lim_{t\to\infty} \left(\sum_i A_{1,i} - \sum_k A_{2,k} \right) \to 0 \tag{2}$$

then the storage element will maintain its original energy level. Ideally, the above condition can be fulfilled by K_1 without any information about the capacitor by just ensuring

$$\lim_{t\to\infty} \int_0^t \triangle P\, dt = 0, \quad \triangle P \triangleq (V_L i_L - \eta_1 V_{fc} i_{fc}) \tag{3}$$

In the presence of losses in C_2 with discharge and charge efficiencies η_2 and $\bar{\eta}_2$ respectively, Eq.(2) is modified to

$$\lim_{t\to\infty} E_A = \lim_{t\to\infty} \left(\sum_i \frac{A_{1,i}}{\eta_2} - \sum_k \bar{\eta}_2 A_{2,k} \right) \to 0. \tag{4}$$

If we assume η_2 and $\bar{\eta}_2$ to be known then, using $\triangle P$ as defined in Eq.(3), Eq.(4) is satisfied by K_1 by ensuring

$$\lim_{t\to\infty} I_e = 0, I_e \triangleq \int_0^t \left[\frac{\eta_2^{-1} + \bar{\eta}_2}{2} + \frac{\eta_2^{-1} - \bar{\eta}_2}{2} \operatorname{sgn}(\triangle P) \right] \triangle P dt \tag{5}$$

However, η_2 and $\bar{\eta}_2$ will be unknown to K_1. Therefore, we need to build a robust control around this principle to handle such uncertainty in a decentralized manner. The next sections will demonstrate the validity of the main principle.

B. Assumptions

The decentralized controller will be designed based on the following assumptions

1) It is assumed that C_2 has an efficiency of η_2 for discharging and $\bar{\eta}_2$ for charging the ultra-capacitor. We also assume that $\eta_{2,min} \leq \eta_2, \bar{\eta}_2 \leq \eta_{2,max}$.
2) Controller K_1 measures V_{fc}, V_L, i_L, and η_1 is known to K_1. It does not have measurements of i_{uc}, V_{uc} or η_2. However, K_1 has knowledge of $\eta_{2,min}$ and $\eta_{2,max}$. K_1 commands C_1 to draw i_{fc}.
3) Controller K_2 measures V_{uc}, i_{uc}, V_L and i_L, but does not have measurements of i_{fc}, V_{fc} or η_1. K_2 commands C_2 to maintain V_L.

C. Implementation and Simulations

To demonstrate that energy conservation can be used in principle to design decentralized control, we consider a simplified scenario. We assume that in addition to the local information mentioned in Assumption 2, controller K_1 has exact knowledge of η_2 and $\bar{\eta}_2$. Next, in designing K_1, we recall that the commanded i_{fc} must be based on the actual fuel flow $\dot{N}_f$ for transient control of U, as detailed in [1]. Also, $\dot{N}_f$ is driven by the demanded fuel $\dot{N}_{f,d}$, which in turn is determined from $i_{fc,d}$. Thus, the command i_{fc} to C_1 is determined as follows:

$$\dot{N}_{f,d} = \frac{i_{fc,d}\mathcal{N}_{cell}}{4nFU_{ss}}\beta \;\Rightarrow\; i_{fc} = \frac{4nFU_{ss}\dot{N}_f}{\mathcal{N}_{cell}\beta}, \tag{6}$$

where $\beta = [1 - (1 - U_{ss})\, k]$. From Eq.(6) we note that designing K_1 reduces to the design of the reference $i_{fc,d}$. The design of $i_{fc,d}$ is based on the following observation: In load-following mode, the fuel cell provides the entire power demand at steady-state and uses transient perturbations in power to regulate the ultra-capacitor SOC. With this goal, and incorporating the approach outlined in section III-A, we formulate $i_{fc,d}$ as:

$$i_{fc,d} = \frac{V_L i_L}{\eta_1 V_{fc}} + k_i I_e,\; k_i > 0 \tag{7}$$

where I_e is defined in Eq.(5). This design is implemented and simulation results are summarized in Fig.4. The parameter values chosen are

$$C = 25\text{F}, \eta_1 = 0.8,\; \eta_2 = \bar{\eta}_2 = 0.8,\; k_i = 0.01 \tag{8}$$

The power demand $V_L i_L$ is subjected to step changes. We note that K_2 simply maintains the constant voltage V_L across the load. Fig.4(a) confirms the control of SOC and Fig.4(b) plots $V_L i_L$ and $\eta_1 V_{fc} i_{fc}$.

IV. DECENTRALIZED CONTROL DESIGN

A. Design of K_1 using a Lower Bound on η_2 and $\bar{\eta}_2$

Next consider a more realtistic case where K_1 has no knowledge of η_2 and $\bar{\eta}_2$ but knows a lower bound $\eta_{2,min} \leq$

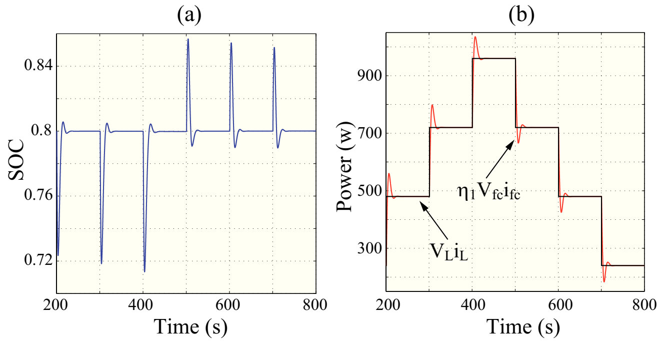

Fig. 4. Energy Conservation based Control with Known η_2 and $\bar{\eta}_2$

$\eta_2, \bar{\eta}_2$. Accordingly, in Eq.(7), instead of using I_e from Eq.(5), a conservative I_e is used as shown

$$I_e \triangleq \int_0^t \left[\frac{\eta_{2,min}^{-1} + \eta_{2,min}}{2} + \frac{\eta_{2,min}^{-1} - \eta_{2,min}}{2} \mathrm{sgn}(\triangle P) \right] \triangle P dt \tag{9}$$

Simulation results with I_e calculated using Eq.(9) are shown in Fig.5. The parameter values chosen were same as in Eq.(8). Additionally, $\eta_{2,min} = 0.7$ was chosen. The conser-

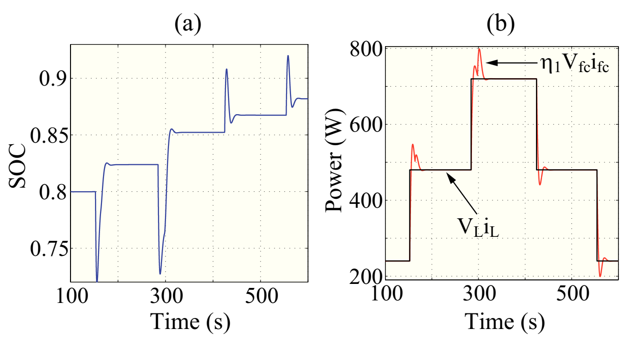

Fig. 5. Energy Conservation with a Conservative Estimate of η_2 and $\bar{\eta}_2$

vative nature of this approach can be inferred from Fig.5(a) where the SOC builds up with changes in power demand. The power demand and supplied power are plotted together in Fig.5(b). Therefore, we now have a conservative control K_1 which will gradually lead to over-charging the ultra-capacitor. Since we consider the energy storage device to be of finite capacity, we must regulate the SOC. To address this in a decentralized manner two approaches are discussed in subsequent sections.

B. Dissipation Based Approach for Designing K_2

One way to regulate the ultra-capacitor's SOC is to dissipate the extra energy through a variable resistance connected to the ultra-capacitor. Granted that this would lead to additional energy loss, but it is a simple yet effective way to control the SOC. Two different configurations for dissipation are shown in Fig.6. One is to add a resistance in parallel with capacitor Fig.6(a), and the other is to connect in series Fig.6(b). The energy dissipation can be controlled by K_2 by actuating the switch shown in both configurations in Fig.6, e.g. using pulse-width-modulation (PWM). Since the SOC is a local information for K_2, charge management is done locally without any information about the fuel cell. In this

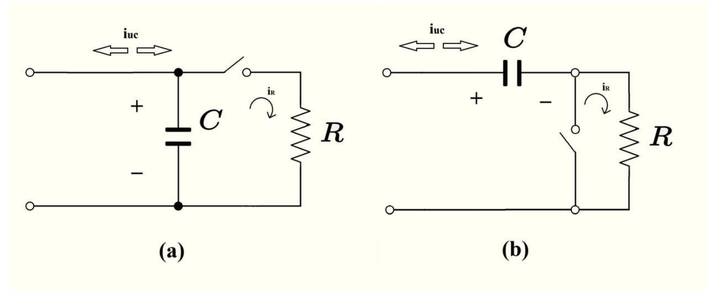

Fig. 6. Two Configurations for Dissipation

work, only configuration (a) is adopted since it allows K_2 to handle the charge-discharge in a decoupled manner. The following equation represents case (a) in Fig. 6:

$$C\dot{V}_{uc} = -(i_{uc} + i_R), \quad \dot{V}_{uc} = -\frac{1}{C}(i_{uc} + V_{uc}\sigma_R) \tag{10}$$

where σ_R is the effective conductance that can be varied by changing the duty cycle of switching. We assume $R = 25\Omega$, and hence

$$\begin{array}{l} \text{duty cycle} = 0 \;\Rightarrow\; \sigma_R = 0 \\ \text{duty cycle} = 1 \;\Rightarrow\; \sigma_R = 0.04 \end{array} \tag{11}$$

1) A PI Controller: The objective here is to treat σ_R as a control input and to design a control law that will stabilize the equilibrium $V_{uc} = V_{uc,d}$ and $V_{uc,d}$ is such that $V_{uc,d}/V_{uc,max} = 0.8$. For our ultra-capacitor, $V_{uc,max} \approx$ 16V and hence $V_{uc,d} = 13$V. Since for constant load under steady-state $i_{uc} = 0$, a proportional controller of the form $\sigma_R = [k_{p,uc}(V_{uc} - V_{uc,d}) - i_{uc}]/V_{uc}$ will suffice. However, a PI controller will better perform under load variations. Hence, the following PI control law is proposed:

$$\sigma_R = \frac{k_{p,uc}}{V_{uc}}(V_{uc} - V_{uc,d}) + \frac{k_{i,uc}}{V_{uc}} \int_0^t (V_{uc} - V_{uc,d})\, dt \tag{12}$$

Results for step changes is depicted in Fig.7. In contrast to

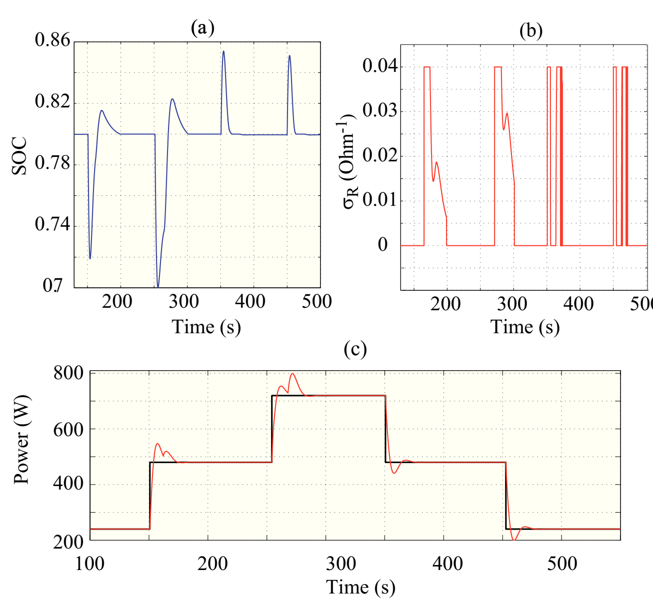

Fig. 7. System response with a PI controller for dissipation

Fig.5(a) where the SOC control was not implemented in K_2, the SOC converges to 0.8 with the PI control of Eq.(12) implemented in K_2. The manner in which the resistance R is used in the PI controll is evident from Fig.7(b). The integrator is also held once upper saturation in σ_R is reached from below or lower saturation is reached from above. Also, it can be observed that as SOC drops below 0.8, the resistance switches off and when it exceeds 0.8, the resistance becomes effective.

2) Frequency Separation and Frequency Domain Design: Note that in Eq.(12), we did not incorporate i_{uc}, which is a local information and can be measured. The main reason for this is that we want σ_R to primarily respond to changes in V_{uc} and not respond to perturbations in i_{uc}. Thus, i_{uc} can be considered as a disturbance input in Eq.(10). Note also that in load-following mode, i_{uc} would be close to zero and hence the noise-to-signal ratio of its measurement is expected to be high, especially when load variations are gradual. Since the change in SOC is expected to be a gradual process, we want σ_R to respond only to the low frequency component of V_{uc}. Hence, $k_{p,uc}$ and $k_{i,uc}$ should be tuned to low values so that closed-loop dynamics is slower compared to the dynamics of i_{fc}. Thus in designing the decentralized control we deliberately aim for separating the operating frequencies of K_1 and K_2, with the latter operating at much lower frequencies compared to the former.

Leaving aside the high frequency noise, it is expected that the frequency content $\Omega_{i_{uc}}$ of i_{uc} to consist of the frequency content of i_L and that of i_{fc}. This is evident from Eq.(1). With this general notion, one can design a loop-shaping control law for σ_R, [19]. Considering a controller $K_{ls}(s)$ connected in series to the plant $G(s) = -1/(Cs)$ and a standard negative feedback loop, one can write

$$\begin{aligned} E(s) &= \tfrac{1}{1+L(s)} V_{uc,d}(s) + \tfrac{G(s)}{1+L(s)} i_{uc}(s) \\ E(s) &\triangleq (V_{uc,d}(s) - V_{uc}(s)), \quad L(s) = K_{ls}(s)G(s) \end{aligned} \tag{13}$$

where, the control input is $i_R = V_{uc}\sigma_R$. Since $V_{uc,d}(s) = V_{uc,d}/s$, reference tracking, disturbance rejection and noise rejection can be simultaneously achieved by a design of $K_{ls}(s)$ of the form

$$K_{ls}(s) = \frac{1}{s}\bar{K}_{ls}(s) \tag{14}$$

where $\bar{K}_{ls}(s)$ is designed to give high gains for $\omega \in \Omega_{i_{uc}}$ and a high frequency roll-off with -40db/dec or faster for $\omega > \Omega_{i_{uc}}$. The details of frequency domain design will be pursued in future work.

C. Voltage Regulation Based Approach for K_2

Using dissipation for controlling the SOC is based on the premise that extra energy will be lost. The main idea in the voltage regulation method is to prevent this loss. Note that energy loss would be prevented if the fuel cell controller K_1 has accurate knowledge of η_2 and $\bar{\eta}_2$. Hence, the objective of this design is to develop a mechanism by which the fuel cell can learn the aforementioned efficiencies without direct sensing or communication with K_2. To this end, we propose the following approach. As mentioned in section III-B, K_2 can manipulate V_L. Therefore K_2 can manipulate V_L based on the SOC. As charge builds up, V_L can be increased gradually by K_2. Not only will it regulate V_{uc}, but since V_L is a global variable, the fuel cell can simultaneously use the low frequency component of V_L to improve its lower bound $\eta_{2,min}$.

Load fluctuation is an undesirable phenomenon in the power networks. Therefore, the aforementioned voltage regulation method, even though is capable of inducing the fuel cell to improve its $\eta_{2,min}$ estimate, must be designed in a way such that voltage fluctuations are low and they diminish as the esitmate of $\eta_{2,min}$ improves. The voltage was modulated using an integrator

$$V_L = 24 + k_{i,uc}\int_0^t (V_{uc} - V_{uc,d})\,dt, \tag{15}$$

with $k_{i,uc} = 0.005$ for a test simulation. Moreover, as soon as the low frequency component of SOC is sufficiently close to 0.8, the integrator resets V_L to 24V. That results in a saw-tooth type of response as shown in Fig.8(a). On the other hand, at the fuel cell side, an integrator is used which is similar to Eq.(15) to utilize the load deviations from 24V for efficiency estimation.

$$\eta_{2,min}(t) = \eta_{2,min}(0) + k_{i,uc}\int_0^t (V_L - 24)\,dt \tag{16}$$

Results are depicted in Fig.8 demonstrating the response using the above mentioned I-controllers in both K_1 and K_2 sides. In this simulation pulsed changes power demand were applied every 200s. From Fig.8(a), it is clear K_2 is able

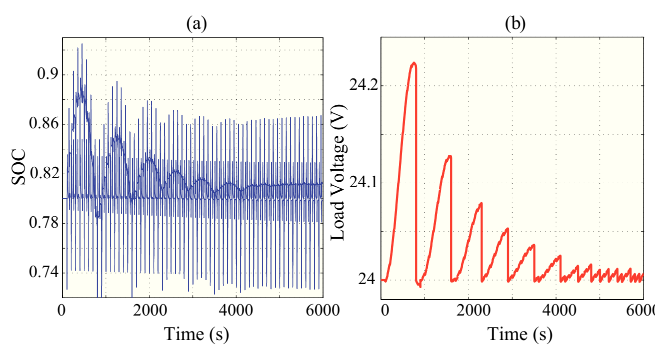

Fig. 8. Simulations with Voltage Modulation and Efficiency Estimation

to maintain the SOC through voltage modulation. Further, Fig.8(b) shows that voltage fluctuations reduce over time. This is primarily due to better estimation of $\eta_{2,min}$ by K_1 over time. The estimation is depicted in Fig.9. Another observation is that at the beginning which corresponds to higher SOC fluctuations, efficiency learning was fast. However, its speed decreased as time proceeded. The estimation process therefore requires not only the voltage modulation but also requires persistent perturbations in the power demand.

V. CONCLUSIONS

A decentralized control approach was developed for a solid oxide fuel cell system hybridized with an ultra-capacitor in

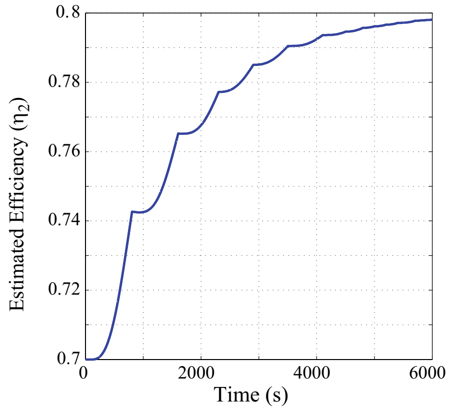

Fig. 9. Estimated η_2

parallel. In the decentralized framework, there are individual controllers for the fuel cell and the ultra-capacitors that do not explicitly communicate with each other but use local information for control. However, the system as a whole satifies the control objectives without jeopardizing any component. A conservation of energy based approach for control was developed. First, a conservative approach was taken to design the decentralized scheme. This approach was extended to a voltage modulation method which essentially imposed energy conservation on the energy storage device and simultaneously provided a means for implicit communication between the controllers using the power line itself. To extend this research in future, a network with more than two elements and eventually, a network consisting of multiple elements will be attempted. The general observation is that migrating to a decentralized control involves a tradeoff between the advantage gained through reduced computation and sensing, with the need for adding a dissipation mechanism or the need for adding an extra capability in power conversion like voltage modulation.

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