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Optimal power distribution control for a network of fuel cell stacks

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ABSTRACT

In power networks, where multiple fuel cell stacks are employed in a series-parallel configuration to deliver the required power, optimal sharing of the power demand between different stacks is an important problem. This is because the total current collectively produced by all the stacks is directly proportional to the fuel utilization, through stoichiometry. As a result, one would like to produce the required power while minimizing the total current produced. In this paper, an optimization formulation is proposed for this power distribution control problem. An algorithm that identifies the globally optimal solution for this problem is developed. Through an analysis of the KKT conditions, the solution to the optimization problem is decomposed into off-line and on-line computations. The on-line computations reduce to solving a nonlinear equation. For an application with a specific V–I function derived from data, we show that analytical solutions exist for on-line computations. We also discuss the wider applicability of the proposed approach for similar problems in other domains.

1. Introduction

Fuel cells have gained considerable attention in the field of power conversion, especially in the past few decades [1–3]. Fuel cells are capable of extracting energy from the fuel more efficiently than internal combustion engines [2]. Due to higher fuel-efficiency, less harmful emissions, low operational noise and absence of moving parts, fuel cells have been proposed for a wide variety of applications [2,4]. The power obtainable from a single fuel cell is rather low in comparison to the power requirement for most of the applications. Hence, to meet realistic power requirements, active surface area has to be increased. In view of this, multiple fuel cells are stacked or connected in series and/or parallel arrangements to enhance the output voltage and power [5,6].

While fuel cell technology has several advantages, there are also problems related to long-term durability and gradual loss of performance over time. The performance degradation could be due to many factors such as electrolyte degradation, catalyst poisoning, water flooding, etc. [2,5]. Such degradation can result in reduced current being drawn from the stack at the same voltage. As a result, the overall system performance could be compromised, and in the worst case of complete stack failure, the whole system could fail [5]. This issue is usually addressed by designing a reliable parallel connected fuel cell architecture with an additional power bus [7] as shown in Fig. 1. Another approach to improve reliability is the use of multiple power sources in the same network [8,9].

There are a wide range of resources available in the literature which deals with issues associated with microgrid management like power distribution, uncertainties related to available resources, cost minimization, etc. [10–13]. Niknam et al. [14] presented a particle swarm optimization algorithm for daily operation management in fuel cell power plants. In this work, Pareto-optimal solutions are obtained for the multi-objective optimization problem which considers minimization of power losses, electrical energy costs and total emissions, and deviation of bus voltages. While considerable research has been devoted to concerns related to output voltage, state of charge, reliability and network configuration, very little work has focused on developing operational strategies that minimize the fuel consumption through on-line control. We address this control problem in this paper.

2. Problem statement

Consider a fuel cell network with N branches and $N_{f,i}$ stacks in the i^{th} branch (as shown in Fig. 2). The control problem is one of minimizing the total current drawn (a surrogate for total fuel uti-

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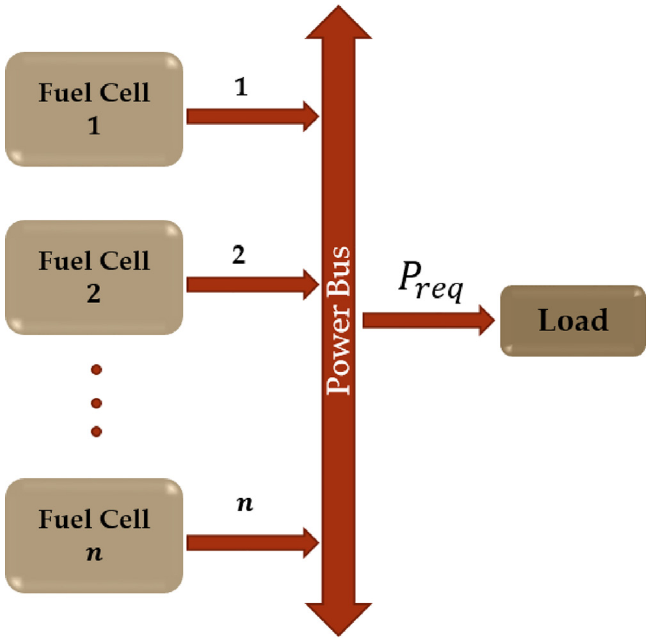

Fig. 1. Schematic of a parallel connected fuel cell network with n branches.

lized) while meeting a fixed power requirement. This can be posed as the following optimization problem (P1).

$$\min_{I_i\ \forall\ i=1:N} \quad I_{net} = \sum_{i=1}^{N} I_i \tag{1a}$$

$$\text{subject to} \quad \sum_{i=1}^{N}\sum_{j=1}^{N_{f,i}} P_{ij} = \sum_{i=1}^{N}\sum_{j=1}^{N_{f,i}} \phi_{ij} V_{ij} I_i = P_{req} \tag{1b}$$

$$V_{ij} \geq V_{ij,lb} \quad \forall \quad i = 1:N; \quad j = 1:N_{f,i} \tag{1c}$$

$$V_{ij} \leq V_{ij,ub} \quad \forall \quad i = 1:N; \quad j = 1:N_{f,i} \tag{1d}$$

where I_{net} is the total current from all branches and I_i represents the current drawn from the i^{th} branch of the fuel cell network. V_{ij}, P_{ij} and ϕ_{ij} are voltage, power produced and efficiency of the j^{th} stack in the i^{th} branch respectively. Currents ($I_i\ \forall\, i = 1:N$) drawn from all branches are the decision variables. Subscripts *lb* and *ub* denote the lower and upper bounds respectively.

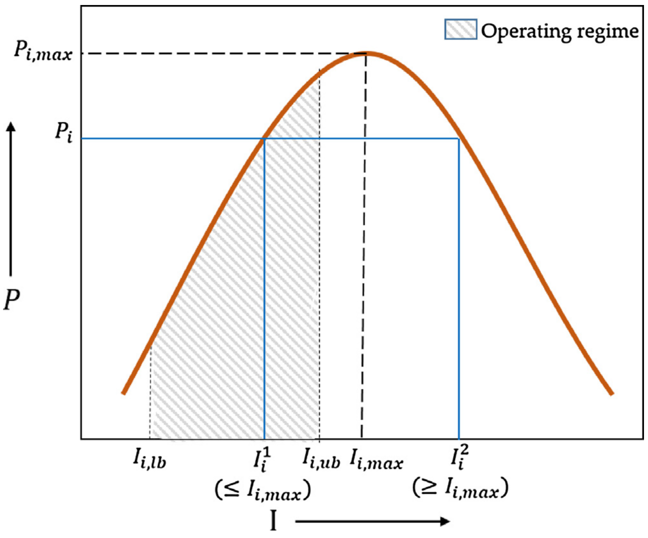

Fig. 3. General power characteristics of a fuel cell stack. I_i represents current corresponding to any power P_i.

Assumptions:

1. The potential across each fuel cell is assumed to be a static map f_{ij}:

$$V_{ij} = f_{ij}(I_i) \quad \forall\, i = 1:N; \quad j = 1:N_{f,i} \tag{2}$$

   Bounds on voltage can thus be transformed to bounds on current if the domain is restricted as in assumption 4.
2. Number of stacks in each branch of the network under consideration, is assumed to be one ($N_{f,i} = 1\ \forall\, i = 1:N$).
3. Fuel cell stacks are not allowed to operate close to open circuit potential (OCP) as it might result in major degradations in fuel cell stack. Thus $I_{i,lb} > 0$ is generally assumed.
4. Fuel cell stacks are not allowed to operate at a current higher than their $I_{i,max}$ (current at which power is maximum, $P_{i,max}$) as shown in Fig. 3. This is because it is possible to find a current $I_i < I_{i,max}$ for any power that can be achievable using a current higher than $I_{i,max}$. If $I_{i,ub} > I_{i,max}$ for any stack i, $I_{i,ub}$ is redefined to be equal to $I_{i,max}$ for that stack.

Though we assume a single stack in each branch, general class of problems with multiple stacks in each branch can be brought

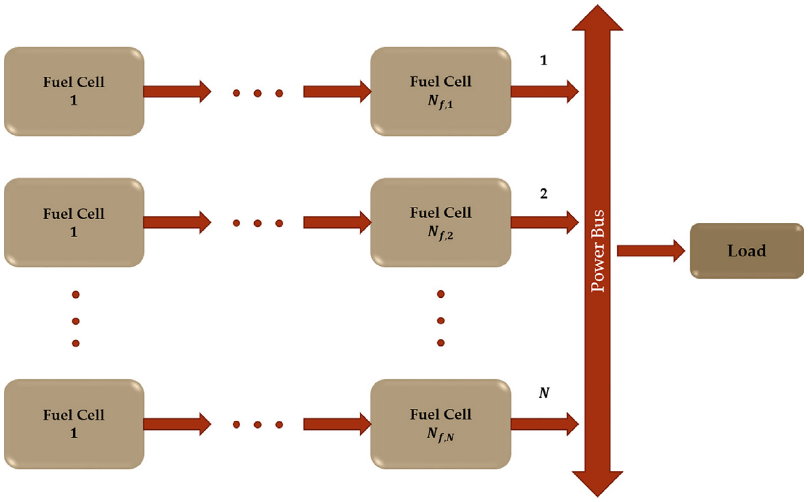

Fig. 2. Schematic of a parallel connected fuel cell network with N branches and $N_{f,i}$ fuel cell stacks in the i^{th} branch.

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