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Modeling and Control Strategy for Grid-Tied Photovoltaic/Fuel Cell Hybrid System in Network Context

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Abstract. Managing power converters is crucial for Photovoltaic (PV) and Fuel Cell (FC) hybrid power systems. This study develops a model and control strategy for a grid-tied hybrid system using the Takagi–Sugeno fuzzy model. The system includes a grid-connected PV/FC and power electronic converters to meet the electric load. First, the study presents the overall grid configuration with dynamic models for the PV, FC, and their power electronic interfaces. A fuzzy logic controller is designed for maximum power point tracking of the PV system. A PI controller manages the methane flow rate in the FC reformer. Additionally, a Nonlinear Fuzzy Converter Control (NFCC) scheme is developed for the grid-side converter connected to the DC-Link. Sufficient conditions are formulated as linear matrix inequalities. This NFCC controller enhances the converters' performance, allowing them to endure grid faults, maintain efficiency, and support the grid by regulating DC bus voltage. The control of the studied system is validated under grid fault conditions. Inverter control incorporates power support to meet network requirements, ensuring fault ride-through and stabilizing grid voltages. A case study of the system, simulated using MATLAB/Simulink, demonstrates the proposed control strategy. Results highlight the system's ability to handle various grid faults effectively.

1 Introduction

Electricity is vital for global development, powered predominantly by finite fossil fuels that emit Greenhouse Gases (GhG) [1]. Renewable Energy Sources (RES) like hydrogen, solar, wind, biomass, geothermal, and marine energy offer sustainable alternatives with minimal GhG emissions [2].

Photovoltaic (PV) energy converts solar radiation into direct current, despite weather dependency and moderate efficiency (10-18%) [3]. Proton Exchange Membrane Fuel Cells (PEMFC) efficiently generate electricity but require further technological advancements [4].

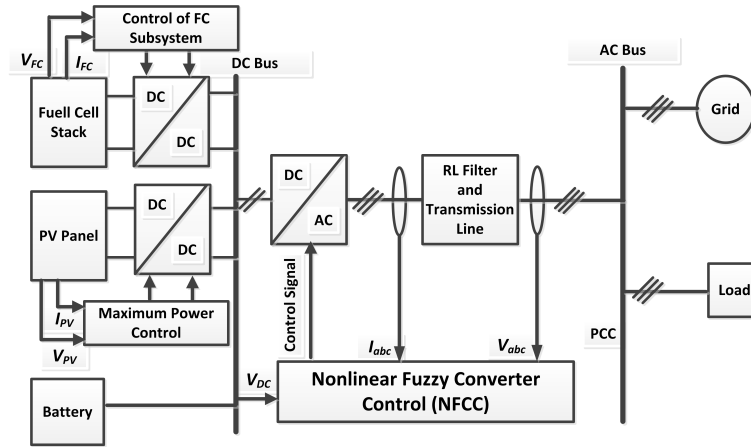


Fig. 1. Overall Structure of the PV/FC hybrid system with proposed control strategy.

Research emphasizes integrating PV and FC in hybrid systems for grid support and mobile energy [5]. Efforts to enhance PV/FC resilience during grid faults use techniques like Linear Quadratic Regulator (LQR) and model predictive control [6].

This paper proposes a grid configuration with dynamic PV and FC models. It introduces a fuzzy logic-based Maximum Power Point Tracking (MPPT) for PV optimization and a PI controller for FC power regulation. A Nonlinear Fuzzy Converter Control (NFCC) enhances grid-side converter performance and stabilizes DC bus voltage using a Takagi–Sugeno (TS) fuzzy model with Linear Matrix Inequalities (LMI).

Key contributions include a MATLAB/Simulink PV/FC model and NFCC implementation. Simulation shows improved Fault Ride-Through (FRT) and stability across varied grid conditions.

The paper is structured as follows: Section 2 details system modeling and control strategies, Section 3 covers stability analysis and proposed control methods, Section 4 presents simulation results, and Section 5 concludes with future research directions.

2 Proposed of PV/FC Hybrid Power Sources Structure

The dynamic modeling block diagram of the PV/FC Hybrid Power Sources (PV/FC-HPS) system, including interfacing power electronics connected to the main grid at the Point of Common Coupling (PCC), is shown in Fig. 1. This diagram outlines the structure of the PV/FC-HPS system, which includes models for PV, FC, DC-link, and the grid.

2.1 Proposed of PEMFC/PV Model Structure

The study model of the PEMFC/PV model in this paper is based on [7], [8]. Therefore, the model details are not presented in this paper.

2.2 Nonlinear DC-Link Model

The DC-AC converter consists of two voltage source converters interconnected through a DC-link, as illustrated in Fig. 1. Neglecting losses in each converter, the comprehensive dynamic model of the grid-connected DC line can be expressed in a compact nonlinear affine form as:

$$\dot{x}(t) = A(x, u)x(t) + B(x)u(t) + W \quad (1)$$

where $x(t)$ denotes the state vector, $u(t)$ represents the input vector, $y(t)$ signifies the output vector, $A(x, u)$ corresponds to the state matrix, $B(x)$ pertains to the input matrix, and W stands for the disturbance. These elements are specified as follows:

$$x(t) = [i_{od} \ i_{oq} \ V_{DC}]^T, y(t) = [i_{od} \ i_{oq} \ V_{DC}]^T, u(t) = [\beta_{od} \ \beta_{oq}]^T, \\ A(x, u) = \begin{bmatrix} -\frac{R_f}{L_f} & \omega_f & 0 \\ -\omega_f & -\frac{R_f}{L_f} & 0 \\ -\frac{3}{4C}\beta_{od} & -\frac{3}{4C}\beta_{oq} & -\frac{1}{CR_1} \end{bmatrix}, B(x) = \begin{bmatrix} \frac{V_{DC}}{2L_f} & 0 \\ 0 & \frac{V_{DC}}{2L_f} \\ 0 & 0 \end{bmatrix}, W = \begin{bmatrix} -\frac{v_{rd}}{L_f} \\ -\frac{v_{rq}}{L_f} \\ 0 \end{bmatrix},$$

The $d - q$ components v_{od} and v_{oq} represent the output inverter voltage, while v_{rd} and v_{rq} denote the grid voltages in the $d - q$ reference frame. The parameters R_f and L_f correspond to the resistance and inductance of the grid filter, respectively, and ω_f denotes the angular frequency of the grid voltage. The control signal (β_i) is determined as the average value of u_i over the PWM period. The DC-link voltage V_{DC} is kept constant by the Grid-Side Converter (GSC)

3 Proposed PV/FC Hybrid System Control strategy

In this section, we describe the control model for the PV/FC hybrid system [9] and analyze its structure with the Nonlinear Fuzzy Converter Control (NFCC) strategy for the grid-side converter, formulated with LMIs to enhance performance and stabilize the grid.

3.1 PV/FC Hybrid System Control Model Analytic Description and Grid Connection

In this paper, we focus on simplifying power system dynamics crucial for regulator synthesis. Assuming $v_{oq} = 0$, the active and reactive power injected into the grid can be calculated as follows:

$$P_{PCC} = \frac{3}{2}v_{od}i_{od}, \quad Q_{PCC} = -\frac{3}{2}v_{od}i_{oq} \quad (2)$$

3.2 FC Subsystem and PV Subsystem Control Strategies

In this study, a control strategy for the FC utilizes a proportional and integral (PI) controller to regulate the methane flow rate in the reformer. The goal is to adjust hydrogen flow based on the FC's output power and current based on the strategies given in [10]. The control strategy for optimizing PV output power is based on the boost DC-DC converter positioned between the PV generator and DC bus. This converter plays a critical role in extracting maximum power and ensuring operation at the Maximum Power Point (MPP) through MPPT control based on [11]. The MPPT controller adapts to varying environmental conditions, such as changes in irradiance and temperature, utilizing a Fuzzy Logic Control (FLC) algorithm.

3.3 Grid Connected Converter Control and Proposed Nonlinear Fuzzy Converter Control (NFCC) a

The primary goal of this subsection is to develop the Nonlinear Fuzzy Converter Control (NFCC) for the grid-side converter connected to the DC-Link. The overall TS fuzzy model is described as follows [12]

$$\begin{aligned} \dot{x}(t) &= \sum_{i=1}^p \mu_i(q(t)) [A_i x(t) + B_i u(t) + W] \\ y(t) &= \sum_{i=1}^p \mu_i(q(t)) [C_i x(t)] \end{aligned} \quad (3)$$

where: μ is the fuzzy sets, and p is the number of rules. To achieve this, dynamic fuzzy controller rules are formulated using the Parallel Distributed Compensation (PDC) method [13] tailored for the fuzzy model (3). The resultant output from the adapted fuzzy controller NFCC is defined as:

$$u(t) = \sum_{j=1}^p \mu_j K_j x(t) \quad (4)$$

where $K_j \in \mathfrak{R}^{m \times n}$ are feedback gain vectors. To analyze the closed-loop fuzzy system, we start with equations (3) and (4) considering $W = 0$. The main results for the global asymptotic stability of the TS fuzzy control system are summarized in the following Theorem:

Theorem 1. *The equilibrium of the fuzzy control system is asymptotically stable across its entire domain when employing the controller (4). This stability is guaranteed if the controller gains are chosen as $K_i = M_i Q^{-1}$, and there exists a positive definite symmetric matrix $P = Q^{-1}$. These conditions ensure the satisfaction of the following LMIs:*

$$\begin{aligned} Q A_i^T + A_i Q + (B_i M_i) + (B_i M_i)^T &\leq 0 \\ Q A_i^T + A_i Q + (B_j M_i) + (B_i M_j)^T & \\ + Q A_j^T + A_j Q + (B_i M_j) + (B_j M_i)^T &\leq 0 \end{aligned} \quad (5)$$

for $i \leq j$

These LMIs are crucial for verifying the stability and robustness of the closed-loop fuzzy control system, ensuring that it operates stably under various operational scenarios.

Proof. The proof can be given directly from [12].

4 Simulation studies

To assess the PV/FC hybrid power system and evaluate the proposed control strategy, MATLAB simulations were conducted based on the model described in Section II. The effectiveness of the strategy was verified under grid faults introduced by varying loads at specific intervals: from $t = 2.5$ sec to $t = 3$ sec and $t = 7$ sec to $t = 8$ sec, with a network fault occurring at $t_s = 5$ during 150ms.

Simulation results depicting the load voltage, current, active power and reactive power are shown in Fig. 2. The trajectories of the DC bus voltage and current are illustrated in Fig. 3. Additionally, the figures presenting the grid and inverter voltages, currents, active power, and reactive power are displayed in Fig. 4 and Fig. 5, respectively

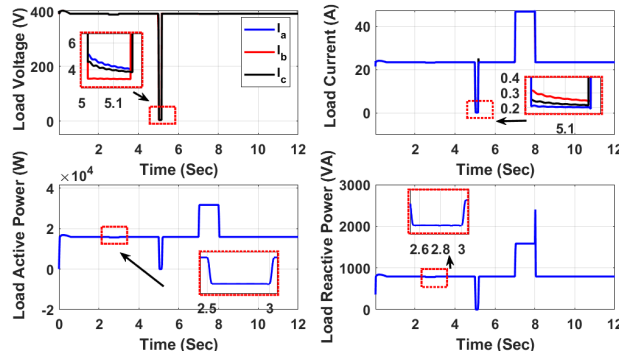


Fig. 2. Trajectories of the load voltage, current, active power and reactive power.

From the simulation results, It can be seen that the responses with varying the load and the grid faults are better damped with the proposed strategy.

5 Conclusion

The paper presented a control strategy for a PV/FC hybrid power system connected to a real network, focusing on precise DC-Link voltage control for both the DC and inverter. The strategy used Nonlinear Fuzzy Converter Control (NFCC) based on a Takagi-Sugeno fuzzy model and Linear Matrix Inequalities (LMIs) for robust system stabilization, especially during network short-circuit conditions.

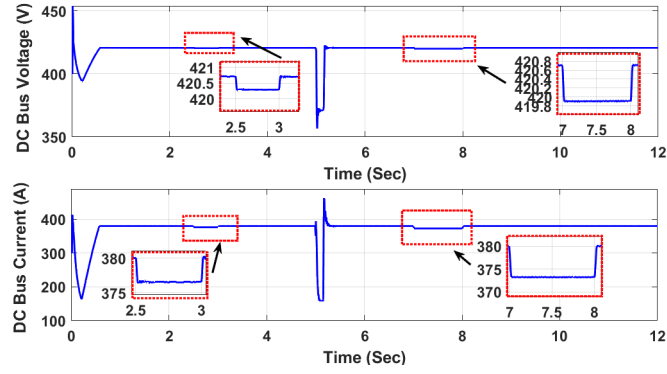


Fig. 3. Trajectories of the DC bus voltage and current.

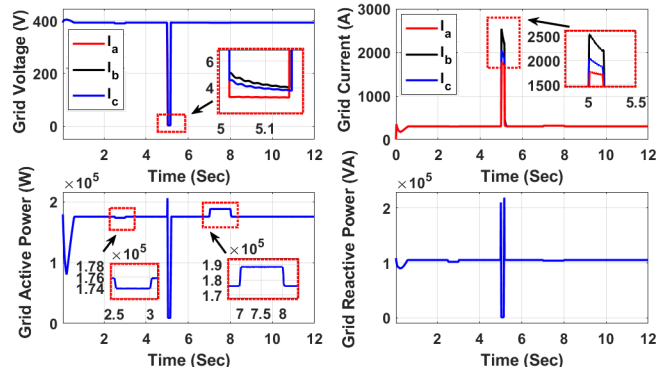


Fig. 4. Trajectories of the grid voltage, current, active power and reactive power.

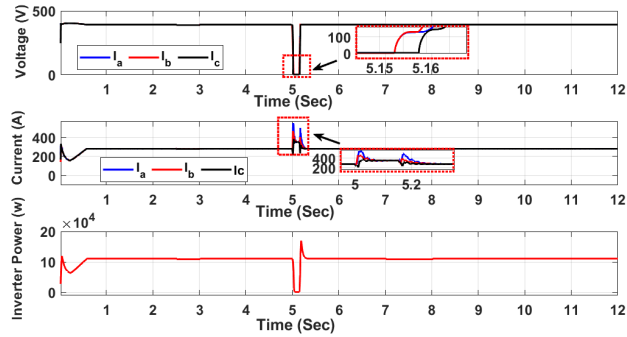


Fig. 5. Trajectories of the inverter voltage, current and power.

Maximum Power Point Tracking (MPPT) employed a fuzzy logic controller to optimize PV performance, while a Proportional-Integral (PI) controller regulated FC output power. This approach enhanced system performance during grid faults and integrated well with the network, adapting to specific grid conditions.

Simulation results demonstrated effective management of PV/FC operation under normal and fault conditions. Future research aims to expand this approach to include additional grid services, such as addressing sub-synchronous resonance in wind farms.

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