Energy Reports 12 (2024) 2958–2970

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

An enhanced maximum power point tracking and voltage control for proton exchange membrane fuel cell using predictive model control techniques

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ARTICLE INFO

Keywords:
Renewable Energy
Proton exchange membrane fuel cell
Maximum power point tracking
Finite-control-set model predictive control
DC-DC boost converter
DC-AC inverter

ABSTRACT

Proton Exchange Membrane Fuel Cells serve as sustainable devices for converting renewable energy sources into electricity, offering advantages such as rapid startup, high power density, and operation at low temperatures. They are highly efficient and environmentally friendly energy sources, yet their non-linear output characteristics under variable conditions present challenges in maximizing power output. Furthermore, they generates direct current, while many electrical devices rely on alternating current. This research addresses the necessity of enhancing the performance and efficiency through the development of an advanced maximum power point tracking technique and voltage control strategy. A modified finite-control-set model predictive control technique is proposed for both maximum power point tracking and voltage control. Specifically, a finite-control-set model predictive control technique approach is employed to modulate the switching signal for both the DC-DC boost converter and the DC-AC inverter. The DC-DC boost converter step up the fuel cell output voltage to the desired level, ensuring it reaches the maximum power point, and a DC-AC inverter to convert the direct current voltage to a pure sinusoidal alternating waveform. The investigation demonstrates the effectiveness of the proposed method in achieving its objectives. The proposed maximum power point tracking technique accuracy achieved the maximum power with a rate of 97 % with excellent respond time within 7 ms. For alternating current power, only less than 1.5 % of total harmonic distortion is recorded. The study evaluates the control scheme under robust operating conditions, demonstrating its effectiveness in optimizing PEMFC output and providing high-quality AC voltage.

1. Introduction

Renewable energy sources have many advantages over fossil fuels as they are cleaner, more sustainable, and less harmful to the environment and human health (Singla et al., 2023). Using renewable energy can also reduce greenhouse gas emissions and mitigate climate change. Fuel cell technology is one of the renewable energies that has high energy conversion efficiency, is environmentally friendly, and has demonstrated promising results using different renewable energy resources (Olabi et al., 2022). Hydrogen is considered as the future fuel as it has no environmental impacts and it could be produced from water by electrolysis and various other methods.

Fuel cells are one such electrochemical device that convert electrochemical energy to electrical energy without a combustion process (Huang et al., 2020). Fuel cells and chemical batteries are similar in that they both convert chemical energy directly into electrical energy. However, the energy of the battery is stored in a battery, whereas the chemical energy of the fuel cell is stored in its external fuel and oxidant (Huang et al., 2020). There are several advantages of fuel cell technology as it is compared to traditional power sources. It is more reliable, efficient silent when operating, and environmentally friendly (Aly and Rezk, 2020). Recently, fuel cells have been applied for portable electronic appliances, and electrical generation of power plants (Karthikeyan et al., 2018).

Proton exchange membrane fuel cell (PEMFC) is one of the most famous types of fuel cells due to its high efficiency, lightweight, low operating temperature, and quick start-up (Fathy et al., 2021). It is

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https://doi.org/10.1016/j.egyr.2024.08.055
Received 5 May 2024; Received in revised form 19 July 2024; Accepted 19 August 2024
Available online 6 September 2024
2352-4847/

Nomenclature

A	Active Area (cm^2)
A_q	Conversion Matrix A
B_q	Conversion Matrix B
C	Capacitance (mF)
C_f	Filter Capacitance (μF)
E_{nerst}	Cell Electric Potential (V)
f	Frequency (Hz)
F	Faraday Constant $(Cmol^{-1})$
k	Discrete Sampling Steps
k_{H_2}	Hydrogen Valve Molar Constant $(kmolatm^{-1} \quad s^{-1})$
k_{O_2}	Oxygen Valve Molar Constant $(kmolatm^{-1} \quad s^{-1})$
k_r	Modelling Constant $(kmolA^{-1} \quad s^{-1})$
n	Number of Electrons
N	Number of Cell
i	Iteration
i_i	Inverter Current (A)
i_s	Source Current (A)
i_L	Maximum Current Density (Acm^{-2})
I_{FC}	Fuel Cell Output Current (A)
I_{mpp}	Maximum Power Point Current (A)
I_{peak}	Peak Current (A)
I_{rms}	Root Mean Square Current (A)
L	Inductance (mH)
L_f	Filter Inductance (mH)
P_{avg}	Average Power (W)
P_{FC}	Fuel Cell Output Power (W)
P_{H_2}	Partial Pressure of Hydrogen Gas (atm)
P_{O_2}	Partial Pressure of Oxygen Gas (atm)
P_{peak}	Peak Power (W)
q_{H_2}	Hydrogen Input Flow $(kmols^{-1})$
q_{O_2}	Oxygen Input Flow$(kmols^{-1})$
R	Gas Constant $(J \quad mol^{-1} \quad K^{-1})$
R_f	Filter Resistance (Ω)
S	Switching State
t	Time (s)
t_m	Membrane Thickness (cm)
T	Operating Temperature (K)
T_s	Sampling Time (μs)
THD	Total Harmonic Distortion (%)
v_{ac}	AC Voltage (V)
v_i	Inverter Voltage (V)
v_s	Source Voltage (V)
V_{act}	Activation Overvoltage (V)
V_{boost}	Boost Converter Output Voltage (V)
V_{cell}	Cell Voltage (V)
V_{conc}	Concentration Overvoltage (V)
V_{FC}	Fuel Cell Output Voltage (V)
V_{ohm}	Ohmic Overvoltage (V)
V_{peak}	Peak Voltage (V)
V_{rms}	Root Mean Square Voltage (V)
ξ_1	Coefficient 1
ξ_2	Coefficient 2
ξ_3	Coefficient 3
ξ_4	Coefficient 4
λ_m	Membrane Water Content
τ_{H_2}	Hydrogen Time Constant (s)
τ_{O_2}	Oxygen Time Constant (s)

Abbreviations

AC	Alternating Current
CSO	Cuckoo Search Optimization
CVTF	Capacitor Voltage Feedback
DC	Direct Current
EA	Evolutionary Algorithm
ES	Extremum Seeking
FCS-MPC	Finite-Control-Set Model Predictive Control
FLC	Fuzzy Logic Control
FSSO	Flying Squirrel Search Optimization
GA	Genetic Algorithms
GFor	Grid-Forming
IBC	Interleaved Boost Converter
IC	Incremental Conductance
ISBO	Improved Satin Bowerbird Optimization
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NN	Neural Networks
NST	Non-shoot-through
PEMFC	Proton Exchange Membrane Fuel Cell
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PR	Proportional-Resonant
PSO	Particle Swarm Optimization
PV	Photovoltaic
P&O	Perturb and Observe
qZSI	Quasi-Z-Source Inverter
RBFN	Radial Basis Function Network
RNN	Rigdelet Neural Networks
SBI	Switched-Boosted Inverter
SMC	Sliding Mode Control
SFO	Sunflower Optimization algorithm
ST	Shoot-Through
VSI	Voltage Source Inverter
ZSI	Z-Source Inverter

suitable for most electrical appliances as it is manageable from a few watts to a few hundred kilowatts (Fathy et al., 2021). PEMFC is highly dependent on the operating temperature, membrane water content, and partial pressure of reactant gases and its output shows a non-linear behavior (Huang et al., 2020;Aly and Rezk, 2020). For example, Fig. 1 shows that different operating temperatures will create different V-I characteristic curves of PEMFC. This means that the fluctuation of the internal parameters of PEMFC will lead to variations in output power. For PEMFC to be implemented as effectively as possible, the cell must be run at the MPP in order to get the optimum power from it (George et al., 2022).This is the first aim of this research to study the PEMFC behaviour and maximize the output power.

The P-I polarization curves in Fig. 1 illustrate a specific maximum power point (MPP) for every operating temperature. Therefore, it is important to determine the MPP so that the efficiency of PEMFC can be maximized. Therefore, a maximum power point tracking (MPPT) technique becomes necessary in tracking the MPP of PEMFC. Derbeli et al (Derbeli et al., 2018). defined the maximum power current estimation equation to the PEMFC model for MPPT for all conditions of that particular PEMFC. It is the new defined polynomial equation that needs to be determined for each PEMFC before the implementation.

Since the MPPT is necessary for PEMFC, many MPPT methods have been introduced. George et al. (2022) reviewed the previous MPPT methods applied in PEMFC. Among the MPPT method, Perturb and Observe (P&O) control strategy and Incremental Conductance (IC) method are the conventional techniques of MPPT. Perturb and Observe