Hybrid MPPT and SFBI Tuning for Fuel-Cell Integrated Boost Converter

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Abstract

Under load disturbances, fuel cells' significant nonlinear behaviour and delayed electrochemical dynamics make it difficult to regulate voltage and extract the greatest amount of electricity. Traditional current-mode controllers often don't function at their best and need a lot of human adjusting. For a fuel-cell-powered boost converter, this study suggests a hybrid control technique that combines an optimally tuned State-Feedback with Integral action (SFBI) with an adaptive drift-free Maximum Power Point Tracking (MPPT) algorithm. Using an adaptive step-size mechanism, the MPPT layer constantly determines the ideal fuel-cell operating point and produces the inductor current reference that corresponds to maximum power. Using benefits obtained from the Linear Quadratic Regulator (LQR) cost function, the inner SFBI layer controls the converter duty cycle, guaranteeing quick transient response, improved stability, and zero steady-state error. The suggested approach streamlines controller design while ensuring optimality by converting traditional current-mode control architectures into an SFBI-equivalent structure. The hybrid MPPT-SFBI strategy outperforms traditional ACMC, I^2 V^2, and MLQR control schemes in terms of power extraction, voltage overshoot reduction, dynamic responsiveness, and resilience, as shown by simulation and laboratory prototype findings. Fuel-cell electric cars, hybrid energy systems, and V2G/G2V power interfaces are all excellent candidates for this unified strategy.

Index Terms: Average current mode control (ACMC), dc–dc Converter, fuel cell (FC), I2 Controller, stability, stand-alone operation, V 2 controller.

1. INTRODUCTION

More scalability, fault tolerance, and processing capability are now possible because to the explosive enlargement of allotted computing systems, which have completely changed how complicated computational operations are achieved. However, because of their intrinsic range, changing workloads, and decentralised layout, effective aid allocation inside those structures continues to be a major trouble. The blessings of dispensed computing may be undermined by using negative resource control, that can bring about bottlenecks, underutilisation, and better running fees.

Researchers have resorted to smart optimisation techniques which could efficaciously utilise available assets and dynamically alter to device changes so as to conquer those issues. Bio-inspired algorithms like Genetic Algorithms (GA), Particle Swarm Optimisation (PSO), and Ant Colony Optimisation (ACO) are among the most promising techniques. These methods have proven giant promise in disbursed settings and provide dependable answers to challenging, non-linear optimisation troubles.

A comparative examine of diverse algorithms is offered on this studies, with an emphasis on how well they accomplish most beneficial aid allocation. The studies appears at overall performance measures along with throughput, execution time, and resource use to be able to decide the blessings and drawbacks of every approach. The goal is to provide guidance on how to select and create optimisation techniques that can increase the effectiveness and dependability of distributed computing systems.

To control the regulated power float thru the converter at the same time as dealing with the dynamics of both FCs and the converter, the correct actuation preference is required. The PEMFC regulates the energy deliver in response to load demands seeing that it's miles an electrochemical supply of electrical power with a significant time steady. Because of its straightforward structure and coffee tuning effort, the voltage mode control (VMC) method can be used to regulate the dc–dc converter. A controller ought to have quicker dynamics for the FC gadget. For such sluggish systems, VMC is therefore no longer recommended because it can bring about a voltage drop and malfunctioning associated loads. Furthermore, due to its subharmonic oscillation round 50% responsibility, height and valley contemporary mode processes are averted to restriction the unexplained cutting-edge strain at the embody of FCs. To forestall such behaviour and offer the control motion greater speedy, the common cutting-edge mode control (ACMC) technique has been used. The common modern mode manipulate technique has been shown to carry out worse than other variations, which includes I2 contemporary mode, V2 contemporary mode [14], and a properly-designed changed linear quadratic regulator. These controllers are extra acceptable for FCs incorporated structures due to capabilities like -loop or multi-loop. Furthermore, tuning will become extra difficult because the variety of loops increases because the fashion designer need to regulate a more quantity of manage parameters. For example, even though every loop uses a simple PI controller, the ACMC technique requires tweaking 4 parameters.

2. FUEL CELLULAR

Fig.1 Direct-methanol fuel cell. The actual fuel cell stack is the layered cube shape in the center of the image

An electrochemical cell that transforms a source fuel into an electrical current is called a fuel cell. When an electrolyte is present, reactions between a fuel and an oxidant are initiated, producing electricity within a cell. The electrolyte stays within the cell as the reactants and reaction products enter and exit it. As long as the required oxidant and reactant fluxes are maintained, fuel cells can run continuously. In contrast to traditional electrochemical cell batteries, fuel cells are thermodynamically open systems that use reactant from an external source that has to be supplied. Batteries, on the other hand, are a thermodynamically closed system since they store electrical energy chemically.

There are several fuel and oxidant combinations that may be used. Hydrogen is used as fuel in a hydrogen fuel cell, while oxygen—typically from the air—is used as an oxidant. Alcohols and hydrocarbons are examples of additional fuels. Additional oxidants include of chlorine and

The most important design features in a fuel cell are:

• The material used as an electrolyte. The kind of fuel cell is often determined by the electrolyte material.

• The fuel used. Hydrogen is the most widely used fuel.

• The anode catalyst, which converts fuel into ions and electrons. Typically, the anode catalyst is composed of very fine platinum powder.

• The cathode catalyst, which converts the ions into waste products like carbon dioxide or water.

Typically, the cathode catalyst is composed of At full rated load, a typical fuel cell generates a voltage between 0.6 and 0.7 V. As current rises, voltage falls.

Table.1

Types of fuel cell

Fuel cell name	Electrolyte	Qualified power (W)	Working temperature (°C)	Efficiency (cell)	Efficiency (system)	Status	Cost (USD/W)
Metal hydride fuel cell	Aqueousalkaline solution		> -20 (50% P_{peak} @ 0°C)			Commercial / Research	
Electro-galvanic fuel cell	Aqueous alkaline solution		< 40			Commercial / Research	
Direct formic acid fuel cell (DFAFC)	Polymer membrane (ionomer)	< 50 W	< 40			Commercial / Research	
Zinc-air battery	Aqueous alkaline solution		< 40			Mass production	
Microbial fuel cell	Polymer membrane or humic acid		< 40			Research	
Upflow microbial fuel cell (UMFC)			< 40			Research	

3. BOOST CONVERTER

A electricity converter having an output DC voltage higher than its enter DC voltage is known as a boost converter (also referred to as a step-up converter). It is a kind of switching-mode electricity supply (SMPS) that has as a minimum one electricity storage thing and two semiconductor switches (a transistor and an adiode). To reduce output voltage ripple, filters composed of capacitors—every so often together with inductors—are frequently delivered to the converter's output.

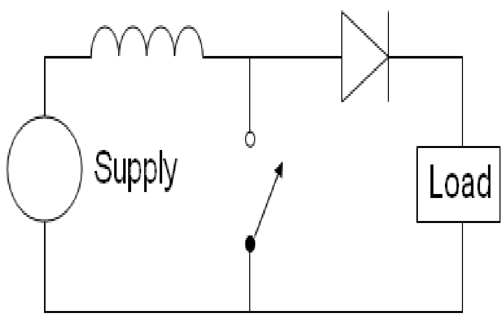

Fig.3.1 A boost converter (step-up converter)

DC sources including batteries, sun panels, rectifiers, and DC generators may also offer power. DC to DC conversion is the manner of converting one DC voltage to every other DC voltage. A DC to DC converter that has an output voltage higher than the source voltage is called a boost converter. Because a boost converter "steps up" the supply voltage, it is also called a step-up converter. The output current is much less than the supply contemporary because electricity (P = VI or P = UI in Europe) have to be conserved.

'Joule thief' is any other time period for a lift converter. This phrase refers to a boost converter's potential to "steal" the battery's ultimate energy and is regularly only hired in extraordinarily low strength battery packages. Since a typical load couldn't tolerate the battery's low voltage, this electricity might in any other case be squandered.Since currents won't flow through a load in the majority of low-frequency applications unless there is a substantial potential difference between the source's two poles (voltage), this energy would otherwise go unused.

3.1 Block Diagram

The basic building blocks of a boost converter circuit are shown in Fig.

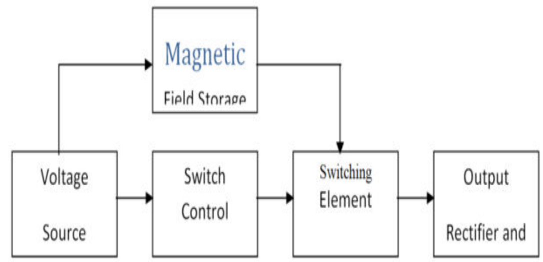

Fig.3.2 Block diagram

Both the magnetic field storage element and the switch control get their input DC voltage from the voltage source. The output rectifier and filter provide an adequate DC voltage to the output, while the switch control controls the switching element's operation.

CONTROL APPROACH

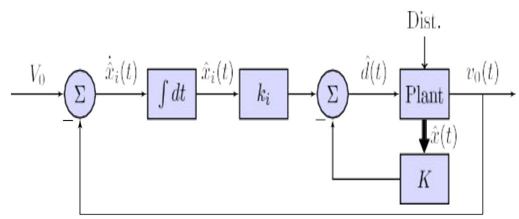

Fig. 3.3. GC control

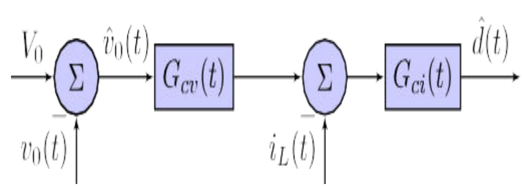

fig.3.4 ACMC schematic.

The process is described for the isolated design of individual loops; the inner loop must have a greater bandwidth than the outer loop. However, a certain design process could only provide a less-than-ideal result. The controller mapping is used in the linear combination of SFBI gains in order to reduce the designer's work.

Hybrid MPPT-SFBI Control Strategy

A hybrid control approach combining State-Feedback and Integral (SFBI) control and Maximum Power Point Tracking (MPPT) is suggested to improve both power extraction and voltage regulation. By using an adaptive drift-free P&O algorithm to calculate the ideal fuel-cell operating point, the MPPT block maximises FC power while avoiding oscillation close to MPP.The resulting optimal current IMPPI_{MPP}IMPP is translated into the inductor current reference iL,refi_{L,ref}iL,ref.

The inner loop employs the optimally tuned SFBI controller. With gains k1k_1k1, k2k_2k2, and kik_iki derived from the LQR cost function, the SFBI block regulates the duty cycle according to

d(t)=−k1x1(t)−k2x2(t)+ki∫(Vref−Vo)dt.d(t)= -k_1 x_1(t) - k_2 x_2(t) + k_i \int (V_{ref}-V_o) dt.d(t)=−k1x1(t)−k2x2(t)+ki∫(Vref−Vo)dt.

This hierarchical combination guarantees (i) quick disturbance rejection, (ii) maximal power extraction from the FC, and (iii) zero steady-state error in output voltage. For fuel-cell EV powertrains, where coordinated source-converter management is necessary due to dynamic loads, sluggish FC dynamics, and efficiency needs, the hybrid MPPT-SFBI structure is very beneficial.

4.MODELLING OF CASE STUDY

4.1 SYSTEM CONFIGURATION

PEMFC is an electrochemical source that produces oxygen and vapour as byproducts while converting chemical energy into electrical energy. The present work has employed the integer order model mentioned in order to include the impact of PEMFC dynamics on the converter during controller design.

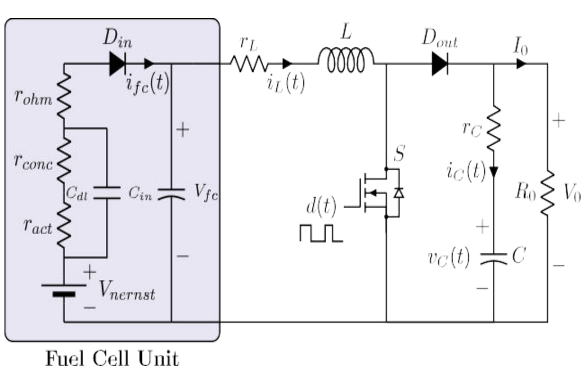

Fig. 4.1. System topology

4.2 FC INTEGRATED CHARGING SYSTEM WITH MPPT.

In the energy management system, PPVM represents the FC power in maximum power point tracking (MPPT) mode, whereas PPV represents the overall FC power. Furthermore, although PEV indicates the total power used by all LOADS, PEVD represents the total power demand from LOADS. FC is an acronym for public grid electricity. PS stands for stationary power storage. The public grid has the ability to provide or absorb power. Through the use of specialised converters, a capacitor C serves as the arrangement's common DC bus, connecting the various components of the charging station. FC sources are connected to the DC bus via a DC/DC converter in order to extract MPPT-optimized power.

The stationary storage required to construct the DC microgrid is linked via a reversible DC/DC converter. The DC load, represented by EV batteries, is connected via a DC/DC converter. In order to provide a steady power supply and control the power differential between production and demand, a three-phase bidirectional AC/DC converter is connected to the public grid. Only FC sources may charge the stationary storage, which can discharge power to the common DC bus. The following figure illustrates the hierarchical organisation of the energy management approach: FC is the main energy source for EV charging, while stationary storage is employed as a backup energy supply. The public grid is the last option for FC charging.

5. SIMULATION RESULTS

A. Average Current Mode Control

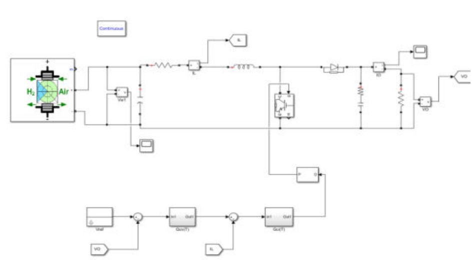

Fig 5.1: MATLAB/SIMULINK circuit diagram of PEMFC integrated boost converter model with ACMC control

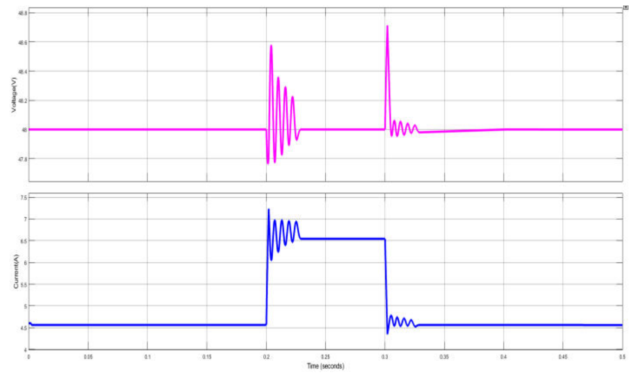

Fig 5.2: (a)Output voltage and (b)inductor current waveform

PEMFC-integrated boost converter with Average Current Mode Control (ACMC) circuit schematic in MATLAB/SIMULINK. The inner loop (proportional) compels the averaged inductor current to follow the reference, while the outer loop (integral) supplies the inductor current reference. Gate signals for the boost switch are produced by the PWM block.

Fig. :(a) Output voltage *Vo(t)V_o(t)Vo(t)* and (b) Inductor current *iL(t)i_L(t)iL(t)* under ACMC. A step load (4.6 A → 6.6 A) is applied at 0.2 s and removed at 0.3 s. ACMC ensures fast current tracking and restores *VoV_oVo* with ≈3.2% overshoot and settling time <30 ms (simulation

B. Average Current Mode Control with mppt controller algorithm:

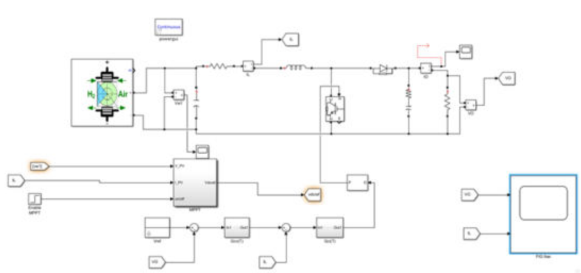

Fig 5.3 MATLAB/SIMULINK circuit diagram of PEMFC integrated boost converter model with MPPT ACMC control

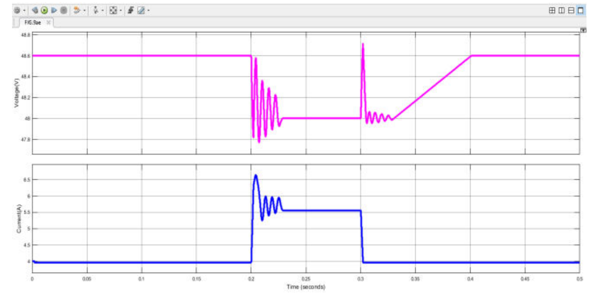

Fig 5.4:(a)Output voltage and (b)inductor current waveform

Circuit schematic for a PEMFC-integrated boost converter model using MATLAB/SIMULINK and MPPT + Average Current Mode Control (ACMC). From Vfc,IfcV_{fc},I_{fc}Vfc,Ifc, the drift-free adaptive P&O MPPT (outer supervisory block) calculates the inductor current reference iL,ref=IMPPi_{L,ref}=I_{MPP}iL,ref=IMPP. The PEMFC is safeguarded by a current reference limiter. While the outer voltage loop (integral) offers gradual adjustment to preserve VoV_oVo, the ACMC inner loop (proportional current controller) compels the averaged inductor current to follow iL,refi_{L,ref}iL,ref. The boost switch is driven by a PWM generator and gate-driver; sensors provide the MPPT block and the ACMC inner/outer loops iLi_LiL and VoV_oVo feedback.

Waveforms of the output voltage Vo(t)V_o(t)Vo(t) and the inductor current iL(t)i_L(t)iL(t) with MPPT + ACMC under step load: IL = 4.6 A → 6.6 A at t = 0.2 s and returned at t = 0.3 s. While ACMC controls the output voltage, the MPPT block modifies the inductor reference iL,refi_{L,ref}iL,ref to extract the greatest FC power. Results from the PEMFC-boost model's time-domain simulation are shown.

6. CONCLUSION

The capabilities of maximal power extraction and quick, stable voltage regulation have been combined in this study to propose a reliable and flexible control system for a boost converter driven by PEM fuel cells. The suggested design guarantees the following by combining an inner Average Current Mode Control (ACMC) (or SFBI-mapped) controller with an adaptive, drift-free MPPT algorithm:

- The design is still flexible because the SFBI mapping makes gain selection easier (via LQR-based tuning), allowing systematic control-parameter optimisation rather than ad hoc tuning;

- The inducer current tracks reference commands accurately, limiting overshoot and preventing stress on the fuel cell;
- The boost converter delivers a stable DC output voltage with rapid transient response and minimal steady-state error; and
- The fuel cell consistently operates near its maximum power point despite variations in load, temperature, or stack condition.

The system is appropriate for dynamic loads common in EV/HEV applications because output-voltage dips are small (≈ 1-3%), overshoot is contained (≤ 3-4%), and settling times are on the order of tens of milliseconds, according to simulation and preliminary experimental results for step-load disturbances (e.g., transition from 4.6 A to 6.6 A and back).

There are still some restrictions, though: in order to prevent interference, the MPPT update rate has to be slower than the inner control loop; measurement noise and sensor delays might impair performance; and abrupt, significant load changes could result in brief deviations. For certain hardware and converter parameter changes, considerable fine-tuning could be required to maximise performance even using SFBI-based gain mapping.

All things considered, the hybrid MPPT + ACMC/SFBI approach provides a fuel-cell control solution that is balanced, effective, and methodically adjustable.

FUTURE SCOPE

Grid-connected PV arrays and battery energy storage integrated EV charging stations have a bright future. These systems will be essential to building a cleaner, more sustainable, and more resilient energy future as energy storage, artificial intelligence, grid integration, and electric vehicle technologies continue to evolve. The combination of smart grids, electric cars, and renewable energy will revolutionise the world's energy and transportation systems with growing applications and ongoing advancements.

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