Grid-Connected Fuel Cell with Upgraded Voltage Profile

Purvaa Saxena and S. K. Jha

Abstract In this work, an electrical network connected to proton exchange membrane fuel cell (PEMFC) is considered. The voltage profile of the system is enhanced by connecting the fuel cell with the boost converter and a seven-level cascaded multilevel inverter. The traditional PID controller does not responds to the nonlinearities of the system. Hence, PID controller is dynamically tuned by the Whale Optimization Algorithm (WOA). The whole architecture is developed in SIMULINK. For testing the effectiveness of the proposed model, the transients are given to the system for short duration and the results are then compared. It is observed that the proposed model has improved voltage response and reduced harmonics. The analysis for the power quality enhancement is confirmed through Total Harmonic Distortion (THD).

Keywords Whale Optimization Algorithm (WOA) · Proton exchange membrane fuel cell (PEMFC) · Boost converter (BC) · Multilevel inverter (MLI) · Cascaded H-Bridge (CHB) · Total Harmonic Distortion (THD)

1 Introduction

Fuel cell is a device responsible for the conversion of chemical energy of hydrogen to electricity [1]. There are various types of FC that can be used in electrical grid. However, PEMFC has been used as energy source in this paper due its high-power density, light weight and less starting time [2].

Conventional PID controller is a linear device which is used to minimize the error of the system [3]. The main drawback of the conventional PID controller is that it does not respond to the nonlinearities of the system. So, to encounter this, the parameters of the PID controller are dynamically tuned by various algorithms such as PSO [4], Genetic Algorithm [5], Bat Search [6] and evolutionary algorithms

P. Saxena (✉) · S. K. Jha
Department of Instrumentation and Control Engineering, Netaji Subhas University of Technology, New Delhi, India
e-mail: purvaas.ie20@nsut.ac.in

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[7]. These algorithms have some shortcomings such as slow convergence speed and precision. So, to overcome these issues, WOA has been implemented in this paper.

Furthermore, the low-level output voltage of the fuel cell is stepped up by the boost converter. The DC voltage of the boost converter is converted to the AC voltage using a three-phase seven-level cascaded multilevel inverter. An MLI gives better system stability along with decreased harmonics. Also, the THD values is reduced by this model. The gate signal to the inverter is given through the PID controller. The parameters of the PID controller are dynamically tuned using WOA algorithm. It has been observed that this controller gives better voltage characteristics and improved efficiency.

This paper shows PEMFC-based grid connected model. The model has been developed in MATLAB/SIMULINK. The proposed model promises to improve the voltage profile during the transient stage. It has been observed that this controller gives better voltage characteristics and improved efficiency when the system is subjected to transients.

2 Mathematical Modelling

2.1 Modelling of PEMFC

This section deals with the electrochemical model of the PEMFC. PEMFC has more advantages over other FC such as it has less starting time, design is compact and low cost. So, PEMFC has been considered in this paper.

A mathematical model is used to predict the dynamic behaviour of the PEMFC. The V_{FC} of the fuel cell is given by:

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohm} - V_{con} \tag{1}$$

where E_{Nernst} is thermodynamic potential and represents reversible voltage, V_{act} is activation voltage, V_{ohmic} is ohmic voltage drop and V_{con} represents concentration losses [9].

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3}(T - 298.15) + \frac{R \cdot T}{2 \cdot F} \ln\left(P_{O_2}^{0.5} P_{H_2}\right) \tag{2}$$

$$V_{act} = -[\xi_1 + \xi_2 \cdot T_3 \cdot T \cdot \ln(CO_2) + \xi_4 \cdot T \cdot \ln(I_{FC})] \tag{3}$$

$$V_{ohm} = I_{fc}(R_M + R_C) \tag{4}$$

$$V_{conc} = -B \ln\left(1 - \left(\frac{J}{J_{max}}\right)\right) \tag{5}$$

where P_{O_2} and P_{H_2} are the partial pressures (atm) of oxygen and hydrogen, T is the absolute cell temperature (K), I_{fc} is the cell operating current (A), ξ_i ($i = 1 \ldots 0.4$) represents the parametric coefficients for each cell model, R_M is equivalent membrane resistance to proton conduction, R_C is the equivalent contact resistance to electron conduction, J_{max} is then maximum current density and J is actual current density.

2.2 Modelling of Boost Converter

Boost converter is a DC-to-DC power electronic converter. It is used to enhance the input voltage. It is also known as step up chopper. The switching of the switch is controlled by the PWM signal. The model consists of input voltage source (V_s), diode (D), inductor (L), switch (S) and capacitor (C). When the switch is in ON state, it offers low resistance path to the current. So, the current flows through switch and back to the source. Meanwhile, the inductor stores the energy. When the switch is in OFF state, the inductor reverses its polarity and the stored energy of inductor is dissipated through the load [8].

3 Control Structure

3.1 PID Controller

Conventional PID controller is a linear device which is used to minimize the error of the system. The most commonly used controller is the PID controller. PID has three basic control behaviours which are proportional, integrator and derivative. The controller has three parameters, namely K_p, K_i and K_d. The parameters of the controller are then dynamically tuned by WOA.

3.2 Seven-Level Cascaded Multilevel Inverter

MLI are the widely used inverters. One of the most common MLI is CHB inverter as it gives better signal quality with reduced THD. The seven-level CHB MLI gives seven steps in the output voltage waveform. If the input voltage is V_{DC} then output voltage will be 3 V_{DC}, 2 V_{DC}, V_{DC}, 0, $-V_{DC}$, -2 V_{DC} and -3 V_{DC} [9].

3.3 Whale Optimization Algorithm

WOA is based on the foraging behaviour of the humpback whales. Foraging behaviour refers to the technique of bubble making. Since whales have slow speed so they cannot catch the fishes. So, they came up with a technique, wherein they form bubbles for catching the fishes. The bubble is basically created in a spiral format around the fishes. This forces the fishes to move towards the surface and the radius of the spiral keeps decreasing [10]. The mathematical model is given as-

(A) Random Prey: It forces the search agent to move away from the present location. It moves randomly in the space for searching. The formula is

$$\vec{D} = \left| \vec{C} \times \overrightarrow{P_{\text{rand}}} - \overrightarrow{P_l^t} \right| \tag{6}$$

$$\overrightarrow{P_l^t} = \overrightarrow{P_{\text{rand}}} - \vec{A} \times \vec{D} \tag{7}$$

where $\vec{P}$ is the various position vectors.

(B) Encircling prey: When $p < 0.5$ and $\left|\vec{A}\right| \leq 1$, it finds the prey and surrounds it. It is given by

$$\vec{D} = \left| \vec{C} \times \overrightarrow{P_*^t} - \overrightarrow{P_l^t} \right| \tag{8}$$

$$\overrightarrow{P_l^{t+1}} = \overrightarrow{P_l^t} - \vec{A} \times \vec{D} \tag{9}$$

where $\overrightarrow{P_*^t}$ is the position vector of tth generation.

(C) Bubble-net attacking: When $p \geq 0.5$, it calculates the distance between search agent and optimal search agent. It then calculates the spiral model to update the position of the search agent.

$$\overrightarrow{P_l^{t+1}} = \overrightarrow{D^l} \cdot e^{bl} \cdot \cos(2\pi l) + \overrightarrow{P_*^t} \tag{10}$$

The pseudocode for WOA is given as

Initialize the whale's population
Set algorithm parameters
Set performance index
Calculate fitness of all search agent
While (termination is not satisfied)
Encircle prey
Search the prey

(continued)

(continued)
Compute the fitness by index
End While
Return the best result
End

4 MATLAB/Simulink Model

In this work, PEMFC is used. PEMFC is coupled with boost converter which is used for increasing the FC output. The boost converter is further connected to a three-phase seven-level CHB MLI which inverts the DC voltage into seven-level AC voltage. The gate signal of the inverter is given through the PID controller. In order to evaluate the performance of the power network, the system is subjected to oscillatory transient fault ($t = 0.3$–0.4 s). The obtained results show that proposed technique gives better results than the conventional PID controller (Fig. 1 and Table 1).

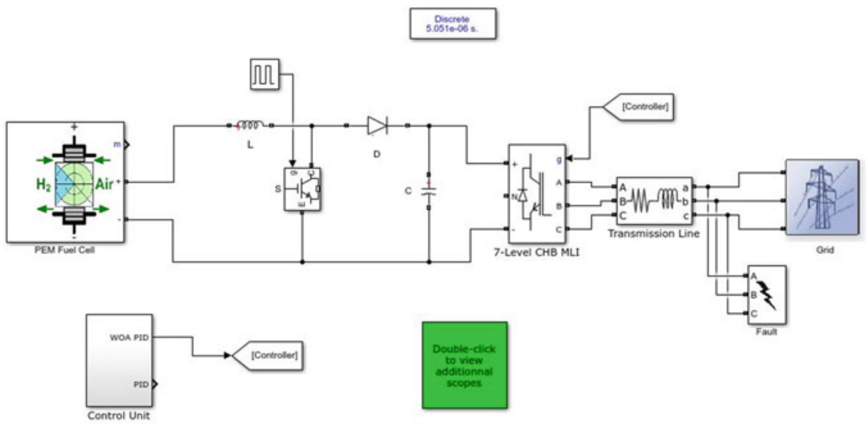

Fig. 1 Simulink model of the proposed system

Table 1 Values of different parameters

Parameters	Values
SOFC	$V_o = 60$ V, $R_1 + R_2 = 1.4\ \Omega$, $R_3 = 1.06\ \Omega$, $C = 1.25$ F
Boost	L = 0.8 mH, c = 100 μF, $F_s = 30$ KHz, $V_o = 100$ V, $V_{in} = 40$ V
Grid	$v = 600$, $x/r = 7$, $f = 50$ Hz

5 Results

Figures 2 and 3 depict the voltage waveforms of the power network during faults for PID and WOA optimized PID, respectively. It is seen from the figures that the harmonic content has been reduced tremendously when the parameters of the PID controller are tuned with WOA algorithm. Moreover, the system tends to become more stable.

Figure 4 show the THD values for PID and WOA-PID. The THD values obtained for PID and the proposed model are 9.08% and 1.15%, respectively. It is seen that the proposed model is more effective in reducing the harmonic contents and gives transient stability.

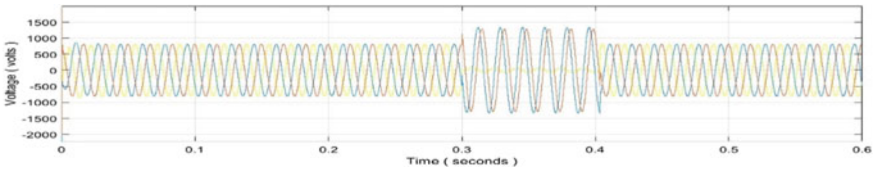

Fig. 2 Voltage profile during fault for PID

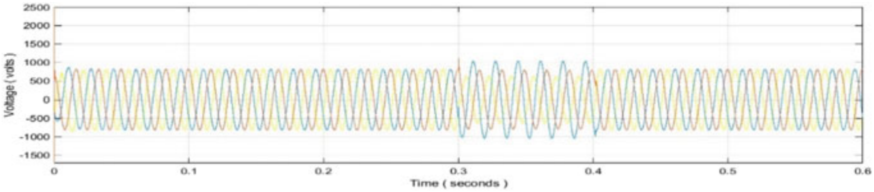

Fig. 3 Voltage profile during fault for WOA optimized PID

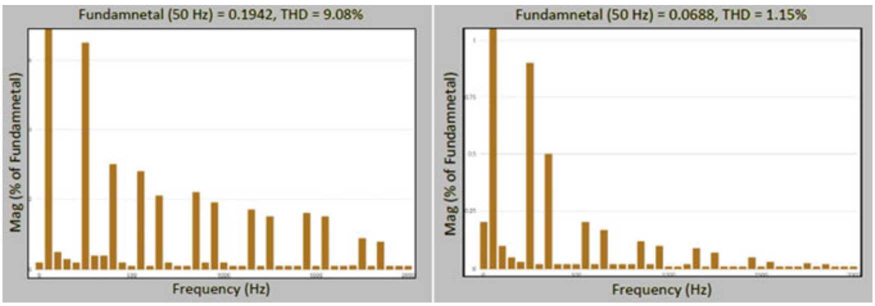

Fig. 4 THD of the voltage for PID and WOA optimized PID, respectively

6 Conclusion

In this paper, a fuel cell connected grid network is proposed, wherein the parameters of the PID controller are dynamically tuned with WOA algorithm. Due to dynamic tuning of the parameters, the PID controller can robustly respond to the nonlinearities of the system. The proposed technique compares the conventional PID controller with the WOA-PID controller. The system is given transients for short duration. By comparing the results, it is observed that during the transients fault, the proposed model is more effective in reducing the harmonic contents and gives transient stability. Moreover, the WOA optimization technique gives better power quality and voltage profile with reduced peak time and rise time thereby, improving the dynamic profile of the system. So, the fuel cell connected grid stands to be a potential candidate for generating electricity in near future.

References

1. Akinyele D, Olabode E, Amole A (2020) Review of fuel cell technologies and applications for sustainable microgrid systems. In: Inventions, pp 5–42
2. Kavya VR, Padmavathy KS, Shaneeth M (2013) Steady state analysis and control of PEM fuel cell power plant. In: International conference on control communication and computing (ICCC), pp 233–237
3. Chopra V, Singla SK, Dewan L (2014) Comparative analysis of tuning a PID controller using intelligent methods. ACTA Polytech Hung, 235–249
4. Ruan J, Zhang B, Liu B, Wang S (2021) The multi-objective optimization of cost, energy consumption and battery degradation for fuel cell-battery hybrid electric vehicle. In: 2021 11th international conference on power, energy and electrical engineering (CPEEE), pp 50–55
5. Lianfeng L, Ting-Cheng C (2019) Parameter optimization of hybrid fuel cell system based on genetic algorithm. In: 2019 IEEE Eurasia conference on biomedical engineering, healthcare and sustainability (ECBIOS), pp 102–104
6. Yang XS (2010) A new metaheuristic bat -inspired algorithm. In: Gonzalez JR et al (eds) Nature-inspired cooperative strategies for optimization (NICSO2010). Springer, SCI 284¸ pp 65–74
7. Buchaniec S, Sciazko A, Mozdzierz M, Brus G (2019) A novel approach to the optimization of a solid oxide fuel cell anode using evolutionary algorithms. IEEE Access 7:34361–34372
8. Hu X, Ma P, Wang J, Tan G (2020) A hybrid cascaded DC–DC boost converter with ripple reduction and large conversion ratio. IEEE J Emerg Sel Top Power Electron 2020:761–770
9. Abhilash T, Kirubakaran A, Somasekhar VT (2017) A novel three-phase seven-level inverter. In: Innovations in power and advanced computing technologies (i-PACT), pp 1–5
10. Zhai Q, Xia X, Feng S, Huang M (2020) Optimization design of LQR controller based on improved whale optimization algorithm: In: 2020 3rd international conference on information and computer technologies (ICICT), pp 380–384