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Energy Management in a Proton Exchange Membrane Fuel Cell-based DC Microgrid Using Feedback Linearization Control and GWO

***Abstract**. This paper proposes a new energy management approch based on th integration of Grey Wolf Optimization (GWO) with Feedback Linearization Control (FLC) for a DC microgrid. The studied hybrid power system uses multiple power sources based on a Proton Exchange Membrane Fuel cell (PEMFC), and supercapacitor (SC). The proposed energy management strategy optimizes the ration use of the sources in order to minimize fuel consumption and maximize the renewable energy sources part. The strategy also takes account on the intrinsic specificities of PEMFC and SC, such as their response time and efficiency, to ensure smooth and stable operation of the system. The fuel consumption, dynamic performance, and service life of power sources can be significantly impacted by the energy management strategy used to accommodate fluctuations in power demand. The proposed strategy performances is verified through extensive simulation results.*

Streszczenie.** W artykule zaproponowano nowe podejście do zarządzania energią oparte na integracji optymalizacji Gray Wolfa (GWO) z kontrolą linearyzacji ze sprzężeniem zwrotnym (FLC) dla mikrosieci prądu stałego. Badany hybrydowy system zasilania wykorzystuje wiele źródeł zasilania opartych na ogniwie paliwowym z membraną do wymiany protonów (PEMFC) i superkondensatorze (SC). Zaproponowana strategia zarządzania energią optymalizuje racjonalne wykorzystanie źródeł w celu minimalizacji zużycia paliw i maksymalizacji udziału energii odnawialnej. Strategia uwzględnia także wewnętrzną specyfikę PEMFC i SC, taką jak czas reakcji i wydajność, aby zapewnić płynne i stabilne działanie systemu. Strategia zarządzania energią stosowana w celu uwzględnienia wahań zapotrzebowania na moc może znacząco wpływać na zużycie paliwa, wydajność dynamiczną i żywotność źródeł zasilania. Efektywność zaproponowanej strategii jest weryfikowana poprzez obszerne wyniki symulacji.* (Zarządzanie energią w paliwie z membraną do wymiany protonów Mikrosieć prądu stałego oparta na komórkach wykorzystująca kontrolę linearyzacji ze sprzężeniem zwrotnym i GWOP***)

Keywords: Energy management, Fuel Cell, Supercapacitor, DC microgrid, Grey Wolf Optimization (GWO).
Słowa kluczowe: Zarządzanie energią, ogniwo paliwowe, superkondensator, mikrosieć prądu stałego, optymalizacja szarego wilka

Introduction

A DC microgrid is an electrical power system that operates on direct current (DC) and is designed to provide reliable and efficient power to a localized area, such as a building, campus, or community [1]. It can operate in isolation or be connected to the main power grid [2]. DC microgrids are becoming increasingly popular due to their numerous advantages over traditional AC microgrids. Some of the benefits of DC microgrids include: Higher efficiency: DC microgrids eliminate the need for DC-AC and AC-DC conversions[3], which can result in significant power losses[4], Better integration with renewable energy sources[5] , Reduced costs[6], Improved power quality[7], Increased control[8]. DC microgrids typically consist of multiple energy sources, such as solar panels, batteries, fuel cells, and generators, as well as DC loads and a DC bus. Energy storage systems are often used in DC microgrids to provide backup power and improve system stability . Overall, DC microgrids offer a promising solution for meeting the growing demand for reliable and sustainable power in localized areas [8][9][10][11].

Integrating Proton Exchange Membrane (PEM) fuel cells into a DC microgrid can offer a dependable and effective power supply. The process of combining hydrogen and oxygen in PEM fuel cells produces electricity as well as byproducts in the form of water and heat [12]. They are highly efficient, with efficiencies of up to 60%, and have the potential to significantly reduce greenhouse gas emissions when powered by renewable sources of hydrogen. PEM fuel cells can be used in DC microgrids to provide backup power, peak shaving, or to meet the base load power requirements of the microgrid. When integrated with renewable energy sources, such as wind turbines or solar panels, PEM fuel cells can help to smooth out fluctuations in power generation and provide a reliable source of power when renewable sources are not available. To integrate PEM fuel cells into a DC microgrid, power electronics are used to convert the DC output of the fuel cell into the appropriate voltage and frequency for the microgrid [13]. The power electronics not only allow the fuel cell to function at peak efficiency, but also regulate the flow of power to and from the cell. Energy storage systems, such as batteries or capacitors, can be used to store excess power generated by the fuel cell and provide backup power during times of low power generation[14]. Overall, PEM fuel cells offer a promising solution for integrating reliable and efficient power generation into DC microgrids. They have the potential to significantly reduce greenhouse gas emissions and increase the sustainability of microgrid operations, while providing a reliable source of power to meet the growing demand for energy [12]. PEMFCs are commonly used in transportation applications, such as fuel cell vehicles (FCVs), where they provide an efficient and clean alternative to traditional internal combustion engines. They are also used in stationary power generation applications, where they can provide reliable and clean energy for homes, businesses, and communities. Despite their many benefits, PEMFCs face challenges such as high costs and the need for infrastructure for hydrogen production, storage, and distribution. However, ongoing research and development efforts are aimed at addressing these challenges and improving the efficiency and scalability of PEMFCs for widespread adoption in various applications [3].

The energy management system (EMS) utilized for various power sources plays a critical role in determining their fuel consumption, dynamic performance, and overall service life. The EMS aims to balance the energy demand and supply in a cost-effective and efficient manner, while also ensuring stable operation and optimal utilization of the available resources [19].

Furthermore, the energy management strategy should consider the fluctuations in energy demand and supply, which can be caused by changes in load demand, weather conditions, and availability of energy resources. The strategy should be able to adapt to these fluctuations and adjust the power output of the various sources accordingly to maintain stable operation and meet the energy demand [20].

Inspired by the hunting patterns of grey wolves, the GWO algorithm is a meta-heuristic optimization technique. The algorithm is based on the social hierarchy and hunting behavior of wolves, which involves cooperation, communication, and competition[15][16][17][18] . The algorithm can be used to optimize complex problems such as energy management in microgrids [19][20][21][22].

Feedback Linearization Control is a control strategy that utilizes feedback to convert a nonlinear system into a linear one. This technique is useful for controlling complex systems such as fuel cell-based microgrids. The control strategy ensures stable operation and optimal utilization of energy resources [23][24][25][26].

To apply GWO for energy management in a fuel cell-based DC microgrid using Feedback Linearization Control, the following steps can be taken:

Identify the objectives and constraints of the microgrid, such as minimizing fuel consumption, maximizing the use of renewable energy sources, and ensuring stable operation.

Develop a mathematical model of the microgrid and identify the control variables, such as the power output of the fuel cells and supercapacitor.

Apply Feedback Linearization Control to the mathematical model of the microgrid to transform the nonlinear system into a linear system.

To meet the objectives and constraints of the microgrid, the control variables (such as the power output of fuel cells and renewable energy sources) can be optimized using GWO.

Evaluate the performance of the microgrid under different operating conditions, such as changes in load demand, weather conditions, and availability of energy resources.

Energy management in a fuel cell-based DC microgrid can be optimized by utilizing GWO in combination with Feedback Linearization Control, optimal performance and efficient utilization of energy resources can be achieved. The algorithm can be used to optimize the power output of the various energy sources in the microgrid, thereby ensuring stable operation and reducing energy costs. This paper is organized as follows: Section 1 provides an introduction. Sections 2 and 3 describe the models of the Proton Exchange Membrane Fuel and Supercapacitor, respectively. Section 4 presents the DC/DC converter, while Section 5 explains the control strategy, including the optimization algorithm discussed in Section 6. The simulation results are presented in Section 7, and Section 8 highlights the primary contributions of this work.

2. Mathematical Modeling

This part describes the mathematical modeling of the converters power level. the supercapacitor and the fuel cell are connected in parallel with the converter. The supercapacitor is connected with the converter as a bidirectional DC-DC converter. A bidirectional DC-DC converter is capable of converting power in both directions, depending on the direction of the power flow. The fuel cell is connected with boost converter. DC/DC converters are electronic circuits used to convert a DC input voltage to a DC output voltage of a different level. They are commonly used in power supply applications where the voltage level of the input source needs to be regulated to provide a constant voltage level to the load [4]. The mathematical model of the converters power level is as follows:

$$
\begin{aligned}
\frac{di_{FC}}{dt} &= \frac{U_{FC}}{L} - \frac{v_{dc}}{L} + \frac{v_{dc}}{L}d \\
\frac{dv_{dc}}{dt} &= \frac{i_{FC}}{C}(1-d) - \frac{v_{dc}}{RC} \\
\frac{di_{SC}}{dt} &= \frac{v_{SC}}{L}d - (1-d)\frac{v_{dc}}{L} \\
\frac{dv_{dc}}{dt} &= -\frac{v_{dc}}{RC} + \frac{i_{SC}}{C}(1-d)
\end{aligned} \tag{1}
$$

Where d is duty cycle,U_{Sc} is the voltage of input voltage, i_{SC} is the currant of FC.

3. Modeling of Proton Exchange Membrane Fuel Cells (PEMFCs)

Proton Exchange Membrane Fuel Cells (PEMFCs) utilize an electrochemical process to convert the chemical energy found in hydrogen and oxygen into electrical energy. The PEMFC uses a polymer electrolyte membrane to transport positively charged hydrogen ions (protons) from the anode to the cathode, where they combine with oxygen and electrons to form water and produce electricity[12].

The PEMFC is a remarkably efficient and environmentally friendly energy conversion technology with the potential to replace traditional combustion-based technologies across various applications, such as transportation, stationary power generation, and portable electronics. Some of the key benefits of PEMFCs include[13]:

1- High efficiency: PEMFCs have a high energy conversion efficiency, typically between 40% and 60%, making them more efficient than traditional combustion-based technologies.

2- Clean energy: PEMFCs produce no harmful emissions, such as nitrogen oxides (NOx) or sulfur dioxide (SO2), and the only byproduct is water, making them a clean energy source.

3- Flexible fuel options: PEMFCs can use a variety of fuels, including hydrogen, natural gas, methanol, and ethanol, making them versatile energy conversion technologies.

4- Low noise and vibration: PEMFCs operate quietly and with low vibration, making them suitable for use in noise-sensitive environments.

To model Proton Exchange Membrane Fuel Cells (PEMFCs), several methods are employed to simulate the intricate electrochemical and thermal processes that take place within the cell. Analytical methods involve solving simplified mathematical models to obtain analytical solutions that describe the performance of the PEMFC. These models often assume one-dimensional transform and neglect complex processes such as water management and cell flooding. However, analytical models can provide valuable insights into the fundamental processes of the cell and are useful for understanding the basic principles of PEMFC operation[11].

The simplified equivalent electrical circuit of a fuel cell consists of several components that represent the various electrochemical processes that occur within the FC. The equivalent electrical circuit of a fuel cell is shown in the Fig 1[4].\

Proton Exchange Membrane Fuel Cells (PEMFCs) are often considered the first option of fuel cell technology for many applications, including transportation, stationary power generation, and portable devices. One reason for this is that PEMFCs have a relatively high Nernst voltage, which is a measure of the cell's theoretical voltage output based on the chemical potential of the reactants and products.

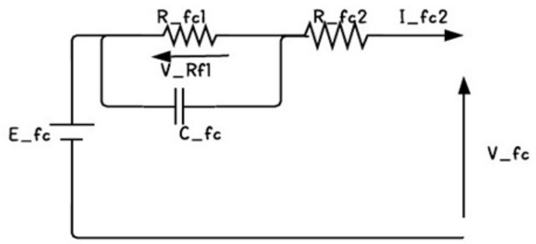


Fig.1. electrical circuit of a FC.

The Nernst voltage of a PEMFC depends on several factors, including the temperature, pressure, and concentrations of the reactants and products. the Nernst voltage of a PEMFC operating on pure hydrogen and oxygen is around 1.23 V with the temperature and pressure (25°C, 1 atm). The models of the PEMFC is expressed as [12]:

(2) $$V_{FC} = E_n - V_{act} - V_{ohm} - V_{con}$$

The terms used in the context are Vact, Vohm, and Vcon, which refer to the activation voltage, ohmic voltage, and concentration voltage drops, respectively. The Gibbs free energy change of the overall electrochemical reaction represents the thermodynamic potential of a Proton Exchange Membrane (PEM) Fuel Cell. In the case of a PEM Fuel Cell, this reaction involves the oxidation of hydrogen, resulting in the formation of water:

(3) $$2H_2 + O_2 \rightarrow 2H_2O$$

The Gibbs free energy change (ΔG) for this reaction is given by:

(4) $$\Delta G = \Delta H + T\Delta S$$

Where ΔH is the change in enthalpy, ΔS is the change in entropy, and T is the temperature in Kelvin.

The thermodynamic potential of a Proton Exchange Membrane (PEM) Fuel Cell for the reaction is calculated for temperature less than 100C° as follow

(5) $$E_n = E^0 - \frac{RT}{nF}\ln(Q)$$

where E, E° are the cell and the standard cell potential, respectively, R is the gas constant, n is the number of electrons transferred in the reaction, is, F is the Faraday constant (96,485 A s/mol), T is the temperature (Kelvin),and Q is the reaction quotient.

The voltage activation loss in a PEM fuel cell is a complex phenomenon that relies on various factors, such as the materials used, the cell's design, and the operating conditions. Minimizing this voltage loss is crucial to enhance the efficiency and performance of PEM fuel cells. On the other hand, the ohmic loss in a Proton Exchange Membrane (PEM) Fuel Cell occurs when there is a voltage drop due to the resistance of the electrolyte, electrodes, and current collectors in the cell. This resistance can be modeled as an electrical resistance in series with the cell, and it is directly proportional to the current flowing through the cell. The ohmic loss can be obtained as follows:

(6) $$V_{act} = I_{fc}(\mathrm{R}_m + \mathrm{R}_C)$$

The ohmic resistance of the membrane, denoted as Rm, is a function of the membrane's specific resistivity ρm, which is measured in ohm-centimeters, the thickness of the membrane l (centimeters), and the membrane surface A (centimeters ^{2}) as

(7) $$\mathrm{R}_m = \rho_m(\frac{l}{A})$$

The specific resistivity of the membrane ρ_m can be calculated as follows

(8) $$\rho_m = \frac{181.6\left[1 + 0.03\frac{I_{fc}}{A} + 0.062\frac{T}{303}(\frac{I_{fc}}{A})^{2.5}\right]}{\left[\lambda - 0.634 - 3\frac{I_{fc}}{A}\right]e^{4.18.\frac{T-303}{T}}}$$

The membrane material's water content is represented by an adjustable parameter λ .

The transport of reactants and products through the porous electrode and membrane structures of a PEM Fuel Cell can cause the depletion of reactants or accumulation of reaction products near the electrode surface, resulting in a voltage difference known as the concentration voltage drop. The concentration voltage drop is an important factor to consider in the performance and efficiency of a PEM fuel cell, as it represents a loss of potential energy that can reduce the overall efficiency of the cell. Minimizing the concentration voltage drop in a PEM fuel cell is therefore an important consideration for improving the performance and efficiency of the cell. Can be defined as follows:

(9) $$V_{con} = -\beta\ln(1 - \frac{J}{J_{\max}})$$

The technical specifications for the PEMFC used in the pre-set model include an adjustable parameter β, current density (J), and maximum current density (Jmax) (A.cm-2).

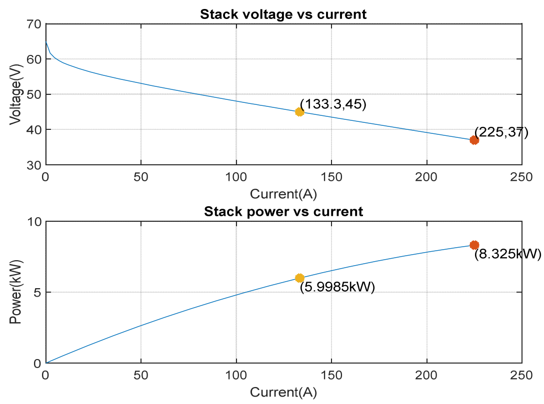


Fig 2. Characteristics of Stack Voltage and Power as Functions of Currents.

Fig 3 shows the stack voltage versus current characteristic and stack power versus current characteristic

4. Model of Supercapacitor

An electrochemical capacitor, commonly known as a supercapacitor, is an energy storage device that utilizes electrostatic charge separation between electrodes and an electrolyte to store energy. The device typically consists of two porous electrodes separated by a thin electrolyte layer. When a voltage is applied, positive and negative charges separate, forming a double layer of charge at the electrode-electrolyte interface. This double layer behaves like a capacitor, storing electrical charge. Figure 6 depicts a simplified equivalent circuit of a supercapacitor [4]:

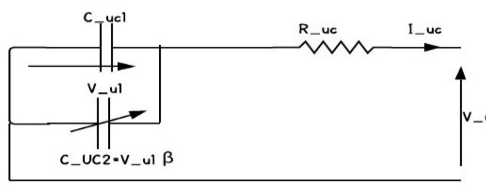


Fig 3. Simplified electrical circuit of supercapacitor

In the equivalent model, R_uc is the internal resistance, C_uc1 and C_uc2 are the capacitances which are in parallel where C_uc2 =βV_u1fluctuates linearly with the ultracapacitor pack of voltage[4].The equation which belongs to the equivalent [4] circuit is as follows:

$$I_{uc} = -(C_{uc1} + \beta V_{uc1}) \frac{dV_{u1}}{dt} \qquad (10)$$
$$V_{uc} = V_{u1} - R_{uc} I_{uc}$$

Where the voltage across the capacitance C_{uc1} is V_{uc1}
The SOC of the supercapacitor [4] is described in the following equation 11

$$SOC_{uc} = \left(\frac{V_{uc}}{V_{uc\max}} \right)^2 \qquad (11)$$

Where the maximum voltage of supercapacitor is denoted as $V_{uc\max}$
The plot of supercapacitor charge characteristic from MATLAB/simulator is shown in fig 4.

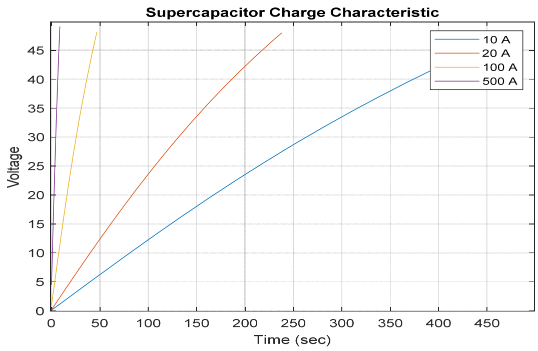


Fig 4. Charge characteristic of supercapacitor

5. Feedback Linearization technique

In control systems, the feedback linearization technique is utilized to convert a nonlinear dynamic system into a linear one. This method involves finding an appropriate feedback control law that neutralizes the nonlinear dynamics of the system, resulting in linearity. The fundamental concept of feedback linearization is to introduce a variable transformation that converts the nonlinear system into a linear system. This is accomplished by utilizing a coordinate transformation that nullifies the nonlinear terms of the original system [24]. The transformed system can then be controlled using linear control techniques. The feedback linearization technique has several advantages. First, it can be used to stabilize nonlinear systems and ensure that they are controllable and observable [22]. Second, it can be used to design control systems for nonlinear systems that are difficult to control using traditional control techniques. Generalized form of a nonlinear system:

$$\dot{X} = f(x) + g(x)u \qquad (12)$$
$$y = h(x)$$

Where x is the state of the system and y is the output of the system. f and g are the function with $g \neq 0$, and u is the control of the system. The original model is transformed from x states to ψ states, the new model can be obtained as follows:

$$\psi = \varphi(x) \qquad (13)$$

With

$$z = \begin{vmatrix} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_3 \end{vmatrix} = \begin{vmatrix} L_f^{1-1} h(x) \\ L_f^{2-1} h(x) \\ \vdots \\ L_f^{r-1} h(x) \end{vmatrix}$$

The linear model of the system can be reformulated as follows:

$$\psi = A\psi + Bv \qquad (14)$$
$$u = Cz$$

Where v can be reformulated by using any linear control approach. For A state feedback, v can be written as $v = -Kz$. The control low (u) can be obtained as follows:

$$u = \frac{v - L_f^{r-1} h(x)}{L_g L_f^{r-1} h(x)} \qquad (15)$$

The control strategy can indeed be employed to control the boost converter in a Fuel Cell (FC) system. This control strategy involves two feedback control loops, an inner current control loop, and an outer voltage control loop

5.1 Linearization of inner current loop of the boost converter

The regulation of current through the inductor of a boost converter is the responsibility of the inner current control loop. This control loop modifies the duty cycle of the converter to sustain the desired current level, which is typically established by a reference signal. Its purpose is to ensure that the converter can accommodate the fluctuating input current from the FC and provide a constant output current to the load. The current loop model is obtained from the model in Equation (1) and expressed in Equation (12) format :

$$\frac{di_{FC}}{dt} = \frac{U_{FC}}{L} - \frac{v_{dc}}{L} + \frac{v_{dc}}{L} d \qquad (16)$$
$$y_1 = i_{FC}$$

The relative degree (r_d) of the current loop is calculated by[25].

$$L_g h(x) = \frac{\partial h(x)}{\partial x} g(x) = \frac{1}{L} v_{dc} \qquad (17)$$
$$L_f h(x) = \frac{\partial h(x)}{\partial x} f(x) = \frac{1}{L} (U_{FC} - v_{dc})$$

The relative degree of the current loop is one degree[24]. According to the Eq. (15), the output of current loop can be written as follows:

$$d = \frac{L}{U_{FC}} \left(v - \frac{(U_{FC} - v_{dc})}{L} \right) \qquad (18)$$

Substituting this Eq(18) in Eq. (16)

$$\frac{di_{FC}}{dt} = \frac{1}{L}(U_{FC} - v_{dc}) + \frac{v_{dc}}{L} \frac{v - \frac{1}{L}(U_{FC} - v_{dc})}{\frac{U_{FC}}{L}} = v \qquad (19)$$
$$y_1 = i_{FC}$$

Current error is used controllable variable, $v_{FCref} = K(i_{FCref} - i_{FC})$ the current loop is linearized. The outer curent control loop of SC also can linearized using the same method.

5.2. Linearization of inner voltage loop

The outer voltage control loop regulates the Dc bus voltage of the buck boost converter by adjusting the Dc bus reference voltage for the inner current control loop. This control loop ensures that the Dc bus voltage of the buck boost converter remains constant despite changes in the input voltage from the SC and the load. The voltage control loop also can linearized using the same method from the model in Eq (1).

(20)
$$dv_{dc} = \frac{1}{c}\left(\frac{U_{SC}}{U_{dc}} i_{SCref} - i_{dc}\right)$$
$$y_2 = v_{dc}$$

The relative degree of the voltage loop is one degree in Eq.(20). it is expressed as.

(21)
$$L_g h(x) = \frac{\partial h(x)}{\partial x} g(x) = \frac{U_{SC}}{c v_{dc}}$$
$$L_f h(x) = \frac{\partial h(x)}{\partial x} f(x) = \frac{1}{c} i_{dc}$$

Voltage error is used controllable variable, $i_{ref} = k_v(v_{dcref} - v_{dc})$. the both control loops in a system are linearized, this means that they are represented by linear models, and the control algorithms used to regulate these systems are also linear.

6. Energy Management with Grey Wolf Optimizer using Feedback Linearization Control

GWO is a nature-inspired optimization algorithm that mimics the social behavior of grey wolves. It has been successfully applied to solve various optimization problems. The integration of GWO and FLC for energy management in a Fuel Cell system can be achieved by using GWO to optimize the FLC parameters. The objective of the optimization is to minimize the error between the actual and desired system responses. the feedback linearization method can be employed to regulate the power output of the Fuel Cell system. This technique adjusts the input variables, such as fuel flow rate and air flow rate, to achieve the desired power output. The energy management system based on GWO-FLC can provide several benefits for Fuel Cell systems, such as improved energy efficiency, reduced operating costs, and increased reliability. The GWO-FLC-based energy management system can also adapt to changing environmental conditions, such as variations in the temperature and humidity. The proposed objective function is derived from the combination of the energy stored in the DC-bus capacitor and that of the SCs. The aim of this part is to design an energy management based on GWO technique. Indeed, the key idea is to incorporate the merits of fast optimization process of the GWO in order to find the optimal fuel cell power trajectory

(22)
$$J_{GWO} = \lambda_1\left(\Delta\varsigma_{SC}[k] + \Delta\varsigma_{Bus}[k]\right) + \lambda_2 T_s\left(\Delta\varsigma_{SC}[k-1] + \Delta\varsigma_{Bus}[k-1]\right)$$

Where $\Delta\varsigma_{SC} = \varsigma^*_{SC} - \varsigma_{SC}$, $\Delta\varsigma_{Bus} = \varsigma^*_{Bus} - \varsigma_{Bus}$, ς_{Bus} is the dc-bus capacitive energy , ς_{SC} is the SCs energy, λ_1 and λ_2 are constant gains whose the design is presented in next section , T_s is the sample time.

To mathematically represent the encircling process of grey wolves in the hunting process, we can use the following equation:

(23)
$$X(k+1) = X_p(k) - AD$$
$$D = \left|CX_p(k) - X(k)\right|$$

where, X_p is the positions of the three best grey wolves in the population. D represent the distances of the three grey wolves from the prey. C is a constant value (encircling coefficient) and X is the position of the prey (the optimal solution). As previously mentioned, the FC supplied variable part of the required power Dp, power reference have to be limited between 10 and 90% of its maximum power, the power reference can be calculated as

(24)
$$P_{FC}^{ref} = 0.1 P_{FC}^{\max} \le k_{FC} Dp \le 0.9 P_{FC}^{\max}$$

*k*FC is the power sharing gain where 0.6< *k*FC <1.

(25)
$$k_{FC} = 0.4 \frac{SoC_{\max} - SoC}{SoC_{\max} - SoC_{\min}} + 0.6$$

7. Simulation Results

MATLAB simulations were utilized to demonstrate the capabilities of the GWO with Feedback Linearization control. The emphasis of the simulations was on the design methodology of the proposed strategy

7.1 Startup Response of DC Bus voltage

Figure. 5, shows the dynamic behavior of DC Bus voltage with GWO using Feedback Linearization Control. The output reaches 80V given as Vref at 0.05 sec when Feedback Linearization Control is used.

7.2 The source voltage Variation

In Figure. 6, the source voltage is varied from 45V to 30V at 1 sec. It can be seen that GWO using Feedback Linearization Control is robust. The former takes 0.035 sec to reach the final value.

7.3 Change in power demand

Figure. 7, shows that GWO using Feedback Linearization Control takes 4ms to reach the final value at the load variation instant. When the load is varied from P_{load} = 1600 w to P_{load} = 3200 w at time 1sec

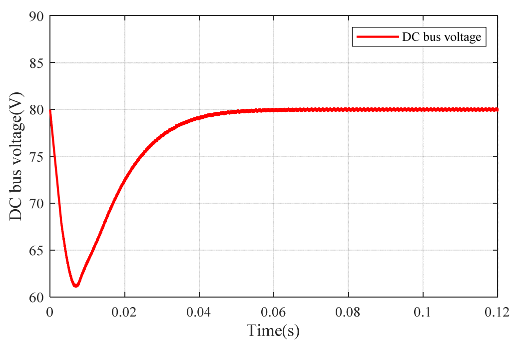
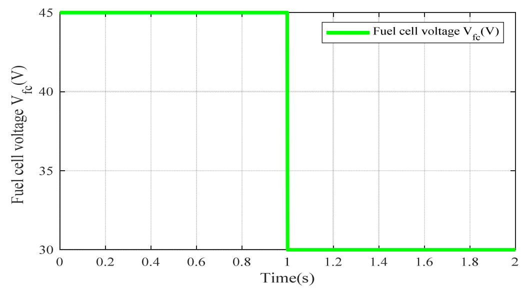
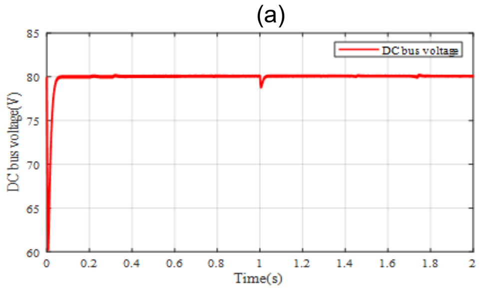


Fig. 5. Startup Response with GWO using Feedback Linearization Controller



(a)



(b)

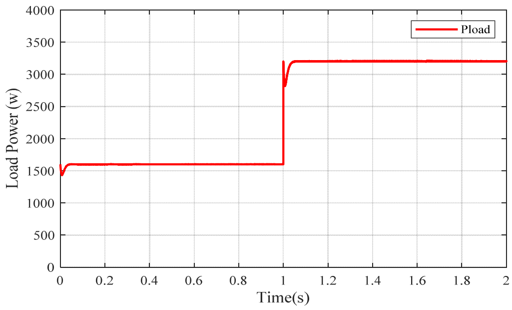
Fig. 6. Regulation of DC bus voltage corresponding to change in source Voltage with GWO using Feedback Linearization Controller: (a) Fuel cell voltage (b) DC bus voltage

7.4 DC bus Reference Voltage Variation

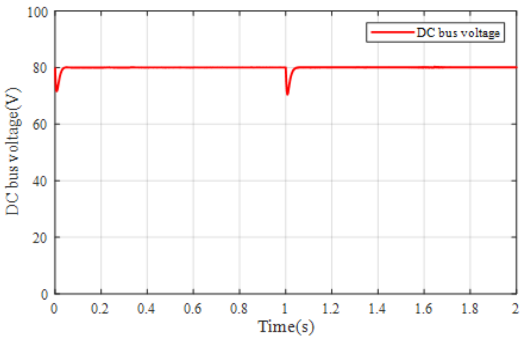
Figure. 8, that Vref has been varied from 80V to 60V at 1sec. Feedback Linearization Control stalks the system to reach final value within 0.055ms.

7.5- Energy Management *with GWO using Feedback Linearization Control*

In Figure 9, the DC bus voltage is established at 80 V. In order to ensure steady operation of the power system, it is critical to monitor the DC bus voltage and adjust the power supply as needed to sustain a stable voltage level. If the power profile is constant, the DC bus voltage will remain stable, assuming that the power supply is sufficient to meet the demand. However, the power demand varies over time, which can lead to fluctuations in the DC bus voltage.



(a)



(b)

Figure 7. Regulation of DC bus voltage corresponding to change in Load Power with GWO using Feedback Linearization Controller

Figure 9, shows the power evolution under power profile with GWO using Feedback Linearization Control. The power evolution under a power profile in a fuel cell system will depend on a variety of factors, including the characteristics of the fuel cell itself, and the load being powered. The power evolution in a fuel cell system under a power profile is a critical aspect of energy management, as it determines how the system will respond to changes in demand and how efficiently it will operate.

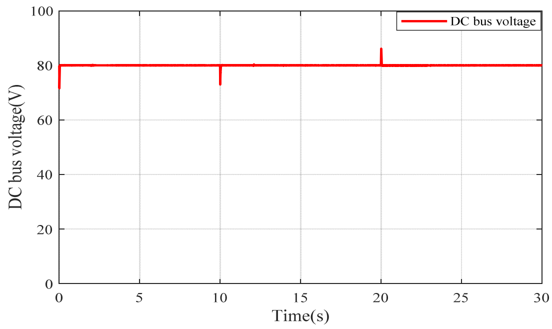


Fig.e 8. DC bus voltage evolution under power profile with GWO using Feedback Linearization Control.

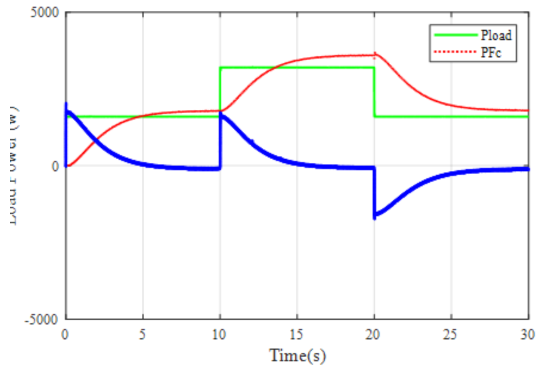


Fig. 9. Power evolution under power profile with GWO using Feedback Linearization Control.

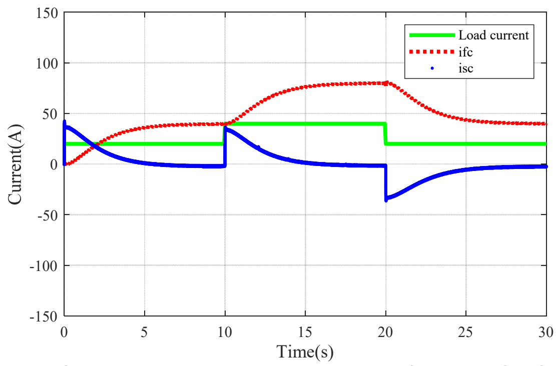


Fig 10. Current evolution under power profile with GWO using Feedback Linearization Control.

Figure 10, shows the Current evolution under power profile with GWO using Feedback Linearization Control. The current evolution in a fuel cell system under a power profile is an important aspect of energy management, as it determines how the current flow through the system will change over time in response to changes in demand.

Based on Table 1, it can be concluded that implementing the GWO with Feedback Linearization Control yields superior control performance with greater robustness compared to the PI controller (in terms of Setting Time (TSe) and Maximum Peak Overshoot (MPO)). Robustness refers to a controller's ability to maintain its performance in the presence of disruptions in the system being controlled

TABLE 1. Comparison between GWO using pi and GWO using feedback linearization control

	At Startup Response		Change in power demand		***The source voltage Variation***	
	GWO using PI	GWO using FLC	GWO using PI	GWO using FLC	GWO using PI	GWO using FLC
T_{Se}(s)	0.15	0.05	1.2	0.055	0.1	0.025
MPO (%)	5.02	-	6.04	-	3.04	-

8. Conclusions

This paper presents the application of a GWO-based Energy Management Strategy (EMS) and a DC microgrid with Feedback Linearization Control. The primary aim of the proposed strategy is to enhance energy management in the microgrid while ensuring system stability. Feedback Linearization is a control method that transforms a nonlinear system into a linear one, simplifying the use of classical linear control techniques like PI controllers. The advantage of this approach is that it can overcome the limitations of traditional PI controllers, especially for systems that have complex nonlinear dynamics. In power converters, the Feedback Linearization technique has been shown to improve the performance of the control system compared to traditional PI controllers. This is because power converters have nonlinearities in their dynamics, which can lead to poor performance and instability when controlled with traditional linear controllers. Overall, the combination of GWO and Feedback Linearization Control can provide an effective solution for energy management in a fuel cell-based DC microgrid, enabling optimal utilization of the available energy sources and efficient operation of the microgrid.

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