FL-DTC Control of SEIG-Based Standalone Wind System with Battery–Supercapacitor Hybrid Storage

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***Abstract*—** This research examines methods to enhance the efficiency of a freestanding wind energy system using a Self-Excited Induction Generator (SEIG). A Fuzzy Logic Direct Torque Control (FLDTC) approach is used to smooth out ripples in both electromagnetic torque and stator flux, taking magnetic saturation into account. A significant contribution of this study is the efficient control of the DC-link voltage. A specialized control loop that combines Direct Torque Control (DTC) with an Energy Management System (EMS) makes this possible. The system also has a Hybrid Energy Storage System (HESS), which is made up of batteries and supercapacitors, to make it even more stable. The EMS coordinates the HESS, which helps keep the power flow stable and the system running smoothly even when circumstances change. The simulation findings show that the suggested control approach is both strong and effective, which shows that it might be used reliably in stand-alone wind energy applications.

***Index Terms*—**Energy Storage Systems, FLDTC Control, Self-Excited Induction Generator, Stand-Alone.

I. INTRODUCTION

Wind energy is becoming one of the most significant renewable sources since it is plentiful and good for the environment. Its use in autonomous microgrids is a potential way to provide power to distant areas while lowering the environmental impact of fossil-fuel-based energy systems [1][2].

Among the numerous generating technologies employed in such arrangements, the Self-Excited Induction Generator (SEIG) stands out as a vital component. Because it is easy to use, cheap, strong, tiny, and requires little upkeep, it is extensively used in small standalone installations [3][4]. Compared to alternative machines, such as Permanent Magnet Synchronous Generators (PMSG) or Doubly-Fed Induction Generators (DFIG), which give great performance but need complicated and expensive control systems, the SEIG remains an appealing and practical solution for isolated applications [4].

In recent years, variable-speed wind turbine (VSWT) systems based on SEIGs have received considerable attention. Beyond its structural and economic benefits, the SEIG is capable of sustaining residual magnetism even after an abrupt loss of excitation due to overload or short circuit. Its self-excitation may be done either by a capacitor bank linked to the stator terminals or via a rectifier/inverter system supplied with a single DC-bus capacitor [5][6]. However, the extremely intermittent nature of wind makes it challenging to maintain steady voltage and frequency levels—an inherent issue for SEIG-based generating systems [3][6].

To address these restrictions, numerous control mechanisms have been considered. Rotor Flux-Oriented Control, for example, is extensively utilized but remains difficult and largely reliant on machine settings [6]. In this setting, Direct Torque Control (DTC) has emerged as a powerful option owing to its structural simplicity, quick dynamic response, and decreased parameter sensitivity [3]. Despite these benefits, traditional DTC still offers limitations such as substantial torque and flux ripples, variable switching frequency, and sensitivity to parameter fluctuations [3][7]. Integrating fuzzy logic into DTC offers an effective approach, allowing better management of nonlinearities and uncertainties without depending on an exact machine model, hence enhancing resilience and improving overall control performance.

In parallel, delivering a consistent and dependable power supply in standalone mode demands effective energy storage. A Hybrid Energy Storage System (HESS) combining batteries and supercapacitors is especially important for this purpose. Batteries give high energy density but restricted power density, while supercapacitors provide high power density and extended cycle life, but with lesser energy capacity. Their combination provides both efficient smoothing of power fluctuations and quick correction of transient load changes [8][9]. A specific energy management method is also employed to coordinate power sharing between the storage units and the generator, further boosting system stability.

The main contributions of this work can be summarized as follows:

• Improved SEIG modeling and performance through consideration of magnetic saturation using a polynomial representation of the magnetizing inductance (Lm).

• Development and validation of an FLDTC strategy to ensure reliable voltage regulation for a SEIG supplying an autonomous load.

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• Effective DC-bus voltage regulation under varying wind and load conditions.

• Integration of a battery–supercapacitor HESS with a dedicated energy management algorithm to optimize power flow and reinforce system stability.

II. GLOBAL OVERVIEW OF THE STUDIED SYSTEM

The studied system consists of a wind energy conversion chain integrating a SEIG, whose electrical energy is converted into direct current by means of an AC/DC converter to supply a DC bus. This bus plays a central role by providing power to the load while being coupled to a hybrid storage device composed of a battery and a supercapacitor, each connected through a bidirectional converter. The battery ensures long-term energy management, whereas the supercapacitor rapidly compensates for power fluctuations and transients. The figure below provides an overview of the system and how its different components are connected. To keep the system running reliably, several control strategies work together. These include regulating the DC bus voltage, using MPPT to capture as much wind energy as possible, managing the power flow between the storage devices, and applying FLDTC to the generator to control both the stator flux and electromagnetic torque. By coordinating these functions, the system remains stable, delivers continuous power, and operates efficiently—even when the wind conditions are unpredictable and constantly changing.

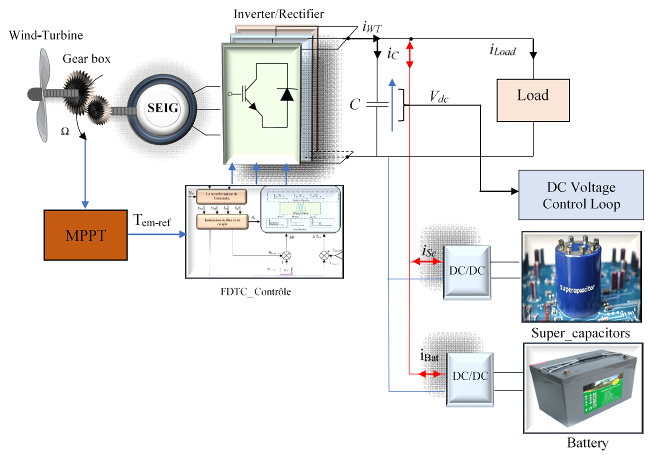

Fig. 1. Configuration of the proposed standalone SEIG-based wind energy system.

III. MATHEMATICAL REPRESENTATION OF THE SYSTEM COMPONENTS

A. Modeling of Wind Turbine

The wind’s kinetic energy is first turned into mechanical power and subsequently into electrical power via the turbine. This conversion is represented using basic aerodynamic models, while the collected wind power is estimated by traditional mathematical formulas [5][10].

$$P_t = \frac{1}{2} C_p(\lambda).\rho.S(t).v^3 \tag{1}$$

$$T_{em} = \frac{C_{P\max}}{\lambda_{opt}^3}.\frac{\rho}{2}.\pi.\frac{R_t^5}{G^3}.\Omega^2 \tag{2}$$

B. SEIG Generator Model Development

Implementing the DTC technique needs a dynamic model of the induction machine in the stationary (α-β) frame. By adding magnetic saturation, the electrical equations are developed to guarantee an accurate description for control. Further information on the modeling technique and machine settings are given in [3].

C. Mathematical Modeling of Energy Storage Devices

- *Battery Modeling*

An RC equivalent model is chosen to describe the battery, since it adequately defines the internal electrical activity. The integration into the DC bus is handled by a bidirectional buck–boost converter. Figure (2) displays the accepted circuit model, with the battery voltage stated by the following relation [10][11]:

$$V_{Bat} = E_b - R_i.i_{Bat} - v_{cBat} \tag{3}$$

The State of Charge (SoC) of a battery provides a critical indication that reflects the amount of stored energy left with regard to its rated capacity. It is generally represented as a percentage:

$$SoC(t) = 1 - \frac{Q_d(t)}{C_b} \int i_{Bat}(t).dt \tag{4}$$

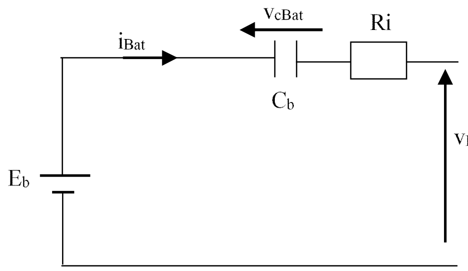

Fig. 2. Electrical schematic of the battery.

In this expression, C_b denotes the nominal capacity (Ah), E_b the open-circuit electromotive force, R_i the internal resistance, i_{bat} the battery current, V_{Cbat} the capacitor voltage, while $Q_d(t)$ corresponds to the electric charge stored in the battery at time t.

- *Modeling of the Supercapacitor*

To complement the limited dynamic response of batteries and mitigate their degradation, supercapacitors are integrated as auxiliary storage. Thanks to their high power density and fast response, they efficiently handle transient power fluctuations through a bidirectional buck–boost converter. Their behavior is modeled by a simplified equivalent circuit with two RC branches, capturing both short-term dynamics and slower internal energy redistribution[10][11]. The adopted electrical schematic is shown in Figure 3.

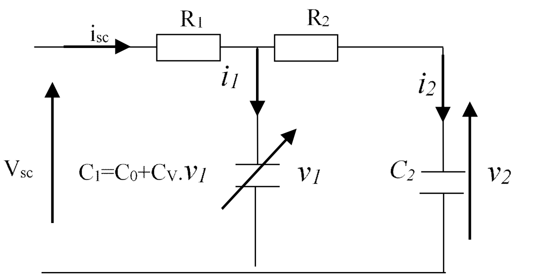

Fig. 3. Equivalent electrical circuit of the supercapacitor.

Neglecting leakage current, the voltage Usc is approximated by a simplified model [10]:

$$U_{sc} = N_S Vsc = N_S . v_1 + R_1 \frac{I_{sc}}{N_p} \tag{5}$$

The expression of the voltage v_1 is given by [12]:

$$v_1 = \frac{-C_0 + \sqrt{C_0^2 + 2C_v Q_1}}{C_v} \tag{6}$$

In this model, the current i_1 is related to the instantaneous charge Q_1 and capacitance C_1 according to:

$$i_1 = \frac{dQ_1}{dt} = C_1 \frac{dv_1}{dt} \tag{7}$$

in which the charge Q_1 is given by the following expression:

$$Q_1 = C_0 v_1 + \frac{1}{2} C_v v_1^2 \tag{8}$$

IV. SEIG Control Using FLDTC Strategy

The FLDTC technique, developed from conventional DTC, replaces hysteresis controllers and switching tables with a fuzzy logic controller. This approach reduces torque and stator flux ripples while maintaining a fast dynamic response. The fuzzy controller takes the torque error, flux error, and sector angle as inputs, and outputs the corresponding switching vectors (V0, V1…, V6).

The fuzzy logic switching scheme is defined through 36 rules, illustrated in table I.

TABLE I: FUZZY DTC SWITCHING TABLE

Δ_φ	Δ_{Tem}	Sectors S_i					
		S_1	S_2	S_3	S_4	S_5	S_6
N	N	V_6	V_1	V_2	V_3	V_4	V_5
	Z	V_0	V_7	V_0	V_7	V_0	V_7
	P	V_2	V_3	V_4	V_5	V_6	V_1
P	N	V_6	V_1	V_2	V_3	V_4	V_5
	Z	V_7	V_0	V_7	V_0	V_7	V_0
	P	V_3	V_4	V_5	V_6	V_1	V_2

Figure 4 illustrates the fuzzy inputs: the torque error uses three linguistic variables (N, Z, P), the flux error uses two (N, P), and the flux position is divided into six fuzzy sets (s1–s6) with triangular membership functions.

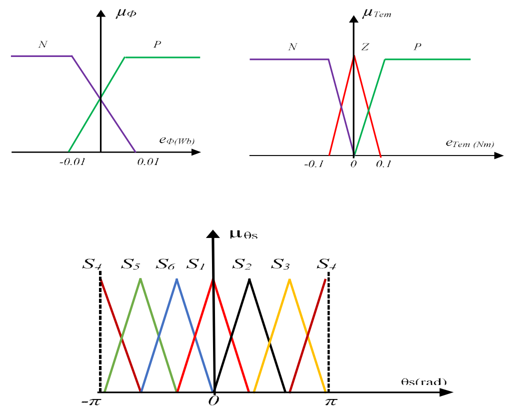

Fig. 4. Fuzzy input membership functions.

Figure 5 presents the membership functions applied for selecting voltage vectors.

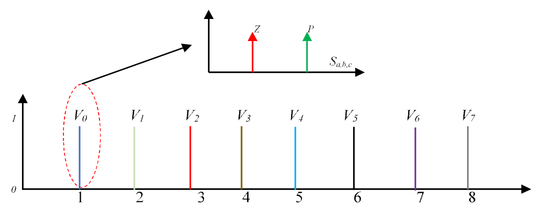

Fig. 5. Fuzzy output membership functions.

The implementation of any control technique requires a mathematical model that accurately describes its operating principle; accordingly, the DTC is established on its dedicated model.

The magnitude of the stator flux is computed from its components (Φsα, Φsβ), as expressed below [3][13]:

$$\begin{cases} \Phi_{s\alpha} = \int_0^t (V_{s\alpha} - R_s i_{s\alpha}) dt \\ \Phi_{s\beta} = \int_0^t (V_{s\beta} - R_s i_{s\beta}) dt \end{cases} \tag{9}$$

$$\Phi_s = \sqrt{\Phi_{s\alpha}^2 + \Phi_{s\beta}^2} \tag{10}$$

The electromagnetic torque is expressed as a function of the stator current components ($i_{s\alpha}$, $i_{s\beta}$), the stator flux components ($\Phi_{s\alpha}$, $\Phi_{s\beta}$), and the pole pair number (p).

$$T_{em} = p(\Phi_{s\alpha} i_{s\beta} - \Phi_{s\beta} i_{s\alpha}) \tag{11}$$

V. PROPOSED ENERGY MANAGEMENT STRATEGY

The figure 6 illustrates the regulation loop of the DC bus voltage in a hybrid wind–battery–supercapacitor system. The measured voltage V_{dc} is compared with its reference value $V_{dc\text{-}ref}$. The resulting error is processed by a PI controller, which generates the global reference current idc-ref. This current is then managed by the Energy Management Strategy, which distributes it into two components:

The battery reference current ($i_{Bat\text{-}ref}$), and the supercapacitor reference current ($i_{SC\text{-}ref}$).

Each reference is compared with the actual currents and regulated by PI controllers associated with the respective DC/DC converters of the battery and the supercapacitor. Finally, the DC bus balances the input from the wind turbine (i_{WT}), the currents exchanged with the storage devices (i_{Bat} ,i_{SC}), and the load demand (i_{Load}).

This regulation loop ensures the stability of Vdc while optimizing the power sharing between the battery (long-term support) and the supercapacitor (fast transients).

At any given time, the sum of these two reference currents must equal the global reference current, thereby ensuring DC bus voltage stability and optimal energy management.

$$i_{dc-ref} = i_{Bat-ref} + i_{Sc-ref} \tag{12}$$

The DC bus voltage Vdc is given by the following relation:

$$C\frac{dv_{dc}}{dt} = i_{WT} - i_{Sc} + i_{Sc} + i_{Bat} + i_{Load} \tag{13}$$

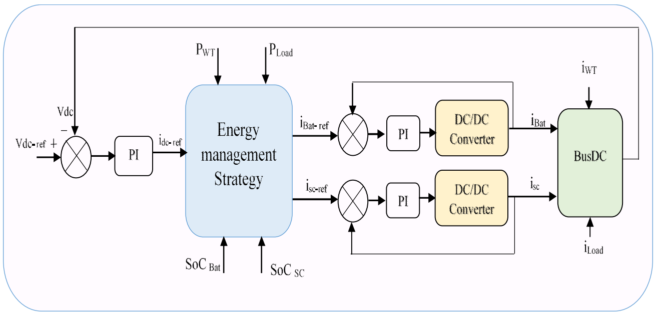

Fig. 6. DC bus voltage regulation loop in a HESS.

The flowchart depicted in Figure 7 depicts the energy management technique employed for the hybrid storage system. Starting from the input power demand, the algorithm decomposes the power profile into low- and high-frequency components. The low-frequency component is allocated to the batteries, which are appropriate for long-term energy supply, while the high-frequency component is handled by the supercapacitors, which can effectively react to quick transients. In addition, the state of charge (SoC) of each device is taken into consideration to avoid undue stress and to prolong their lifespan. Based on this method, the algorithm calculates the reference currents for both storage units, guaranteeing optimum and dependable power sharing while respecting the operating restrictions of the battery and the supercapacitor.

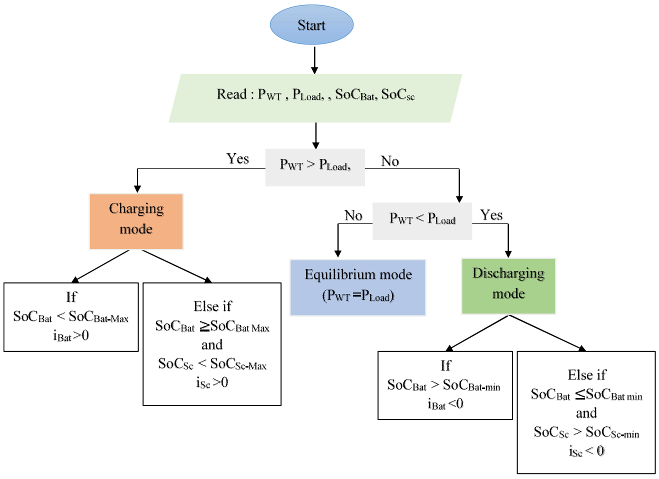

Fig. 7. Magnetization as a function of applied field.

VI. Obtained Results and Discussion

In this part, the efficacy of the suggested control approach is tested using thorough simulation testing. The examined system consists of a freestanding wind turbine driving an SEIG, managed by the FLDTC control strategy, and backed by a HESS made of a battery and a supercapacitor.

The simulations are carried out under different operating scenarios to assess the robustness of the proposed approach. The main parameters of the SEIG are identical to those presented in our previous work [3]. For all cases, the reference DC bus voltage is set to 580 V.

In this work, the stator flux reference value is set to its nominal value, i.e: $\Phi_{s\_ref} = \Phi_{s\_nom} = 0.7Wb$ (14)

The variation profile of the generator drive speed is shown in Figure 8.

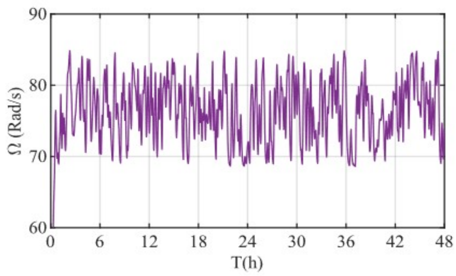

Fig. 8. Generator drive speed.

- *Evaluation of FDTC Control Performance*

The performance evaluation of the FDTC strategy is based on the regulation of the electromagnetic torque and the stator flux. As shown in Figures (9) and (10), the estimated quantities accurately follow their reference values, demonstrating good control precision. It is also important to note that torque and flux ripples are mitigated, which improves the quality of the delivered energy and contributes to the overall stability of the system. Figure (IV.11) illustrates the circular trajectory of the stator flux with a nominal radius of 0.7 Wb, which is consistent with relation (14).

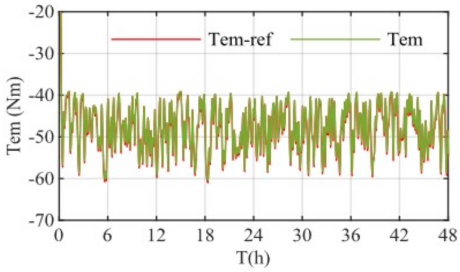

Fig. 9. Electromagnetic torque waveform.

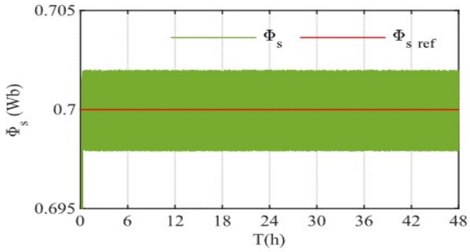

Fig. 10 The stator flux magnitude.

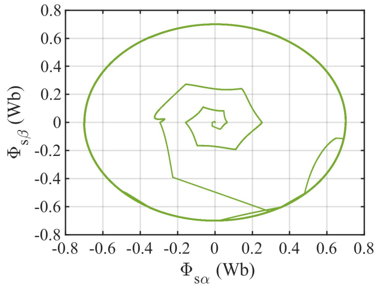

Fig. 11. Stator flux trajectory.

- *DC bus voltage regulation*

As seen in Figure 12, the DC bus voltage closely matches its reference value of 580 V, indicating effective and steady control. It is worth stressing that the DC bus plays a significant role in the overall system design, as it provides the essential interconnection point between the wind turbine, the load, the battery, and the supercapacitor. Therefore, keeping a steady Vdc is of crucial significance, as it directly effects both the dependability of energy management and the balance of power exchanges among the various parts of the system. The observed findings demonstrate that the suggested control technique effectively protects this stability, hence enabling efficient and resilient global system functioning.

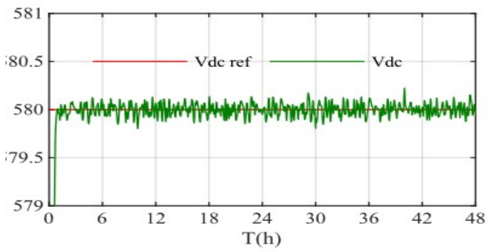

Fig. 12. DC bus voltage

- *Performance Assessment of the HESS across Different Operating Intervals*

Figures 13 and 14 depict the development of power and currents in the wind turbine-battery-supercapacitor hybrid system, illustrating the usefulness of the proposed energy management technique.

0 h – 10 h: During this early period, the (P_{Load} > (|P_{WT}|). This needs the usage of storage devices. The supercapacitor reacts initially by quickly generating power peaks to correct for sudden imbalances, while the battery provides a more consistent and continuous contribution, ensuring supply continuity.

Between **10** and **30 h**, wind turbine production achieves global balance with load (|PWT|≈PLoad). The powers and currents of the battery and supercapacitor approach zero, but do not totally cancel out. They wobble around zero because of wind randomization and the dynamic changes required to maintain equilibrium. This phase shows little storage activity.

30 h – 42 h: Since P_{Load} < |P_{WT}|, the surplus energy is stored in the battery (i_{Bat} > 0, charging), while the supercapacitor smooths rapid fluctuations around equilibrium. The current profiles confirm this complementary behavior.

42 h – 48 h: In this interval, the sharp load increase makes wind generation insufficient; the supercapacitor compensates for fast transients, while the battery provides stable and sustained support, confirming their complementarity.

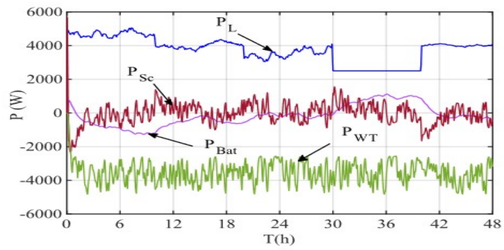

Fig. 13. Power waveforms..

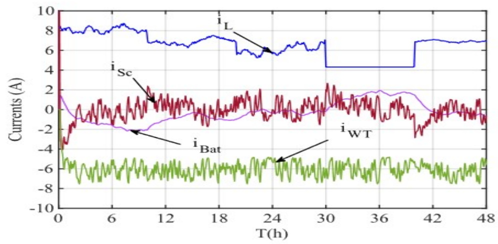

Fig. 14. Current waveforms..

Figures 15 and 16 show the progression of SoC, BT and supercapacitors. It vividly depicts the dynamics of charging and draining of each device, emphasizing their complimentary roles in energy management.

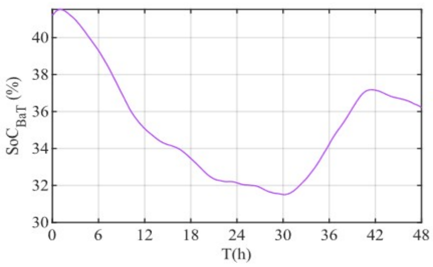

Fig. 15. State of charge of battery.

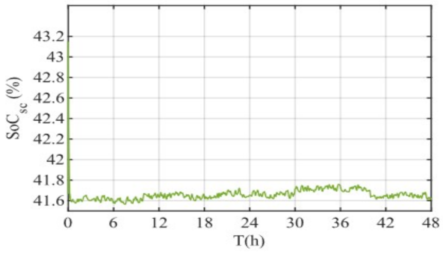

Fig. 16. State of charge of supercapacitor.

The last figure (17) depicts the reference currents, showing the evolution of the battery current ($i_{Bat\ ref}$), the supercapacitor current ($i_{Sc\ ref}$), and the total demand current ($i_{dc\ ref}$). The curves clearly demonstrate that the condition $i_{dc-ref} = i_{Bat-ref} + i_{Sc-ref}$ is systematically satisfied, confirming the proper operation of the energy management strategy.

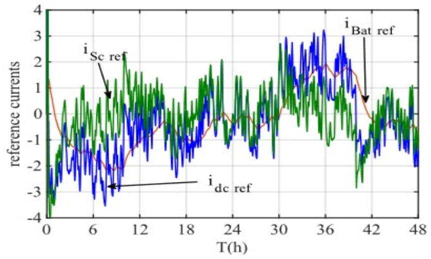

Fig. 17. Evolution of reference currents.

VII. Conclusion

This study aimed to improve the performance of an SEIG-based standalone wind energy system by using a FLDTC approach in conjunction with a HESS. The findings show that the suggested control accurately regulates the electromagnetic torque and stator flux while greatly reducing their ripples. Furthermore, reliable DC-link voltage management was accomplished under a variety of wind and load situations, demonstrating the durability of the chosen technique. The complimentary functioning of the battery and supercapacitor resulted in more effective energy management, with the supercapacitor managing quick transients and the battery maintaining long-term balance. Overall, the research demonstrates that the goals indicated in the introduction were effectively accomplished, proving the efficacy of the suggested control and management system for dependable standalone wind energy applications.

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