Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by:
The Libyan Center for Solar Energy Research and Studies

A New Advanced Strategy for Controlling the Charging and Discharging of a Storage Unit in a Microgrid Using a Finite Control Set Predictive Model

Abdelaziz Youssfi[1*], Youssef Ait El Kadi[2].

[1,2]Engineering and Applied Physics Research Team (EAPT), High School of Technologies, Sultan Moulay Slimane University, Beni Mellal, Morocco.

E-***mail:*** [1] Abdelaziz.youssfi@usms.ma .

SPECIAL ISSUE ON:

The 2024 1st International Conference on Materials Sciences and Mechatronics for Sustainable Energy and the Environment
October 1-3, 2024 at Béni-Mellal, Morocco

KEYWORDS

Finite control set model predictive control; FCS-MPC; Advanced Control; Bidirectional DC-DC Converters; Microgrid; Control and Optimization; storage Units, Renewable Energy.

ABSTRACT

Storage units are critical in microgrids to ensure stable operation, making optimal and robust control during charging and discharging essential. In this work, we propose a novel finite control set model predictive control (FCS-MPC) strategy to manage the charging and discharging of a battery in a DC microgrid powered by renewable energy. Unlike traditional Proportional-Integral (PI) controllers, the FCS-MPC approach optimizes control actions in real-time, considering system constraints and providing enhanced dynamic response. This work demonstrates the superiority of FCS-MPC in controlling a bi-directional DC/DC converter under various test scenarios, ensuring continuous power supply to a 15W DC load. Simulations in Matlab/Simulink validate the proposal, showing that the FCS-MPC delivers higher efficiency and better performance compared to the PI controller.

*Corresponding author.

DOI: https://doi.org/10.51646/jsesd.v14iSI_MSMS2E.404

استراتيجية متقدمة جديدة للتحكم في شحن وتفريغ وحدة التخزين في شبكة ميكرو باستخدام نموذج تنبؤي بمجموعة تحكم محدودة

عبد العزيز يوسفي ، يوسف أيت القاضي.

ملخص: تلعب وحدات التخزين دورًا حاسمًا في الشبكات الميكروية لضمان التشغيل المستقر، مما يجعل التحكم الأمثل والمتين أثناء الشحن والتفريغ ضروريًا. في هذا العمل، نقترح استراتيجية جديدة للتحكم التنبؤي بالنموذج باستخدام مجموعة تحكم محدودة (FCS-MPC) لإدارة شحن وتفريغ البطارية في شبكة ميكرو DC تعمل بالطاقة المتجددة. على عكس وحدات التحكم التقليدية من نوع التناسبي-التكاملي (PI)، يعمل نهج FCS-MPC على تحسين إجراءات التحكم في الوقت الفعلي مع مراعاة قيود النظام وتقديم استجابة ديناميكية محسّنة. يوضح هذا العمل تفوق نهج FCS-MPC في التحكم بمحول DC/DC ثنائي الاتجاه تحت سيناريوهات اختبار متنوعة، مما يضمن توفيرًا مستمرًا للطاقة لحمل DC بقدرة 15 واط. تم التحقق من صحة الاقتراح من خلال محاكاة باستخدام برنامج Matlab/Simulink، حيث أظهرت النتائج أن FCS-MPC يوفر كفاءة أعلى وأداءً أفضل مقارنة بوحدة التحكم PI.

الكلمات المفتاحية – التحكم التنبؤي بالنموذج باستخدام مجموعة تحكم محدودة؛ FCS-MPC؛ التحكم المتقدم؛ محولات DC-DC ثنائية الاتجاه؛ الشبكات الميكروية؛ التحكم والتحسين؛ وحدات التخزين؛ الطاقة المتجددة.

1. INTRODUCTION

The world's current energy potential depends mainly on traditional energy sources such as oil, natural gas, coal, etc. Growth in energy demand results in a decrease in these sources [1]. Otherwise, conventional energy sources have a significant negative effect on the environment, such as the emission of toxic gases and greenhouse gases [2], [3].

For this reason, renewable energy has become a worldwide focus of attention, as it is a clean and permanent source, unlike traditional sources, Renewable primary energy comes from natural phenomena such as solar radiation, wind, wave and tide, biomass, etc [4]. Researchers are exploiting these phenomena to establish sources that can meet the world's energy needs, including photovoltaic sources, wind power, green hydrogen, etc [5], [6], [7].

To make the most of renewable energy sources, researchers have proposed a number of techniques, such as storage techniques [8], hybridization with traditional sources [9] or interconnection techniques and energy injection into the power grid [10], [11], [12], [13]. The aim of these techniques is to ensure the production of electrical energy on a permanent and non-intermittent basis [12], [14].

In this context, our work will address a technique for exploiting renewable sources based on battery storage for Microgrids applications, the objective being to ensure the supply of an electrical load permanently connected to a renewable energy source that may be intermittent (night for solar or absence of wind for wind turbine) by implementing a finite set control model predictive FCS-MPC, to this end, we have proposed an average storage system that can supply the load regardless of the state of the source.

A bidirectional DC/DC converter is proposed for energy management between the battery and the source on the one hand, and between the battery and the load on the other, this converter operates in two directions, one direction for Boost mode and the other direction for Buck mode [15], [16], [17]. The switches are controlled in such a way as to favour the source that has optimum electrical energy production, and so we have constructed two modes of operation depending on the direction of energy flow in the bidirectional converter. If the production of the renewable energy source is maximum, the controller will decide to operate in Buck mode (battery charging), otherwise the controller will decide to operate in Boost mode (battery discharging).

A finite control set model predictive control FCS-MPC is proposed in this work to optimize bidirectional DC/DC converter performance in both system operating modes, this type of control is based on current and past state data to predict the future state within a precise prediction horizon [18], [19]. M. R. Basir Khan has developed a model of a DC microgrid with an energy management system based on model predictive control MPC[20], [21].

In this context, traditional controls have been implemented, such as PI and PID control for the control of a bidirectional DC/DC converter [22], [23], [24], as well as robust sliding mode control [25], [26], otherwise, works propose intelligent control such as fuzzy logic and neural network for the control of this type of converters [7], [17], [21], [24], the performance of a complex-order PI controller is evaluated for the control of a DC-DC converter in[27], An intelligent control strategy based on adaptive neuro-fuzzy inference system (ANFIS) is also implemented for the control of a Boost converter[24], and a Buck converter[28].

Also, predictive model control is used in major works[19], Ademola-Idowu A used this control for frequency stability in a low inertia microgrid [29], Aguilera R illustrated the stability and performance of MPC for power converters, and a PI-MPC control is implemented for the control of a Boost converter was realized in [30], on the other hand, Felip A has implemented a short-horizon FCS-MPC controller with input and state linearisation to solve the problem of the instability of the internal dynamics of a boost converter [31], we also found that Zhehan Yi has proposed a control strategy for hybrid multi-bus microgrids based on predictive control FCS-MPC[32].

The aim of our contribution is to highlight the effectiveness and performance of predictive model control in DC microgrids for permanent energy production; to help us and give us the information we need to implement and develop this type of control, and also to help engineers integrate this control into renewable energy power plants.

2. DESCRIPTION AND METHODS

The proposed system contains a DC voltage source connected to a 2.5 Ah battery, and a load that requires P= 15W at 15V, together forming a microgrid as shown in Figure 1.

The bi-directional DC/DC converter via battery, DC source and load is the key element of this work, and our aim is to establish optimal control of the converter for integration into the microgrid.

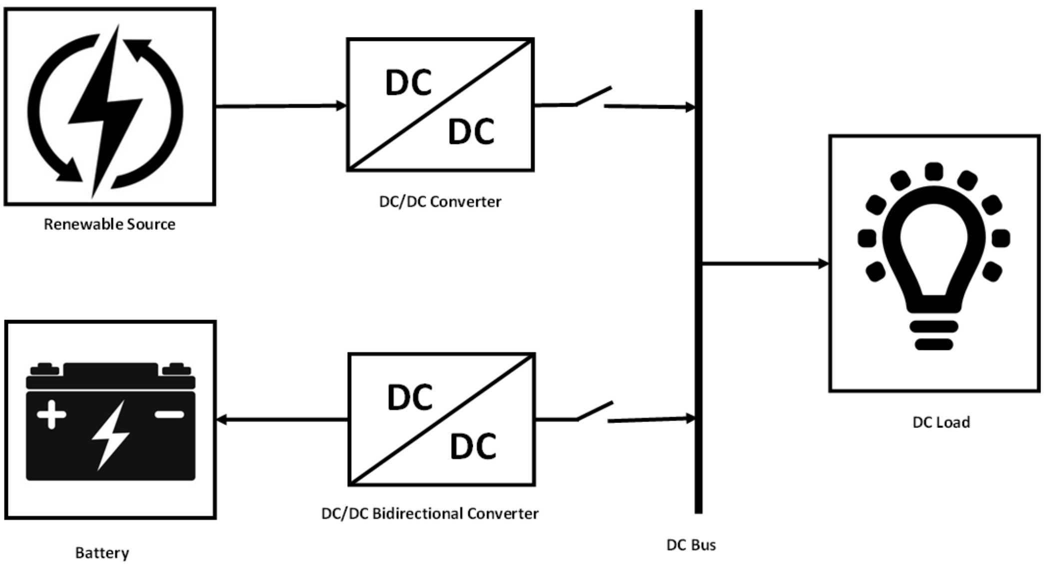

Figure 1. Proposed power system topology.

2.1. Bidirectional DC-DC converter design and modelling

To develop our system control, we need to choose the right model to describe the system's dynamic and static behaviour. In our application, the state-space model is the most compatible with the FCS-MPC optimizer, this representation is the most appropriate for complex non-linear systems, unlike the other representations, this model is defined in continuous time by[33] :

$$\begin{cases} \dfrac{dx(t)}{dt} = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \quad (1)$$

Where $x(t)$ is the system state vector, $u(t)$ is the system control or input vector and $y(t)$ is the system output vector, as well as A, B and C are system matrices.
The bi-directional DC-DC converter as shown in Figure 2 has the advantage of operating in two modes. When the battery is fully charged, the DC voltage source will deliver current to the connected load, in which case the converter operates in boost mode. On the contrary, when the battery is less charged, the DC voltage source in this case will deliver current to the battery, ensuring supply to the connected load, so the converter will operate in Buck mode [34].

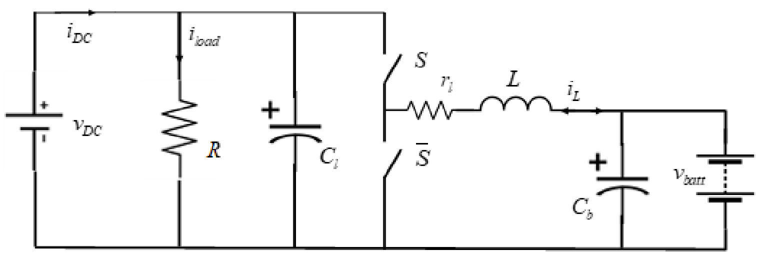

Figure 2. Bidirectional DC/DC converter circuit [34].

In reality, we're looking at two different model systems: the first is a Boost converter, the second is a Buck converter. So, we treat the two modes successively, based on the small signal analysis [33]:

- **Boost mode:**

In this mode, the energy source is the battery, the main V_{DC} source is disconnected, and the battery is in discharge mode. The inverter inputs are: $\vartheta_{in}(t)=\vartheta_{batt}$ and $i_i(t)=i_L(t)=i_{batt}$, and the outputs are: $\vartheta_o(t)=\vartheta_{load}$ and $i_o(t)=i_{load}$. So, the continuous-time state model associated with this mode is:

$$\begin{cases} \begin{bmatrix} \dfrac{di_L(t)}{dt} \\ \dfrac{d\vartheta_0(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{r_L}{L} & -\dfrac{(1-S)}{L} \\ \dfrac{(1-S)}{C_l} & -\dfrac{1}{RC_l} \end{bmatrix} \begin{bmatrix} i_L(t) \\ \vartheta_0(t) \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix} \begin{bmatrix} \vartheta_{in}(t) \\ 0 \end{bmatrix} \\ \begin{bmatrix} i_L(t) \\ \vartheta_0(t) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_L(t) \\ \vartheta_0(t) \end{bmatrix} \end{cases} \quad (2)$$

- **Buck mode:**

In this mode, the load and battery receive their energy requirements from the Vdc source, the battery is in charge mode, the inputs in this case are : $\vartheta_{in}(t)=\vartheta_{DC}$ and $i_i(t)=i_{DC}-i_{load}$, and the outputs are $\vartheta_o(t)=\vartheta_{batt}$ and $i_o(t)=-i_L(t)=i_{batt}$, the continuous-time state model associated with this mode is :

$$\begin{cases} \begin{bmatrix} \dfrac{di_L(t)}{dt} \\ \dfrac{d\vartheta_0(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{r_L}{L} & -\dfrac{1}{L} \\ \dfrac{1}{C_b} & -\dfrac{1}{RC_b} \end{bmatrix} \begin{bmatrix} i_L(t) \\ \vartheta_0(t) \end{bmatrix} + \begin{bmatrix} \dfrac{S}{L} \\ 0 \end{bmatrix} \begin{bmatrix} \vartheta_{in}(t) \\ 0 \end{bmatrix} \\ \begin{bmatrix} i_L(t) \\ \vartheta_0(t) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_L(t) \\ \vartheta_0(t) \end{bmatrix} \end{cases} \qquad (3)$$

2.2. FCS-MPC controller concept and design for bidirectional DC-DC control

As opposed to conventional controllers, the basic principle of the FCS-MPC controller is to predict the future behaviour of the state variables of the system x(t) based on knowledge of its current and past states. Finite control set model predictive control is simply an optimization algorithm that tends to generate several solutions based on different scenarios, and then executes the most optimal solution, so that the decision of the FCS-MPC controller is linked to the optimal cost function g, the FCS-MPC then consists of two parts, a prediction part and a cost function optimization part [16, 17], Figure 3 illustrates the predicted output from current and past data in a prediction horizon.

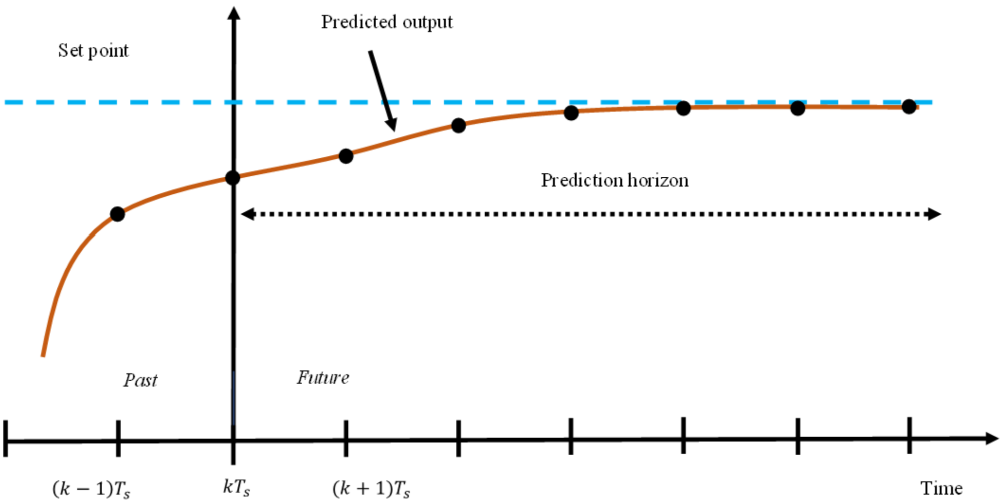

Figure 3. Control concept using the Model Predictive [35].

In the prediction block, a model of the predicted variable(s) is constructed from discrete-time system state vectors, generally discretized using Euler's method of first approximation due to its simplicity, as shown in Eq. (4).

$$\frac{dx}{dt} \simeq \frac{x(k+1)-x(k)}{T_s} \qquad (4)$$

In order to construct the appropriate prediction model for the system, the future variable and the reference variable go to the cost function optimization block in order to establish a control law S_i With $i = 1,\dots n$, such that n is the number of switching states of the converter, the cost function representation for the FCS-MPC controller is illustrated in Eq. (5):

$$g(i) = \left| x^*(k+1) - x(k+1) \right| \qquad (5)$$

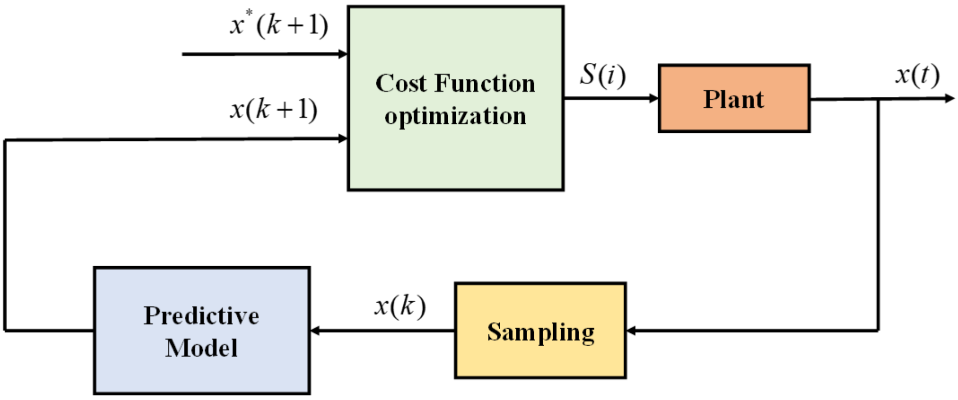

Figure 4. FSC-MPC controller structure[31].

In accordance with our work, the prediction algorithm starts by calculating the predicted current at the future sampler i_L *(k+1)* based on the current of the current sampler inductance i_L *(k)* and the other system parameters, the prediction function is given from the system state representation in two modes successively Eq. (2) and Eq. (3) [30].

$$\frac{di_L^{(boost)}}{dt} = -\frac{r_L}{L} i_L(t) - \frac{1-S}{L} \vartheta_0(t) + \frac{1}{L} \vartheta_{in}(t) \quad (6)$$

$$\frac{di_L^{(buck)}}{dt} = -\frac{r_L}{L} i_L(t) - \frac{1}{L} \vartheta_0(t) + \frac{S}{L} \vartheta_{in}(t) \quad (7)$$

According to the Euler approximation, we have established the two predictive models associated with the boost and buck modes successively in Eq. (8) and Eq. (9).

$$i_L(k+1)^{(boost)} = i_L(k) + \frac{T_s}{L}\left[\vartheta_{in}(k) - r_L i_L(k) - (1-S)\vartheta_0(k)\right] \quad (8)$$

$$i_L(k+1)^{(buck)} = i_L(k) + \frac{T_s}{L}\left[S\vartheta_{in}(k) - r_L i_L(k) - \vartheta_0(k)\right] \quad (9)$$

Figure 5 shows the FCS-MPC controller architecture proposed in this work, the FCS-MPC controller inputs are : the reference current i_L^* *(k+1)* generated by the PI controller, the actual current i_L *(k)* entering or leaving the battery, the actual input voltage ϑ_{in} *(k)*, the actual output voltage ϑ_o *(k)*, and the Boolean operating mode={0,1}, the FCS-MPC controller output is a commutation signal *S(i)* to control the bidirectional DC/DC converter.

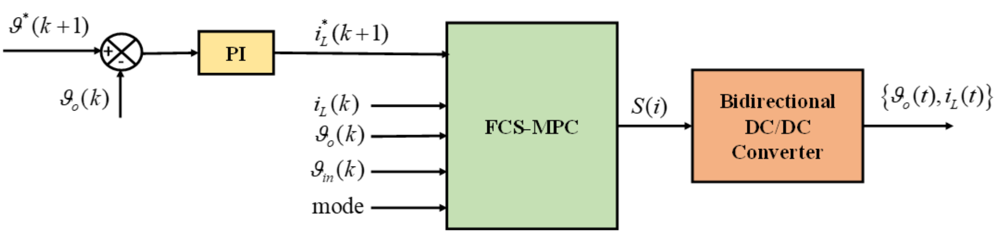

Figure 5. Proposed FCS-MPC controller structure.

The reference current i_L^* *(k+1)* is generated by a PI controller is essential to evaluate the quadratic cost function in all iterations *(k+1)*, this function is represented as [30]:

$$g^{mode}(i) = \left| i_L^*(k+1) - i_{L,i}^{mode}(k+1) \right| \quad (10)$$

We have designated an algorithm flow chart Figure 6 that clearly describes the essential steps during acquisition, processing and decision of our proposed controller:

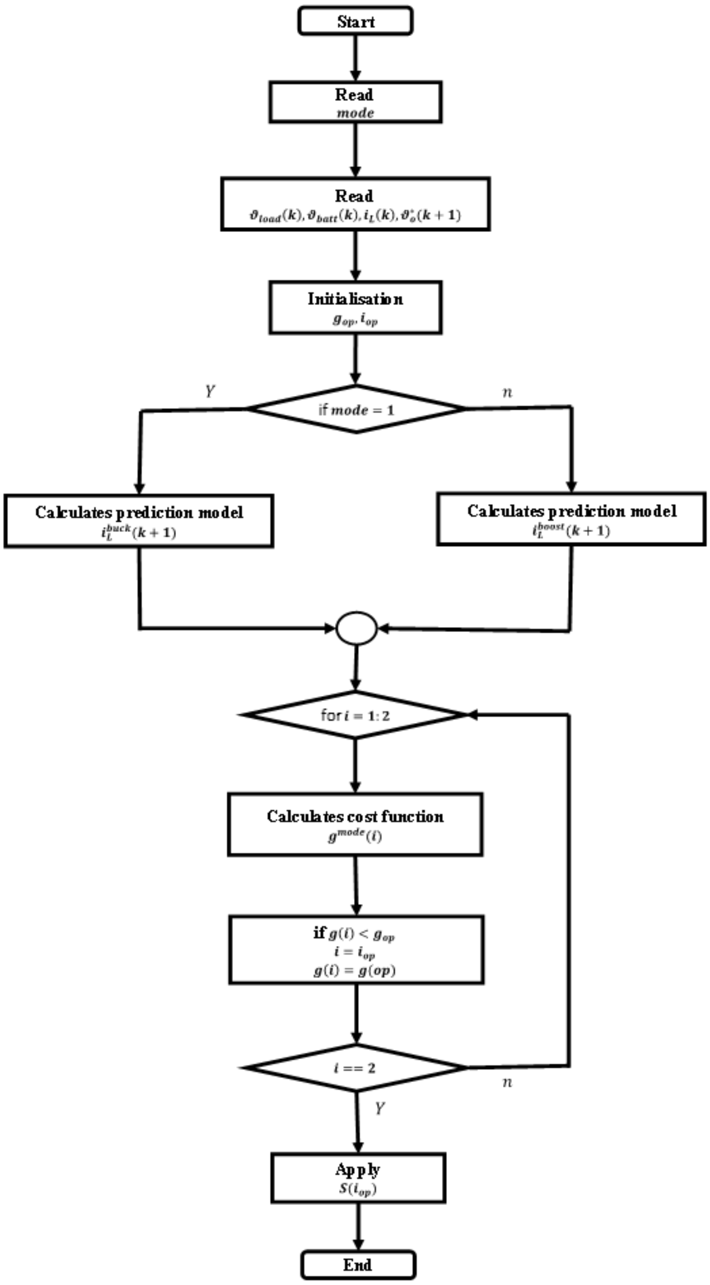

Figure 6. Proposed FCS-MPC organization chart[31].

3. SIMULATION, RESULTS AND DISCUSSION

To validate the performance of our proposed controller, we implemented it to manage a bidirectional power system. A load that requires 15W permanently connects with two energy sources that may be intermittent, the first is a 15V DC generator from a renewable source and the second is a 2.5Ah battery. The intermediary device is a bidirectional DC/DC converter that operates in Buck or Boost mode, depending on the state of the battery and DC source. Table 1 summarizes the parameters of the various components of our system.

Table 1. Study system parameters.

Parameter	Value	Unit
V_{DC}	15	V
i_{DC}	1	A
V_{batt}	6	V
C_{batt}	2,5	Ah
R	15	Ω
L	1	mH
C_b	20	uF
C_l	500	uF
r_l	0.2	Ω
r_c	0.001	Ω
f_s	10	KHz

Figure 7 shows the nominal voltage in discharge mode as a function of battery autonomy.

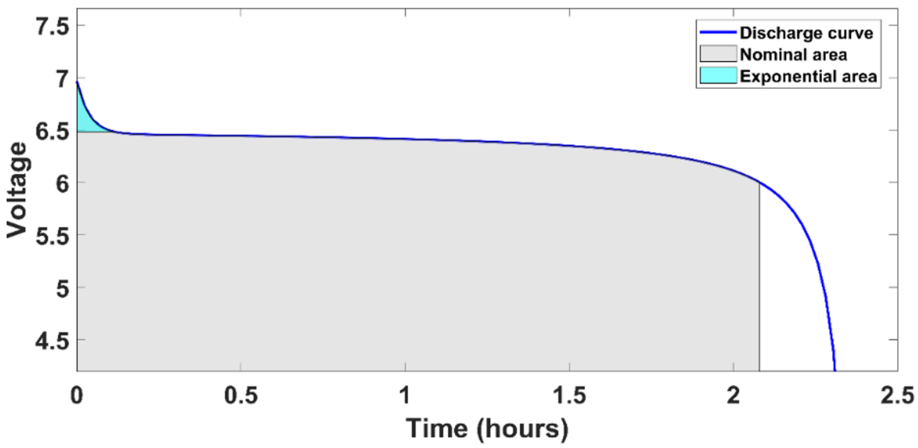

Figure 7. Battery discharge characteristics.

In fact, we've assigned two distinct tasks to our controller: the first is to control the DC-DC converter in two modes, while the second is to manage the energy flow by taking into consideration the battery's state of charge, with the aim of meeting the energy requirements of the load at all times, improving dynamic behaviour in transient conditions, and protecting and ensuring long battery life.

3.1. Simulation

Figure 8 shows the Matlab/Simulink simulation of the energy chain of the system we have described.

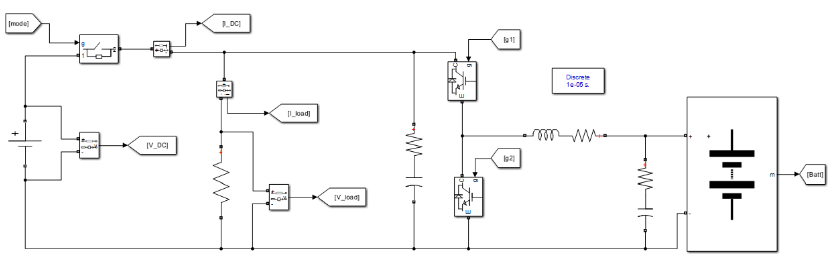

Figure 8. Matlab/Simulink simulation of a bidirectional DC/DC converter.

For the control and management chain, Figure 9 illustrates the simulation of the topology proposed in Figure 5. Input states pass first through a switch system, which decides which input variables and which output variables to use according to mode, then the FCS-MPC controller acquires its variables for processing and control.

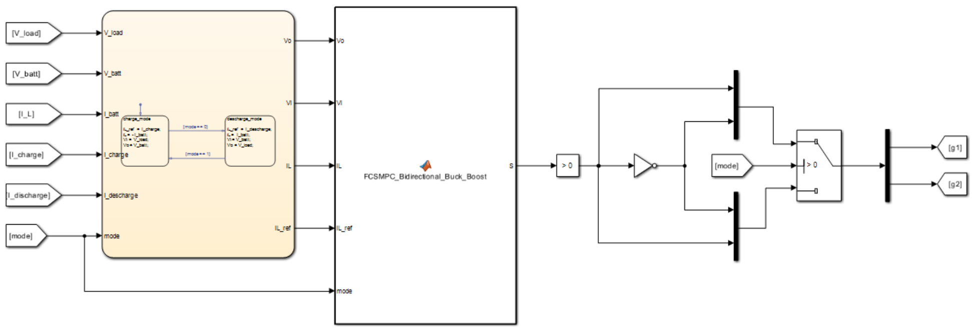

Figure 9. FCS-MPC controller simulation.

A PI controller is selected to determine the reference current $i_L^*(k+1)$ from a reference voltage according to the operating mode illustrated in Figure 10.

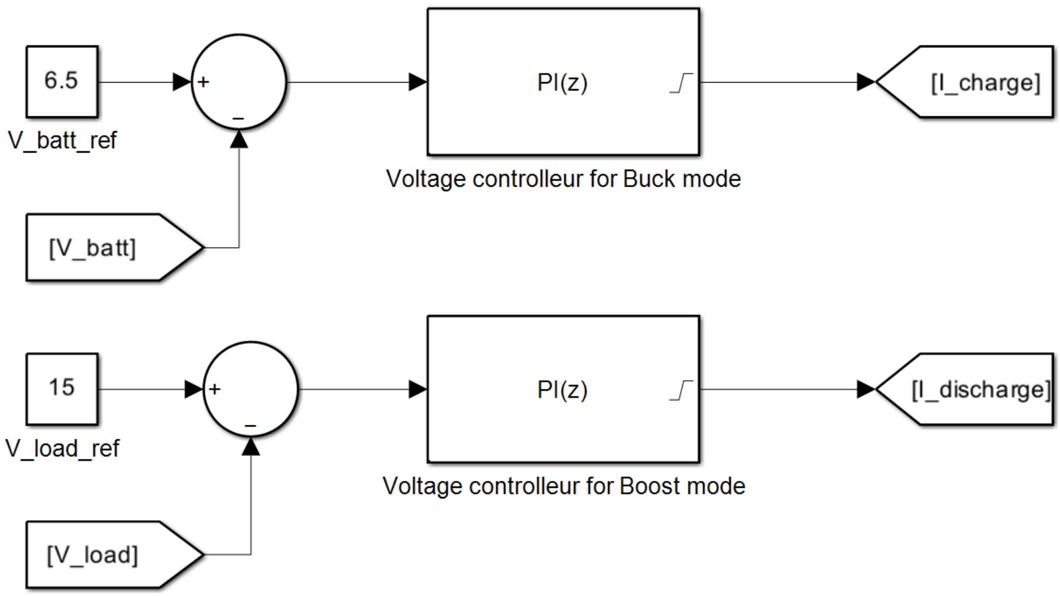

Figure 10. PI controller Simulation.

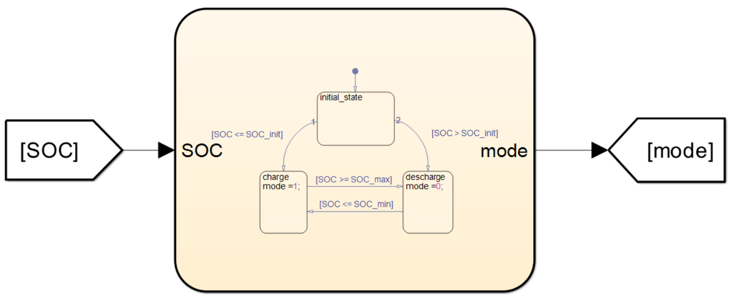

Figure 11. Proposed energy management system for the system.

Figure 11 illustrates the proposed management system for deciding the operating mode according to the state of the battery, the system initially compares the state of charge SOC from the battery with the state of charge $SOC_{init}=50\%$, the decision is based on the following condition: if $SOC<SOC_{init}$, the system decides the charging mode (Buck mode) up to 90%, otherwise the system decides the discharging mode (Boost mode) up to 10%, with $SOC_{init}=50\%$.

3.2. Results

• Buck mode (battery charging)

Assuming initially that the battery is almost empty with (SOC = 10%), the controller decides that the system should operate in battery charge mode, providing power to the load at 15W, with the battery charging at 5W after a transient. Figure 12 illustrates the behavior of the battery voltage and current over the simulation time as a receiver under the FCS-MPC model predictive control and the PI controller, Figure 12(a) and Figure 12(b) represent the current delivered to the battery for the two controllers FCS-MPC and PI successively, and Figure 12(c) and Figure 12(d) represent the battery voltage under this condition for the two controllers successively.

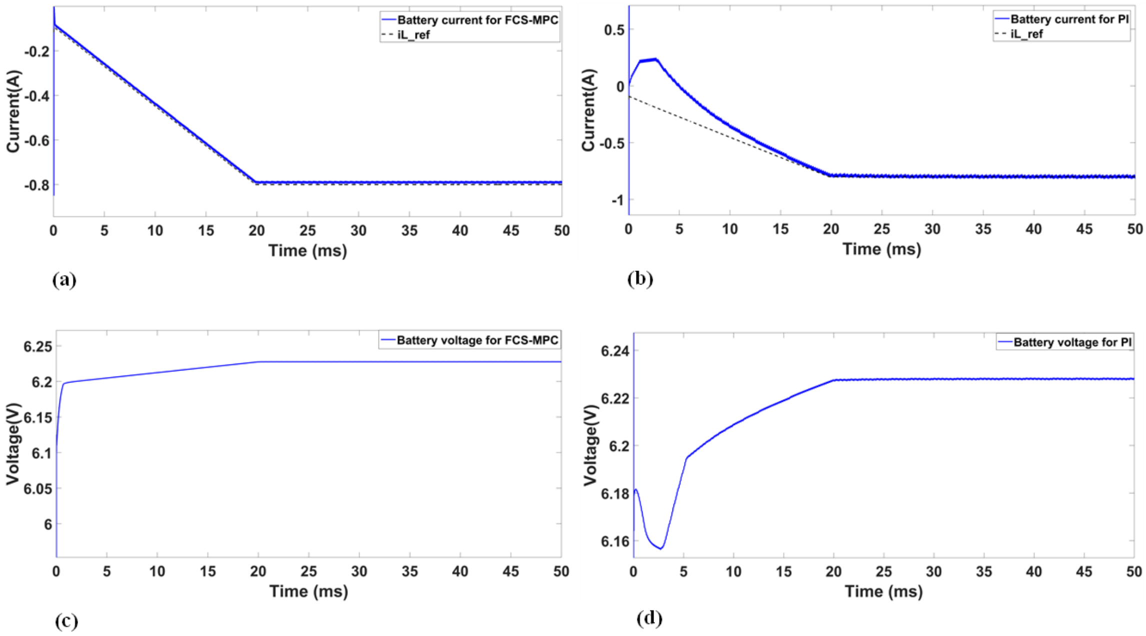

Figure 12. Battery parameters in charge mode.

• Boost mode (battery discharge)

In this case, it is assumed that the battery is almost charged (SOC = 90%), the controller decides that the system should then operate in battery discharge mode in the connected load, as well as the DC source being properly disconnected. Figure 13 shows the behavior of the battery as an energy source over the simulation time, Figure 14 illustrates the behavior of the connected load under the FCS-MPC predictive model control and the PI controller. In Figure 13(a) and Figure 13(b) represent the current delivered to the battery for the two controllers FCS-MPC and PI successively, Figure 13(c) and Figure 13(d) represent the battery voltage under this condition for the two controllers in succession, and in Figure 14(a) and Figure 14(b) show the load terminal voltage at a reference voltage of 15 volts for the FCS-MPC and PI controllers in succession.

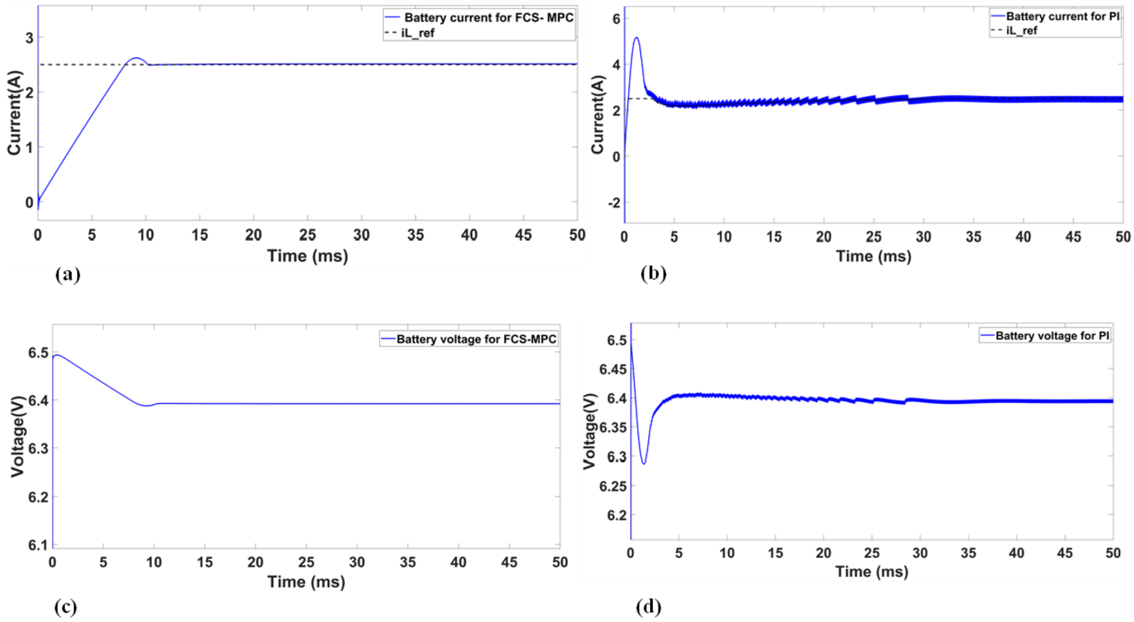

Figure 13. Battery parameters during discharge.

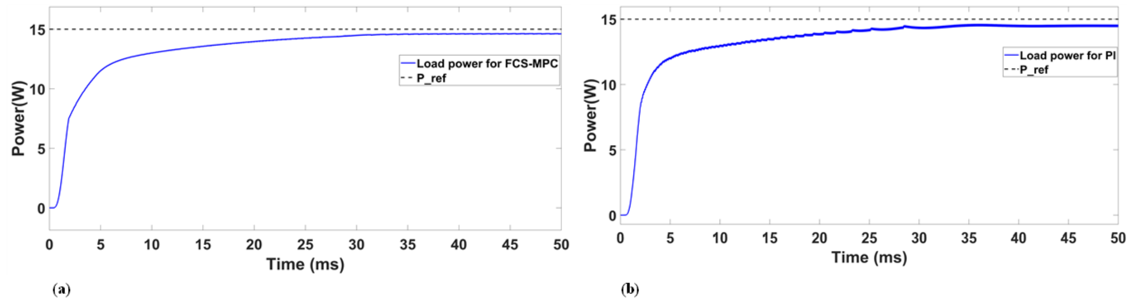

Figure 14. Battery-powered load parameters.

• Instant of switching between the two modes

Initially, we assume that the system started by charging the battery, but according to our specification, when the SOC state-of-charge reaches 90%, the system must switch instantaneously to discharge mode by cutting off the supply from the renewable DC source. Figure 15 illustrates how the system behaves at the instant of switching operating mode for the FCS-MPC and PI controllers. Figure 15(a) represents the power received from the load using the FCS-MPC controller, and Figure 15(b) represents the same situation for the PI controller.

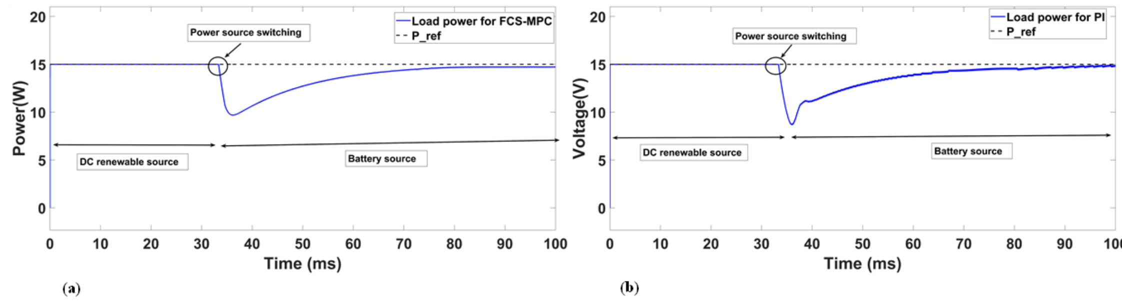

Figure 15. Power consumed by the connected load when the power sources are switched.

3.3. Discussion

To validate the effectiveness of our proposed FCS-MPC controller, we have tested it in three possible situations for controlling Bidirectional DC/DC converters in parallel with the traditional PI controller, the first is testing in Buck mode (battery charging), the second is Boost mode (battery discharging) and the third is the instant of switching between the two modes, Table 2 summarizes the different results for output voltages ϑ_o *(t)* in each mode.

Table 2. Simulation results.

	Boost mode		Buck Mode	
	Setting time (ms)	Steady state error (V)	Setting time (ms)	Steady state error (V)
PI	20	0.12	18.00	0.30
Proposed FCS-MPC	10.13	0.11	10.13	0.28
COPI[27]	15.00	-	-	-
ANFIS (Boost)[24]	30.00	1.58	-	-
ANFIS (Buck)[28]	-	-	14.20	0.20

In boost mode, under FCS-MPC control, the battery voltage begins with a linear transient until it reaches steady state during t_r*=10.13* ms. On the load side, the system maintains the same response time, with zero overshoot on the connected load, so the system is more accurate and follows the setpoint better. However, under PI control, the battery test goes through a drop in the transient regime, and in the steady state, voltage and current show significant ripples. It is therefore clear that the FCS-MPC controller is better suited to improving the performance of the boost converter between the battery and the connected load.

In Buck mode, battery voltage and current evolve linearly until t_r=10.13 ms. without overshoot in the transient regime, after which the system reaches a steady state and starts charging at a voltage of ϑ_{batt}=6.25 V. In this mode, it's clear that the FCS-MPC controller has a significant effect on battery charging. In terms of speed, the response time in this case is very significant, and overshoot and ripple rate are well optimized, compared with other traditional PI controllers.

In the last test, by switching from Buck mode to Boost mode, i.e. by changing the direction of the energy flow from charging to discharging the battery, under the control of FCS-MPC, the battery instantly changes state, passing from receiver to generator, with a brief transient, the load also changes energy source without interruption, and continues to operate with the same characteristics, this FCS-MPC option is very important in microgrids when renewable sources cease to operate, energy storage units can be used to store energy, and the battery can be recharged. By analogy with similar work, Warrier et al [27] found after a PI controller enhancement (COPI) that Boot converter response time is t_r=15.00 ms, for the same system, Youssfi et al[24] have a response time of t_r=30.00 ms and a static error e_{ss}=1.58 ms by implementing ANFIS controller, however, Shaikh et al[28] implemented the same controller for Buck converter control, they found that response time is t_r=14.20 ms, as well as static error is e_{ss}=0.20 ms. Compared with these results, our proposed controller offers a crucial and significant improvement, which better confirms our proposal.

In summary, the simulation test we carried out strongly validates the effectiveness of our proposed controller compared with the traditional PI controller.

4. CONCLUSION

The FCS-MPC controller we have proposed in this contribution has shown that it is capable of controlling and handling the operation of more complex systems with high performance compared to other traditional controllers, such as our proposed bidirectional DC/DC converter for energy flow management in a DC Microgrid, In this context, this work will provide insights for the practical realization of a DC or AC Microgrid controlled by predictive control, as well as manipulating this control for active and reactive power control, harmonic control and fault detection in DC and AC Microgrids.

Author Contributions: Conceptualization: Abdelaziz Youssfi; Methodology: Youssef Ait El Kadi; Software: Abdelaziz Youssfi; Validation: Abdelaziz Youssfi; Formal Analysis: Abdelaziz Youssfi; Investigation: Youssef Ait El Kadi; Resources: Youssef Ait El Kadi; Data Curation: Abdelaziz Youssfi; Writing - Original Draft: Abdelaziz Youssfi; Writing - Review & Editing: Youssef Ait El Kadi; Visualization: Abdelaziz Youssfi; Supervision: Youssef Ait El Kadi; Project Administration: Youssef Ait El Kadi; Funding Acquisition: Youssef Ait El Kadi.

Funding: This work was funded by the Engineering and Applied Physics Research Team. The authors declare that the funding was used to support the research, data collection, analysis, and writing of the manuscript. The authors also state that there are no conflicts of interest related to this funding source.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that there are no competing interests regarding the publication of this paper. All financial and non-financial relationships that could potentially influence the research have been disclosed.

REFERENCES

[1] M. Asif and T. Muneer, "Energy supply, its demand and security issues for developed and emerging economies," Renewable and Sustainable Energy Reviews, vol. 11, no. 7, pp. 1388–1413, Sep. 2007, doi: 10.1016/J.RSER.2005.12.004.

[2] A. M. Omer, "Energy, environment and sustainable development," Renewable and Sustainable Energy Reviews, vol. 12, no. 9, pp. 2265–2300, Dec. 2008, doi: 10.1016/J.RSER.2007.05.001.

[3] D. Sivaraman, S. Pacca, K. Mueller, and J. Lin, "Comparative Energy, Environmental, and Economic Analysis of Traditional and E-commerce DVD Rental Networks," J Ind Ecol, vol. 11, no. 3, pp. 77–91, Jul. 2007, doi: 10.1162/JIEC.2007.1240.

[4] F. Evrendilek and C. Ertekin, "Assessing the potential of renewable energy sources in Turkey," Renew Energy, vol. 28, no. 15, pp. 2303–2315, Dec. 2003, doi: 10.1016/S0960-1481(03)00138-1.

[5] "Property and the Law in Energy and Natural Resources - Google Livres." Accessed: Jan. 19, 2024. [Online]. Available: https://books.google.co.ma/s?hl=fr&lr=&id=QiNr05MoHHMC&oi=fnd&pg=PR5&dq=natural+energy+resources&ots=VkGR3Q_Nqk&sig=wl1O9u6WyYnvC5yVIB27QCItxPA&redir_esc=y#v=onepage&q=natural%20energy%20resources&f=false

[6] Y. A. El Kadi, Y. Lakhal, and F. Z. Baghli, "Compensation of the harmonic pollution by photovoltaic systems under variable solar radiation," Proceedings of 2019 International Conference of Computer Science and Renewable Energies, ICCSRE 2019, Jul. 2019, doi: 10.1109/ICCSRE.2019.8807541.

[7] A. Youssfi, A. Alioui, and Y. A. El Kadi, "Study, simulation and realization of a fuzzy logic-based MPPT controller in an isolated DC microgrid," Indonesian Journal of Electrical Engineering and Computer Science, vol. 34, no. 3, pp. 1420–1433, Jun. 2024, doi: 10.11591/IJEECS.V34.I3.PP1420-1433.

[8] H. Ibrahim, A. Ilinca, and J. Perron, "Energy storage systems—Characteristics and comparisons," Renewable and Sustainable Energy Reviews, vol. 12, no. 5, pp. 1221–1250, Jun. 2008, doi: 10.1016/J.RSER.2007.01.023.

[9] S. M. Dawoud, X. Lin, and M. I. Okba, "Hybrid renewable microgrid optimization techniques: A review," Renewable and Sustainable Energy Reviews, vol. 82, pp. 2039–2052, Feb. 2018, doi: 10.1016/J.RSER.2017.08.007.

[10] S. Silvestre, A. Chouder, and E. Karatepe, "Automatic fault detection in grid connected PV systems," Solar Energy, vol. 94, pp. 119–127, Aug. 2013, doi: 10.1016/J.SOLENER.2013.05.001.

[11] E. Román, R. Alonso, P. Ibañez, S. Elorduizapatarietxe, and D. Goitia, "Intelligent PV module for grid-connected PV systems," IEEE Transactions on Industrial Electronics, vol. 53, no. 4, pp. 1066–1073, Jun. 2006, doi: 10.1109/TIE.2006.878327.

[12] M. A. Eltawil and Z. Zhao, "Grid-connected photovoltaic power systems: Technical and potential problems—A review," Renewable and Sustainable Energy Reviews, vol. 14, no. 1, pp. 112–129, Jan. 2010, doi: 10.1016/J.RSER.2009.07.015.

[13] Y. A. El Kadi, F. Z. Baghli, and Y. Lakhal, "Energy quality optimization in smart grids Faults monitoring by the space vector signature analysis method," 6th International Conference on Optimization and Applications, ICOA 2020 - Proceedings, Apr. 2020, doi: 10.1109/ICOA49421.2020.9094451.

[14] A. Youssfi, Y. Ait, and E. Kadi, "Improving power sharing and enhancing the stability of an isolated AC microgrid by implementing droop control and virtual impedance," E3S Web of Conferences, vol. 582, p. 01001, Oct. 2024, doi: 10.1051/E3SCONF/202458201001.

[15] S. Beheshtaein, R. M. Cuzner, M. Forouzesh, M. Savaghebi, and J. M. Guerrero, "DC Microgrid Protection: A Comprehensive Review," IEEE J Emerg Sel Top Power Electron, pp. 1–1, Mar. 2019, doi: 10.1109/JESTPE.2019.2904588.

[16] N. M. L. Tan, T. Abe, and H. Akagi, "Design and performance of a bidirectional isolated DC-DC converter for a battery energy storage system," IEEE Trans Power Electron, vol. 27, no. 3, pp. 1237–1248, 2012, doi: 10.1109/TPEL.2011.2108317.

[17] Q. Xu, N. Vafamand, L. Chen, T. Dragicevic, L. Xie, and F. Blaabjerg, "Review on Advanced Control Technologies for Bidirectional DC/DC Converters in DC Microgrids," IEEE J Emerg Sel Top Power Electron, vol. 9, no. 2, pp. 1205–1221, Apr. 2021, doi: 10.1109/JESTPE.2020.2978064.

[18] L. Magni and R. Scattolini, "Robustness and robust design of MPC for nonlinear discrete-time systems," Lecture Notes in Control and Information Sciences, vol. 358, no. 1, pp. 239–254, 2007, doi: 10.1007/978-3-540-72699-9_19/COVER.

[19] M. L. Darby and M. Nikolaou, "MPC: Current practice and challenges," Control Eng Pract, vol. 20, no. 4, pp. 328–342, Apr. 2012, doi: 10.1016/J.CONENGPRAC.2011.12.004.

[20] M. R. Basir Khan, J. Pasupuleti, J. Al-Fattah, and M. Tahmasebi, "Energy management system for PV-battery microgrid based on model predictive control," Indonesian Journal of Electrical Engineering and Computer Science, vol. 15, no. 1, pp. 20–26, Jul. 2019, doi: 10.11591/IJEECS.V15.I1.PP20-26.

[21] H. Farsizadeh, M. Gheisarnejad, M. Mosayebi, M. Rafiei, and M. H. Khooban, "An Intelligent and Fast Controller for DC/DC Converter Feeding CPL in a DC Microgrid," IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 67, no. 6, pp. 1104–1108, Jun. 2020, doi: 10.1109/TCSII.2019.2928814.

[22] R. Das and M. A. Uddinchowdhury, "PI controlled Bi-directional DC-DC converter (BDDDC) and highly efficient boost converter for electric vehicles," 2016 3rd International Conference on Electrical Engineering and Information and Communication Technology, iCEEiCT 2016, Mar. 2017, doi: 10.1109/CEEICT.2016.7873094.

[23] R. Das, H. Rashid, and I. U. Ahmed, "A comparative analysis of PI and PID controlled bidirectional DC-DC converter with conventional bidirectional DC-DC converter," 3rd International Conference on Electrical Information and Communication Technology, EICT 2017, vol. 2018-January, pp. 1–6, Jul. 2017, doi: 10.1109/EICT.2017.8275149.

[24] A. Youssfi, Y. Hakam, and Y. A. El Kadi, "Comparative Study of Proportional–Integral, Fuzzy Logic, and Neural Fuzzy Logic Controllers for Boost Converter," Advances in Science, Technology and Innovation, pp. 33–39, 2024, doi: 10.1007/978-3-031-51796-9_4.

[25] R. Ling, D. Maksimovic, and R. Leyva, "Second-order sliding-mode controlled synchronous buck DC-DC converter," IEEE Trans Power Electron, vol. 31, no. 3, pp. 2539–2549, Mar. 2016, doi: 10.1109/TPEL.2015.2431193.

[26] S. C. Tan, Y. M. Lai, and C. K. Tse, "General design issues of sliding-mode controllers in DC-DC converters," IEEE Transactions on Industrial Electronics, vol. 55, no. 3, pp. 1160–1174, Mar. 2008, doi: 10.1109/TIE.2007.909058.

[27] P. Warrier, P. Shah, and R. Sekhar, "A Comparative performance evaluation of a complex-order PI controller for DC–DC converters," Results in Control and Optimization, vol. 15, p. 100414, Jun. 2024, doi: 10.1016/J.RICO.2024.100414.

[28] U. A. Shaikh, M. K. AlGhamdi, and H. A. AlZaher, "Novel product ANFIS-PID hybrid controller for buck converters," The Journal of Engineering, vol. 2018, no. 8, pp. 730–734, Aug. 2018, doi: 10.1049/JOE.2018.0113.

[29] A. Ademola-Idowu and B. Zhang, "Frequency Stability Using MPC-Based Inverter Power Control in Low-Inertia Power Systems," IEEE Transactions on Power Systems, vol. 36, no. 2, pp. 1628–1637, Mar. 2021, doi: 10.1109/TPWRS.2020.3019998.

[30] B. Talbi, F. Krim, A. Laib, A. Sahli, and A. Krama, "PI-MPC Switching Control for DC-DC Boost Converter using an Adaptive Sliding Mode Observer," 2020 International Conference on Electrical Engineering, ICEE 2020, Sep. 2020, doi: 10.1109/ICEE49691.2020.9249934.

[31] F. A. Villarroel et al., "Stable Shortest Horizon FCS-MPC Output Voltage Control in Non-Minimum Phase Boost-Type Converters Based on Input-State Linearization," IEEE Transactions on Energy Conversion, vol. 36, no. 2, pp. 1378–1391, Jun. 2021, doi: 10.1109/TEC.2021.3055733.

[32] Z. Yi et al., "Finite-Control-Set Model Predictive Control (FCS-MPC) for Islanded Hybrid Microgrids," IEEE Power and Energy Society General Meeting, vol. 2018-August, Dec. 2018, doi: 10.1109/PESGM.2018.8586292.

[33] R. H. G. Tan and L. Y. H. Hoo, "DC-DC converter modeling and simulation using state space approach," 2015 IEEE Conference on Energy Conversion, CENCON 2015, pp. 42–47, 2015, doi: 10.1109/CENCON.2015.7409511.

[34] L. S. Yang and T. J. Liang, "Analysis and implementation of a novel bidirectional DC-DC converter," IEEE Transactions on Industrial Electronics, vol. 59, no. 1, pp. 422–434, Jan. 2012, doi: 10.1109/TIE.2011.2134060.

[35] J. Brian Froisy, "Model predictive control: Past, present and future," ISA Trans, vol. 33, no. 3, pp. 235–243, Sep. 1994, doi: 10.1016/0019-0578(94)90095-7.