Set up of a secondary on-board charger fed by PV DC station with grid injection for fast charging the recent city cars

Mohamed Arrach[1], Fatima Ezzahra Tahiri[2], Abdesslam Lokriti[1], Khalid Chikh[1]
[1]Science and Technology for the Engineer Laboratory, Sultan Moulay Slimane University-ENSA, Khouribga, Morocco
[2]Energy and Electrical Systems Laboratory, Hassan II University-ENSEM Casablanca, Casablanca, Morocco

Article Info

Article history:

Received Jun 18, 2024
Revised Jan 16, 2025
Accepted Mar 1, 2025

Keywords:

City cars
Fast charge
Fuzzy logic
Grid injection
MPPT
Phase-shift converter
PV source

ABSTRACT

In this article, we propose a secondary high-power charger provided by a photovoltaic source with grid connection. The high-power charger is composed of a phase shift full bridge (PSFB) DC-DC converter controlled by a constant voltage constant current algorithm based on PI control. The first stage is composed of a PV panel source, controlled by a fuzzy logic using a maximum power point tracking (MPPT) algorithm, associated with a synchronous boost converter to set up the voltage at the standard common 400 V bus level. While the charger is a second stage composed of a phase shift converter for step down and adapting the voltage and the charging current for the battery of the urban electric car. We have also proposed the grid connection with a simple optimization to inject the generated power into the electrical grid when no car is connected to the power station. To achieve this goal, simulation results of the proposed configuration control techniques by using the MATLAB/Simulink environment are presented and discussed at the end of this paper.

Corresponding Author:

Mohamed Arrach
Science and Technology for the Engineer Laboratory, Sultan Moulay Slimane University-ENSA
Khouribga, Morocco
Email: mohamed.arrach@usms.ac.ma

1. INTRODUCTION

Mobility today constitutes one of the major challenges of the energy transition. In addition to the economic cost of acquiring, using, and maintaining a vehicle, it has a significant impact on the environment, particularly in terms of greenhouse gas emissions. Due to environmental concerns, electric vehicles (EVs) are becoming more and more common in the automobile industry [1]. To mitigate climate change, greenhouse gas emissions, and poor air quality, electrifying transportation is seen as a promising alternative to traditional fuel sources [2].

The starting point for thinking about sustainable mobility is based on the choice of means of transport, and particularly cars. The automotive market has been evolving rapidly in recent years, and particularly in recent months, to offer more and more solutions to meet regulatory and environmental concerns, and as is known, the transportation sector shoulders a significant burden, accounting for approximately 62.3% of global fuel consumption in a few years [3].

The issues in EV technology development are battery tube capacity, heavy-size batteries, fast charging, and safe charging infrastructure. In this vision, many major manufacturers are now expressing their ambition to become leaders in the electric car sector. Indeed, electromobility corresponds to the use of electric vehicles. These come in all types and can be classified into three categories: fully electric vehicles, extended range electric vehicles, and hybrid vehicles.

In our case study, we want to deal with a type of urban electric car that is increasingly recommended in urban transport. Moreover, several manufacturers have launched their own cars to meet new requirements for green and sustainable transport. This type of car is characterized by its speed limit of 45 km/h and its small size. It has a 5.8 kWh battery and a range of 75 km. However, to meet the actual purpose of the EVs (reduction in air pollution, reduction in fossil fuel dependency, and an increase in energy security), the electric energy needed for charging the EVs should come from renewable energy sources [4]. As a renewable and clean energy, photovoltaic (PV) energy can be produced anywhere, including urban areas for EV applications [5], [6].

We propose in this work a high-power autonomous and off-board secondary charger based on a photovoltaic source with a mix of converter topologies and a mix of linear and non-linear control. Different fast charger topologies are available depending on their applications [7]. The need for charging stations has become crucial [8]. Car drivers need easy access to fast charging stations to reduce the stress of searching for charging points and their fear about their battery life. At the same time, it is necessary to develop much more availability of charging points with a good connected distribution map and optimal cost of their use [9].

Charging the urban vehicle requires a single-phase charger with a power of 1.8 kW at different points in the city, with a charging time of 3 hours. However, our proposal offers a high-power secondary charger through a DC bus fast charging station with a power of 3.6 kW to reduce the charging time and the occupancy time of the city car.

The charging structures can be AC and DC grid-based [10], [11]. Charging can be of both types- AC and DC charging. AC charging generally specifies level 1 and level 2 charging for on-board chargers, while DC charging is considered Level 3 charging that requires off-board chargers [12]. The proposed scheme for the battery recharging system is based on the setup of a multiport configuration for recharging electric cars to ensure multi-use for other types of cars. Fast charging via a DC bus charger at 400 VDC powered by a PV source and a secondary on-board charger on the urban car based on a full bridge phase shift DC-DC converter (PSFB).

The novelty of this approach is to upgrade the existing configuration of charging methods. We propose adding a high-power secondary on-board charger next to the first existing one. The novelty of this configuration is that the electric car can be charged, in addition to the single-phase charger, with a DC station fed by PV panels to meet the neutral carbon chart, especially in mobility activity. To discuss further the improvement proposed in this work, the paper is divided into three sections. The first one is about the overview of the schema of the proposal. The second is about the theoretical discussion of the circuit. The third one is about the simulation in MATLAB/Simulink and the results discussion. In the end, we have the conclusion and discussion of further perspectives in the common works.

2. METHOD

2.1. Overview of the proposition

As initially discussed in the introduction, the main contribution is based on setting up the urban electric car with a secondary high-power on-board charger in addition to the existing on-board charger. This second charger can be plugged directly into a high DC charging station based on a photovoltaic source, which will also be developed in this work.

In fact, as shown in Figure 1, we propose an upgrade of the existing single socket to a configuration of multi-socket which contains a socket for AC charger as conventional charger with a maximum power level of 1.8 kW and another socket for fast charging through the secondary on-board charger with a power level of 3.6 kW. The proposed configuration has many advantages to overcome the actual one in terms of power levels capability and to meet a redundancy reinforced by adding a second charger.

Figure 1. The proposed multi-socket configuration

In the following description mentioned in Figure 2, the conventional charging is fed only by AC single phase through the low voltage distribution grid with a power limitation of 1.8 kW. While the proposed configuration consists of maintaining the conventional charger and adding a secondary on-board charger fed, in this case, by a photovoltaic direct current station which can be installed in different points in the city. In addition to this configuration, we also proposed a coupled inverter to evacuate the energy produced by the station when no car is connected to keep the proposition more useful.

In fact, to develop further the consistency of the contribution, the PV station is composed of a DC-DC stage based on a synchronous boost converter to step up the voltage coming from PV panels from 320 VDC to 400 VDC in the DC charging bus. We have used a fuzzy logic control enhanced by an MPPT algorithm to maximize the efficiency of PV panels. The secondary on-board charger is composed of a phase shift full bridge converter (PSFB) controlled by a constant current constant voltage algorithm using a PI control loop.

2.2. PV as primary power for a DC power station

We thought about introducing a renewable source to align with new environmental requirements. For this purpose, we propose a photovoltaic source as the primary voltage source of the high-power DC station. To have the requested power source, a series and parallel PV panels combination is possible with PV panels [13].

Furthermore, to be able to maximize the power extracted from photovoltaic panels, several techniques are possible, including the perturb and observe (P&O) algorithm, mentioned in Figure 3. And as illustrated in Figure 4, the algorithm perturbs the operating voltage of the PV module slightly and observes the change in power output. If the power increases due to the perturbation, the algorithm continues to perturb in the same direction. This process is repeated iteratively to constantly track the MPPT.

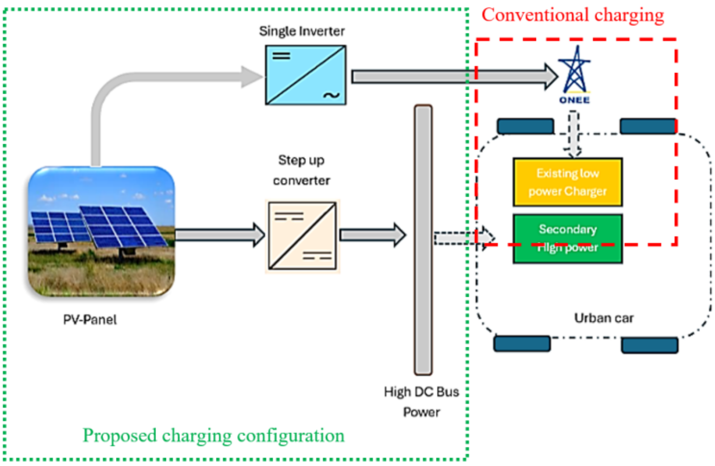


Figure 2. Overview of the proposed charging configuration

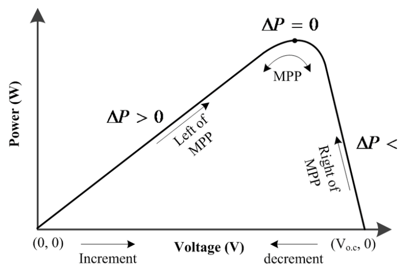


Figure 3. Conventionnel P&O MPPT technique

2.3. Synchronous boost with P&O and fuzzy logic control

The DC station, mentioned in Figure 5, is composed of a synchronous boost converter controlled by fuzzy logic to step up the voltage from 320 VDC to 400 VDC. This topology of the DC-DC converter offers several advantages compared to its conventional boost with a diode. It is called synchronous because the control of the two switches S1 and S2 is carried out in a synchronous way [14].

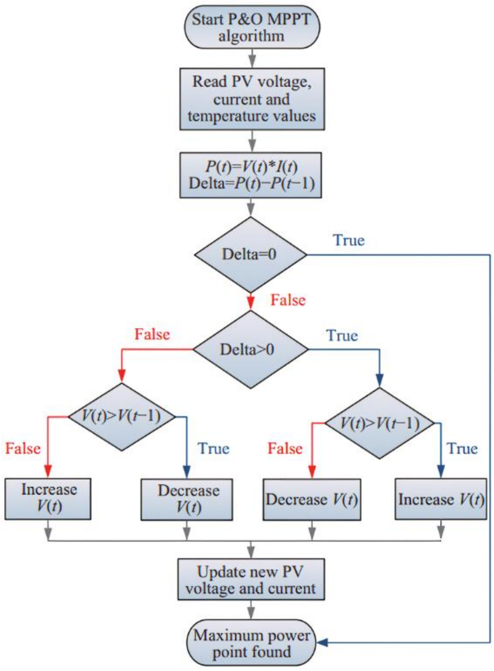


Figure 4. Algorithm steps of the P&O technique

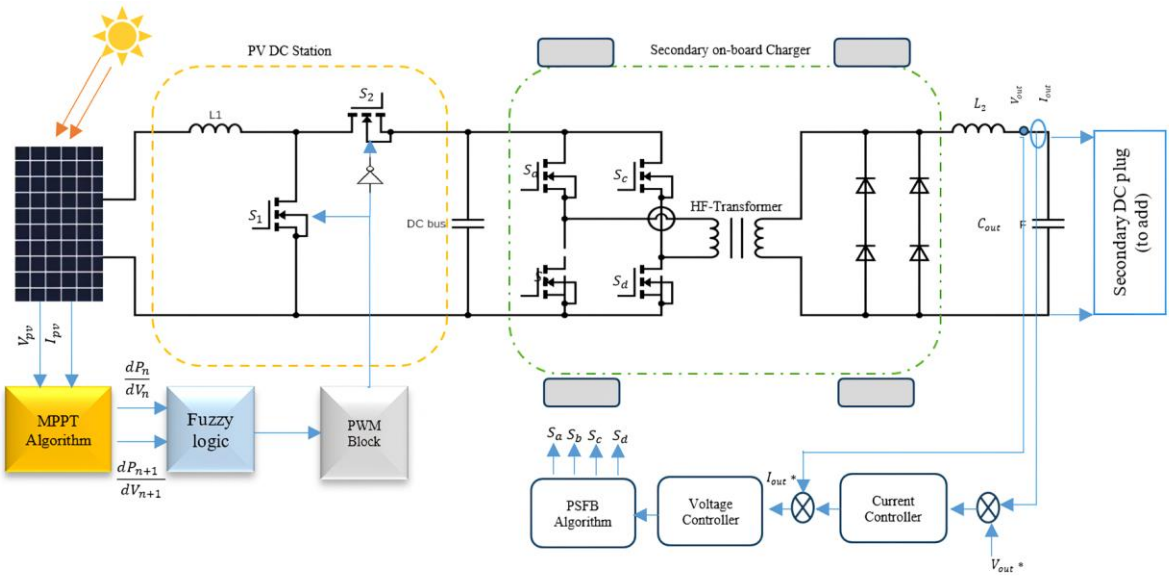


Figure 5. Full circuit of the proposed configuration

2.3.1. Inductor selection

The choice of inductance is crucial. It is the passive component to back up energy in the converter. The greater the inductance, the smaller the ripple is. The value of the inductor is calculated using Kirchhoff's law, in a boost topology, and it's given by (1) and (2).

$$L_1 = \frac{V_{in} \times (V_{dc} - V_{in})}{\Delta I_{L_1} \times f_{sw} \times V_{dc}} \quad (1)$$

$$\Delta I_{L_1} = 0.2 \times I_{L_1} \times \frac{V_{dc}}{V_{in}} \quad (2)$$

Where L_1: inductor in (H), V_{in}: input voltage in (V), V_{dc}: DC bus voltage in (V), I_{L_1}: inductor current in (A), ΔI_{L_1}: estimated ripple current in (A), and f_{sw}: switching frequency in (Hz)

2.3.2. DC bus capacitor selection

The choice of DC bus capacity is important. In fact, it makes it possible to stabilize the voltage and control the ripple in the voltage to avoid voltage drop during excessive current flow. Its value is calculated using Kirchhoff's law and given in (3) and (4).

$$C_1 = \frac{I_{dc} \times D}{f_{sw} \times \Delta V_{dc}} \quad (3)$$

$$\Delta V_{dc} = 0.2 \times V_{dc} \quad (4)$$

After the design of the components of the power stage, the parameters of the synchronous boost converter are mentioned in Table 1.

2.3.3. Design of the fuzzy logic block control

As shown in Figure 6, the fuzzy logic control is designed to track the maximum power for the solar panel with the P&O algorithm. It measures the values of the voltage and current at the output of the PV array. At every discrete iteration, it calculates the PV power to derive the inputs of the controller [15]. By combining fuzzy logic control with the P&O algorithm, the MPPT system can effectively adapt to changing environmental conditions and uncertainties. The fuzzy logic controller provides a flexible and intuitive decision-making mechanism, while the P&O algorithm performs the iterative adjustment of the operating point based on the fuzzy controller's output. Defuzzification then translates the fuzzy output into actionable control signals for the MPPT system.

The logic is translated by the fuzzification of the comparison between the evolutions of the iterations between the states of the errors of the variable $\frac{dP}{dV}$ [16]. It takes a combination of five states (NB: negative big, NS: negative small, Z: zero, PS: positive small, and PB: positive big), which gives a table of rules of 25 combinations of states described in Table 2. Fuzzy logic states from Table 2 are translated by memberships depending on the error between the iterations and the difference of the error. These two states define the output angle. All operations combining membership functions generate new fuzzy states based on logical relationships.

Table 1. Parameters of synchronous boost converter

Parameter	Notation	Value
PV irradiance	1000	W/m²
PV temperature	25	°C
Inductor	L_1	0.6 µH
DC bus capacitor	C_1	8 mF
Switching frequency	f_{sw}	10 kHz
Maximal rated power	P_n	3.6 kW

Table 2. Control combinations of fuzzy logic blocks

E\ΔE	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NB	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PB	PB
PB	Z	PS	PS	PB	PB

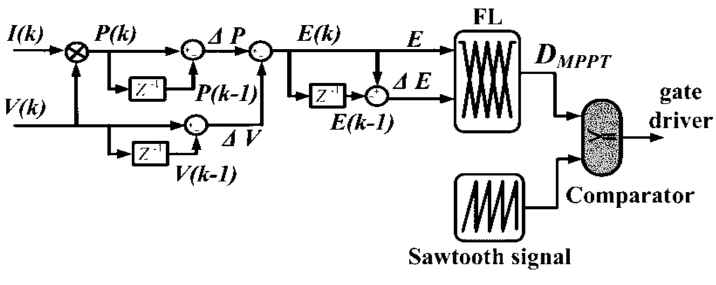


Figure 6. Control diagram of synchronous boost converter

2.4. Design of secondary on-board charger

The high-power secondary charger is designed to provide the electric car with a secondary and backup charger to optimize charging time and, at the same time, guarantee charger availability and redundancy. This charger is based on a full bridge phase shift DC-DC converter with a galvanic isolation insured by a high frequency transformer to step down the voltage from 400 VDC to 48 VDC. Several reasons are behind the choice of this topology in terms of power handling and its better efficiency due to the shifted control [17]. Also, it is extensively employed in medium- and large-scale power applications for its distinct features, such as high voltage conversion ratio, galvanic isolation, and flexibility of operation modes [18], [19].

To recharge the car battery, we opted, as mentioned in Figure 7, for the constant voltage-constant current method widely used in such applications. In fact, the converter control is provided by two loops based on PI blocks defined by Ziegler-Nichols' method. An inner current loop for current control and an outer loop for voltage control. With constant current voltage strategy, the battery is charged at a constant current until a pre-specified voltage threshold is reached, and then the charging switches to a constant voltage until the current decreases below the threshold [20], [21].

The phase shift full bridge converter, also known as "PSFB", is composed of two legs A and B, and four IGBT switches. The voltage feeds the DC bus voltage of 400 VDC into the first side of high frequency transformer. Its second side is connected to a full diode bridge D1-D4 to rectify the AC wave that comes from the input side. While the shifted control between the two legs and of this converter is ensured by a PWM control, at a fixed frequency, complementary between the two switches of the same leg. The parameters of the secondary on-board charger and the car's battery are listed respectively in Tables 3 and 4.

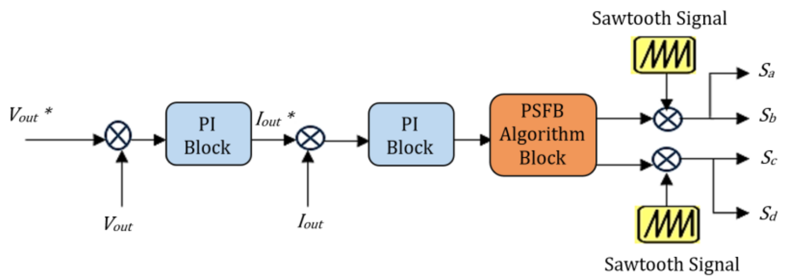


Figure 7. PI control blocks of the second on-board charger

Table 3. Parameters of the secondary on-board charger

Parameter	Notation	Value
Rated input DC voltage	V_{dc}	400 V
Rated output DC voltage	V_{out}	48 V
Turns ratio	N	0.14
Low-pass inductor	L_2	1.5 mH
Output capacitor	C_2	1 mF
Switched frequency	f_{sw}	10 kHz
Maximal rated power	P_n	3.6 kW

Table 4. Parameters of the battery

Parameter	Value
Battery maximal capacity	115 Ah
Capacity at nominal voltage	104 Ah
Fully charged voltage	51 V
Cut off voltage	34 V
Nominal discharge current	50 A
Internal resistance	0.003 Ω

2.5. Single inverter coupled to the grid for power management

In the proposed scheme, we have provided, in addition to the high-power charger, an inverter connected to an electrical grid to evacuate the electrical energy generated from PV panels, as shown in Figure 8. This power is evacuated to the grid when no car is connected to the charging station. Thus, to make our installation more useful and profitable. For this purpose, we designed a single-phase inverter with a level of power at 3.6 kW with a high power factor to keep an optimum power transfer to the grid.

Implementing the injection solution requires a PWM inverter and an LCL-type low-pass filter, as shown in Figure 9. The role of LCL is to filter the harmonics to reduce the rate of harmonic distortion generated by the inverter. Thus, improving the quality of electrical energy injected into the grid.

To control the injected power, Clark-park transformation, and phase locked loop (PLL) are used to be able to have a unit power factor. In fact, the quadratic current component of the reference (d-q) must be canceled. The primary role of the PLL in this grid-tied inverter system is to synchronize the inverter's output voltage and frequency with that of the utility grid [22]. This is crucial for ensuring that the power generated by the inverter can be safely and seamlessly integrated into the grid without causing harmonic pollution. The control of the current coming from the PV inverter passes through two regulation loops, as shown in Figure 10. In fact, the three-phase grid voltages V_g comes through the Clark and Park transformations to get two components V_d and V_q to facilitate the control. The main objective of this transformation is to cancel reactive power and get the grid angle Θ to meet the unity of power factor.

As mentioned, in Figure 11, the first loop is used to calculate the reference current I_r from the DC voltage of the PV field optimized by an MPPT algorithm using fuzzy logic, discussed above in this paper. Then this current is multiplied by the grid angle got from the PLL loop. This calculated current is compared to the inverter I_i via the second current regulation loop, designed by the Ziegler–Nichol method, which is mostly used in the design of PI controllers [23]. And added, then, to the grid voltage V_g. The result of this loop is divided by the PV DC bus voltage to obtain the reference current via a four-pulse PWM block to control the four switches of the single inverter. All parameters of the single-phase inverter are detailed in Table 5.

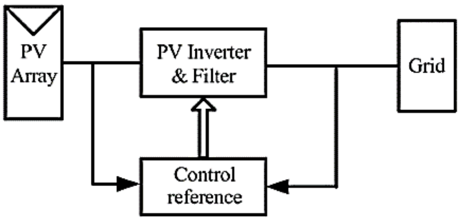


Figure 8. Synoptic of PV inverter connected to grid

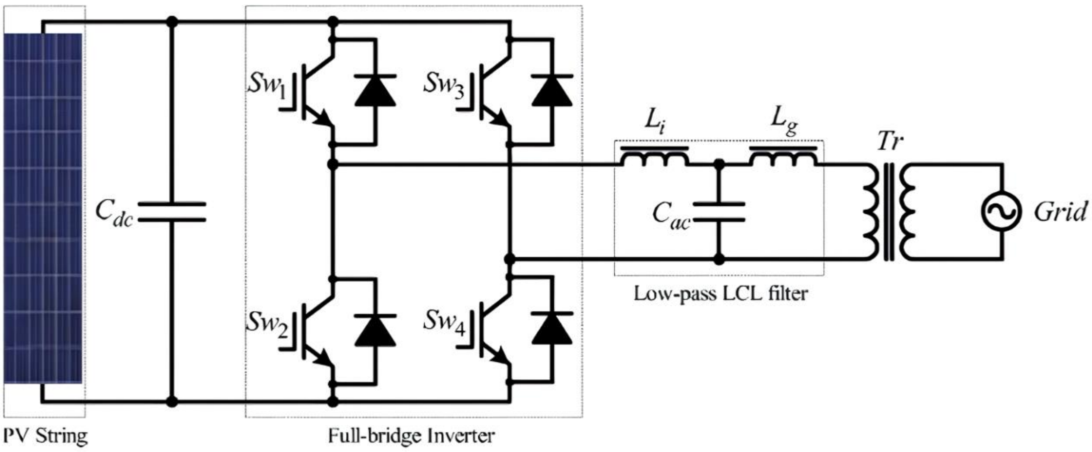


Figure 9. Synoptic of PV coupled inverter

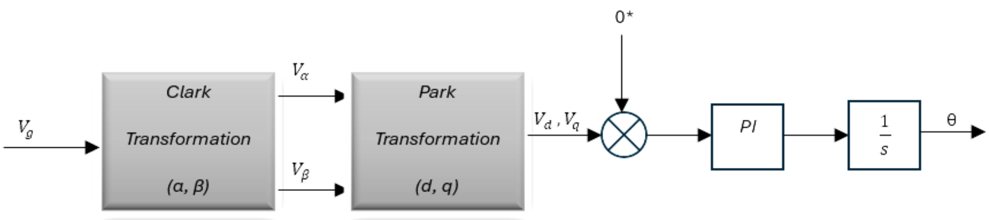


Figure 10. Phase locked loop synoptic loops

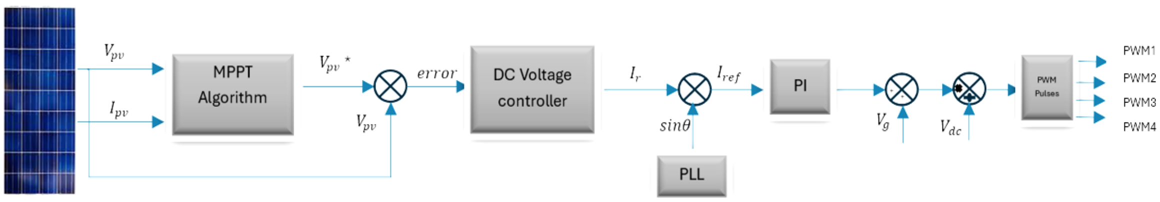


Figure 11. Control loops of the coupled inverter

Table 5. Parameters of the coupled single-phase inverter

Parameter	Notation	Value	Parameter	Notation	Value
PV irradiance	1000	W/m²	Maximal power	P_n	3.6 kW
PV temperature	25	°C	Proportional gain voltage loop	K_{pv}	0.1
Inductor of the inverter side	L_i	4.5mH	Integral gain voltage loop	K_{iv}	0.2
Inductor of the grid side	L_g	4.5 mH	Proportional gain current loop	K_{pi}	22.5
Bus capacitor	C_{ac}	6 μF	Integral gain current loop	K_{ii}	5
Switching frequency	f_{sw}	10 kHz			

3. RESULTS AND DISCUSSION

To defend our proposal, we designed a full scheme of the proposed configuration, shown in Figure 12, under MATLAB/Simulink environment. As previously discussed, the proposed configuration is based on a new on-board charger and fed by a PV DC station. While this station is composed of PV panels followed by a synchronous boost converter controlled by a fuzzy logic control and enhanced by a P&O algorithm to reach an optimum MPPT. Moreover, the proposed on-board charger is a phase shift full bridge DC-DC converter controlled with PI control and to follow a constant current constant voltage strategy to charge the battery. In addition, we have also set up a coupled inverter to evacuate the produced energy from the PV panels.

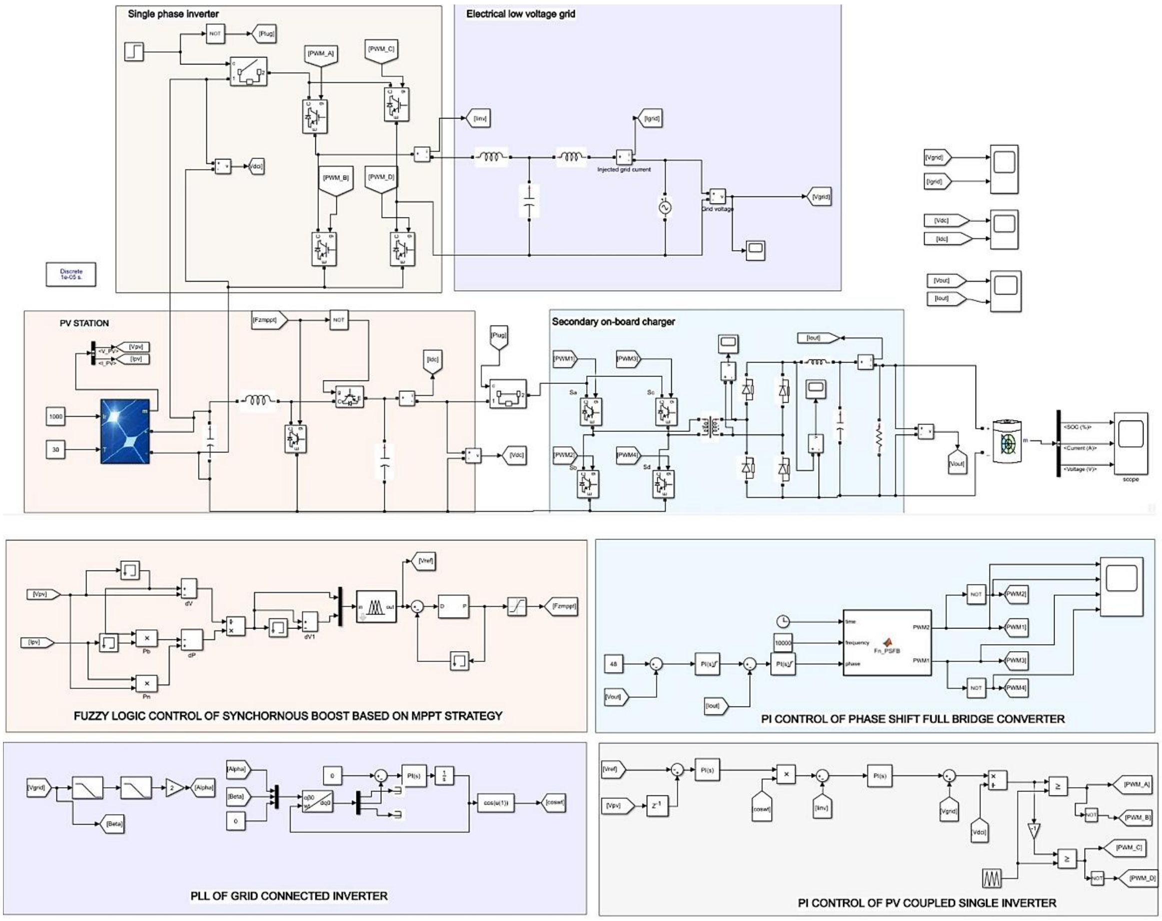


Figure 12. The full view of the proposed configuration under MATLAB/Simulink

We have launched a charging simulation for 10 minutes under the secondary on-board charger of 3.6 kW fed by the DC PV station. We have chosen a case of a battery initially charged to 50%. In fact, after executing the simulation under the conditions mentioned in the previous paragraph, we observe that the current reaches a value of 75 A with a voltage maintained at 48 V as initially previewed. The battery reached a level of 60%. It gets gain of energy of 10%, within 10 minutes, as shown in Figure 13. But in the case of a conventional charger of 1.8 kW, it gets only less than 5% in the same time. Thus, if we consider a sublinear extrapolation behavior of the charging profile, the performance of the secondary charger is good enough in terms of power transfer. It can ensure a good option for fast charging the city car at the PV station. While the primary charger can only be used at home by the end of the day, or by using an electrical public grid available throughout the city.

We can also observe, in terms of control performances, that the fuzzy logic control in the PV station delivers a stable DC bus voltage, as shown in Figure 14. In addition to the control of the secondary on-board charger ensured with two loops composed of the proportional integrator (PI). In fact, the outer loop controls the voltage and generates the reference component of the current. As for the second current loop, it corrects the difference of two values and deduces the phase difference necessary to ensure zero voltage switching in the transistors of the phase shift full bridge DC-DC converter.

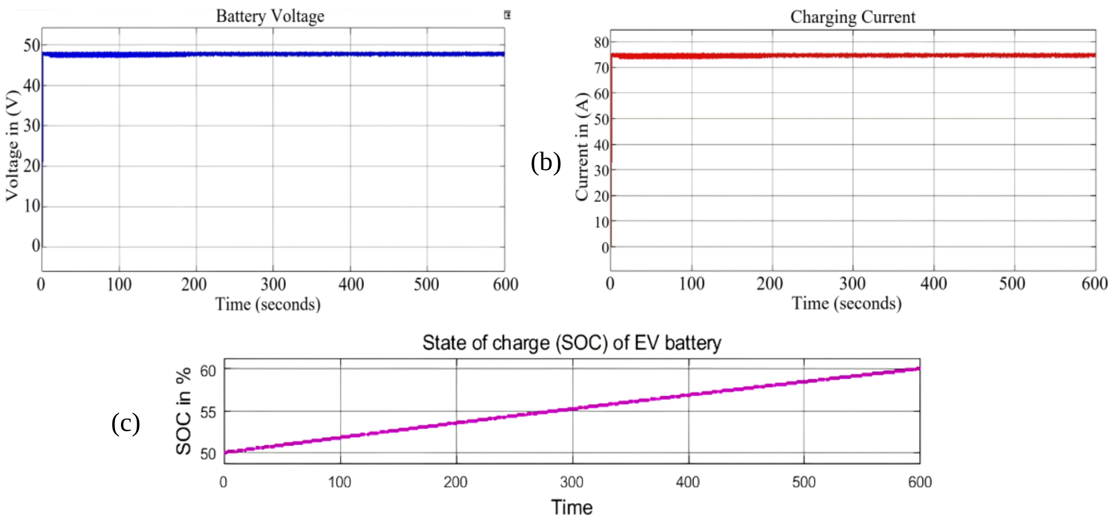


Figure 13. Simulation results of charging an EV battery under 10 minutes with the proposed charger: (a) battery voltage, (b) battery current, and (c) state of charge of the battery

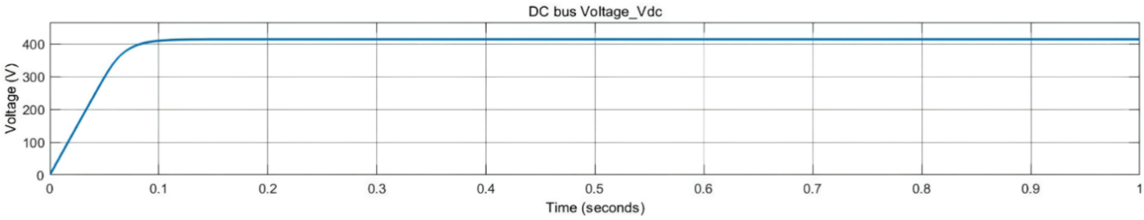


Figure 14. PV DC station output voltage

Moreover, when no electric car is plugged into the charging station, we have added a single-phase inverter, connected to the PV, to evacuate the energy produced by the charging station to the electrical grid to make our proposal more profitable compared to other configurations cited in [24], [25]. In fact, as mentioned in Figure 15, we can observe the current of 16 A RMS injected into the grid at a voltage of 220 RMS in this case. We can see that the current and voltage are well in phase for maximum transfer of active power.

Furthermore, we have established, in Table 6, a comparison between the different existing configurations by comparing them in terms of recharge time, redundancy, environment print, and grid injection as a given option. And we can observe, then, that our configuration meets multiple options compared to the existing ones, cited in previous works [24], [25], with only one embedded low-power charger.

Table 6. Comparison of existing and proposed configurations

Topology	Single phase	Three phase	Proposed configuration
Fast charge	-	+	++
Redundancy	-	-	+
Environmental print	-	-	+
Grid injection (option)	-	-	+

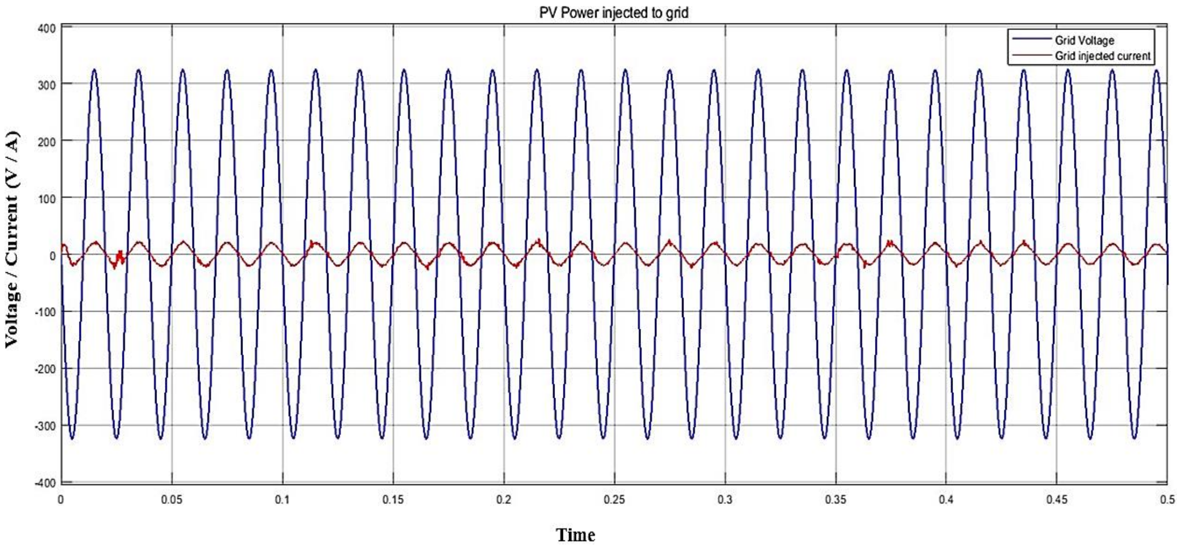


Figure 15. Current and voltage waveforms injected into grid

4. CONCLUSION

In this article, and as part of the promotion of low-carbon urban mobility, we have proposed an optimized configuration for recharging electric car batteries of an urban electric car with a proposal for the implementation of a secondary on-board fast charger with double the power supplied by an electric station based on photovoltaic panels. In addition, we have sized the charging station based on PV panels associated with a boost converter controlled by a fuzzy logic method for regulating the output voltage.

We have also demonstrated that the energy produced by the developed PV station can be evacuated to the low-voltage electrical grid when no car is connected. We have been able to demonstrate that the high-power charging station based on photovoltaic panels constitutes an effective alternative to achieve complementarity with the main domestic charger and the proposed secondary charger. The simulation of the recharge test demonstrated a gain of 50% or almost 100 minutes, with an extrapolation deducted from the recharge time of 10% for 10 minutes under the second proposed charger.

We consider continuing our research on the test and the discovery of other technical solutions to equip the car with other redundancy options to maximize its availability in mobility. In addition, we will set up an experimental bench to design a prototype of the proposed solution at the very low power order by comparing it with other new generation power topologies associated with nonlinear control methods based on artificial intelligence to study their advantages in terms of performance and robustness.

FUNDING INFORMATION

Authors state there is no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Mohamed Arrach	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Fatima Ezzahra Tahiri		✓	✓	✓	✓			✓		✓	✓		✓	
Abdesslam Lokriti	✓	✓		✓		✓				✓	✓	✓	✓	
Khalid Chikh	✓	✓		✓		✓				✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [MA], upon reasonable request. The data, which contains information that could compromise the privacy of research participants, is not publicly available due to certain restrictions.

REFERENCES

[1] B. Ashok and P. A. Michael, "A non-isolated high step-up converter with TID controller for solar photovoltaic integrated with EV," *Analog Integrated Circuits and Signal Processing*, vol. 118, pp. 505–521, 2024, doi: 10.1007/s10470-023-02237-w.

[2] O. Dakka, S. Patthi, J. V. G. R. Rao, and P. Kumar, "A 5-kW unidirectional wireless power transfer EV charger with a novel multi-level PFC boost converter on front-end side," *Journal of Engineering and Applied Science*, vol. 71, no. 1, 2024, doi: 10.1186/s44147-023-00333-2.

[3] T. Aldhanhani, A. Abraham, W. Hamidouche, and M. Shaaban, "Future trends in smart green IoV: Vehicle-to-everything in the era of electric vehicles," *IEEE Open Journal of Vehicular Technology*, vol. 5, pp. 278–297, 2024, doi: 10.1109/OJVT.2024.3358893.

[4] X. Lu and J. Wang, "A game changer: Electrifying remote communities by using isolated microgrids," *IEEE Electrification Magazine*, vol. 5, no. 2, pp. 56–63, Jun. 2017, doi: 10.1109/MELE.2017.2685958.

[5] N. Liu, Q. Chen, X. Lu, J. Liu, and J. Zhang, "A charging strategy for PV-based battery switch stations considering service availability and self-consumption of PV energy," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 8, pp. 4878–4889, Aug. 2015, doi: 10.1109/TIE.2015.2404316.

[6] M. Sechilariu, B. Wang, and F. Locment, "Building integrated photovoltaic system with energy storage and smart grid communication," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1607–1618, Apr. 2013, doi: 10.1109/TIE.2012.2222852.

[7] K. M. Muttaqi, E. Isac, A. Mandal, D. Sutanto, and S. Akter, "Fast and random charging of electric vehicles and its impacts: State-of-the-art technologies and case studies," *Electric Power Systems Research*, vol. 226, p. 109899, Jan. 2024, doi: 10.1016/j.epsr.2023.109899.

[8] V. S. M. B. K., P. Chakraborty, and M. Pal, "Planning of fast charging infrastructure for electric vehicles in a distribution system and prediction of dynamic price," *International Journal of Electrical Power & Energy Systems*, vol. 155, p. 109502, Jan. 2024, doi: 10.1016/j.ijepes.2023.109502.

[9] H. Yu, J. Tu, X. Lei, Z. Shao, and L. Jian, "A cost-effective and high-efficient EV shared fast charging scheme with hierarchical coordinated operation strategy for addressing difficult-to-charge issue in old residential communities," *Sustainable Cities and Society*, vol. 101, p. 105090, Feb. 2024, doi: 10.1016/j.scs.2023.105090.

[10] R. Venugopal *et al.*, "Review on unidirectional non-isolated high gain DC–DC converters for EV sustainable DC fast charging applications," *IEEE Access*, vol. 11, pp. 78299–78338, 2023, doi: 10.1109/ACCESS.2023.3276860.

[11] H. Wang, A. Gaillard, and D. Hissel, "A review of DC/DC converter-based electrochemical impedance spectroscopy for fuel cell electric vehicles," *Renewable Energy*, vol. 141, pp. 124–138, Oct. 2019, doi: 10.1016/j.renene.2019.03.130.

[12] M. Safayatullah, M. T. Elrais, S. Ghosh, R. Rezaii, and I. Batarseh, "A comprehensive review of power converter topologies and control methods for electric vehicle fast charging applications," *IEEE Access*, vol. 10, pp. 40753–40793, 2022, doi: 10.1109/ACCESS.2022.3166935.

[13] B. K. Dey, I. Khan, N. Mandal, and A. Bhattacharjee, "Mathematical modelling and characteristic analysis of Solar PV Cell," in *2016 IEEE 7th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, IEEE, Oct. 2016, pp. 1–5. doi: 10.1109/IEMCON.2016.7746318.

[14] J.-D. Park and Z. Ren, "High efficiency energy harvesting from microbial fuel cells using a synchronous boost converter," *Journal of Power Sources*, vol. 208, pp. 322–327, Jun. 2012, doi: 10.1016/j.jpowsour.2012.02.035.

[15] U. S. Ali, "Z-source DC-DC converter with fuzzy logic MPPT control for photovoltaic applications," *Energy Procedia*, vol. 90, pp. 163–170, Dec. 2016, doi: 10.1016/j.egypro.2016.11.181.

[16] K. Swamynathan, N. Mahalingam, A. Paramasivam, and S. Vijayalakshmi, "PV based OFF grid charging station for E-vehicles using PWM and phase shift controlled interleaved three port converter," *SN Applied Sciences*, vol. 5, no. 12, 2023, doi: 10.1007/s42452-023-05571-w.

[17] K. Bathala, D. Kishan, and N. Harischandrappa, "High frequency isolated bidirectional dual active bridge DC-DC converters and its application to distributed energy systems: an overview," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 2, pp. 969–991, Jun. 2023, doi: 10.11591/ijpeds.v14.i2.pp969-991.

[18] Y. Xie, J. Sun, and J. S. Freudenberg, "Power flow characterization of a bidirectional galvanically isolated high-power DC/DC converter over a wide operating range," *IEEE Transactions on Power Electronics*, vol. 25, no. 1, pp. 54–66, Jan. 2010, doi: 10.1109/TPEL.2009.2024151.

[19] J. Saeed, L. Wang, and N. Fernando, "Model predictive control of phase shift full-bridge DC–DC converter using Laguerre functions," *IEEE Transactions on Control Systems Technology*, vol. 30, no. 2, pp. 819–826, Mar. 2022, doi: 10.1109/TCST.2021.3069148.

[20] S. S. Zhang, K. Xu, and T. R. Jow, "Study of the charging process of a LiCoO2-based Li-ion battery," *Journal of Power Sources*, vol. 160, no. 2, pp. 1349–1354, Oct. 2006, doi: 10.1016/j.jpowsour.2006.02.087.

[21] Y. Li, K. Li, Y. Xie, J. Liu, C. Fu, and B. Liu, "Optimized charging of lithium-ion battery for electric vehicles: Adaptive multistage constant current–constant voltage charging strategy," *Renewable Energy*, vol. 146, pp. 2688–2699, Feb. 2020, doi: 10.1016/j.renene.2019.08.077.

[22] Y. Li, Y. Yang, B. Lv, Q. Tang, and J. Ren, "An improved method of phase-locked loop grid-connected inverter based on capacitor voltage full feedforward," *Energy Reports*, vol. 8, pp. 1341–1349, Jul. 2022, doi: 10.1016/j.egyr.2022.02.011.

[23] M. A. N. Amran, A. A. Bakar, M. H. A. Jalil, A. F. H. A. Gani, and E. Pathan, "Optimal tuning of PI controller using system identification for two-phase boost converter for low-voltage applications," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 12, no. 4, pp. 2393–2402, Dec. 2021, doi: 10.11591/ijpeds.v12.i4.pp2393-2402.

[24] M. Arrach, K. Chikh, and A. Lokriti, "Design and analysis performances of a 3.6 kW new three-phase charger based on synchronous buck converter with low harmonic distortion for urban cars," *Przegląd Elektrotechniczny*, vol. 1, no. 8, Aug. 2023, doi: 10.15199/48.2023.08.44.

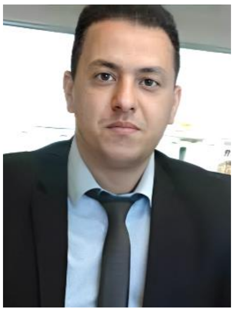
[25] M. Arrach, K. Chikh, and A. Lokriti, "High-power charger with d-q control and conventional buck converter for fast charging a city car," in *International Conference on Electrical Systems & Automation*, 2024, pp. 67–74. doi: 10.1007/978-3-031-51796-9_8.

BIOGRAPHIES OF AUTHORS

Mohamed Arrach was born in Morocco in 1992. He received this state engineer degree in electrical engineering from National School of Applied Sciences of Khouribga (ENSA) in 2016. He is currently preparing its Ph.D. thesis in electrical engineering at Science and Technology for the Engineer Laboratory at ENSA Khouribga-Sultan Moulay Slimane University. His current research's interests are applications of power electronics in electrical vehicles, speed drives, e-mobility, and renewable energies. He can be contacted at email: mohamed.arrach@usms.ac.ma.

Fatima Ezzahra Tahiri was born in Morocco in 1992. She received her engineer's and Ph.D. degrees in Electrical Systems Engineering from the National Higher School of Electricity and Mechanics (ENSEM, Casablanca, Morocco) in 2014 and 2022, respectively. Currently, she is working on research areas including renewable energy, power electronics converters, and control of machines. She can be contacted at email: fatima-ezzahra.tahiri@ensem.ac.ma.

Abdesslam Lokriti is a Professor at National School of Applied Sciences in Khouribga, Moulay Sliman University, Morocco. He has been a permanent member of the Laboratory of Sciences and Technologies for engineers since 2015 at the same school. He Obtained His Ph.D. degree in 2014 from the Sciences and Technology Faculty, Cady Ayyad University, Morocco. His working research reports on electrical machine drives, power electronic converters, and electrical power engineering. He can be contacted at email: abdesslam.lokriti@usms.ac.ma.



Khalid Chikh was born in Morocco in 1982. He received the Master's degree in Electrical Engineering from the Faculty of Science Semlalia in 2007, Marrakech, Morocco, and the Ph.D. degree in electrical engineering in 2013 from the National Higher School of Electricity and Mechanics (ENSEM), Hassan II University, Casablanca, Morocco. He is currently an associate professor at the Electrical Engineering Department at the National School of Applied Sciences of Khouribga (ENSA). His current research interests are in the application of power electronics converters, motor drives, intelligent and digital control using DSP implementations, renewable energy, and energy storage. He can be contacted at email: khalid.chikh@usms.ac.ma.