23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)
Tenerife (Spain), 25th to 27th June 2025
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.23, September 2025

Net-Zero Energy House management with stationary and mobile energy storage batteries

María Isabel Milanés-Montero[1], João Martins[2], Carlos Roncero-Clemente[1], Eva González-Romera[1], Fermín Barrero-González[1] and Javier Gutiérrez-Escalona[1]

[1] Electrical, Electronic and Automation Engineering Department
School of Industrial Engineering, University of Extremadura
Avda. de Elvas, s/n, 06011 Badajoz (Spain)

[2] NOVA School of Science & Technology
Universidade Nova de Lisboa
2829-516 Monte de Caparica, Portugal

Abstract. This paper presents an energy management system for a Net-Zero Energy House. The house is equipped with photovoltaic panels on the roof, a stationary energy storage system, and a Battery Electric Vehicle. The energy management strategy aims to minimize the house interaction with the power grid, enabling internal power flow without impacting upstream of the point of common coupling. The goal is to ensure that the house predominantly operates as a self-sufficient energy system, with the capability to even inject surplus energy back into the grid. The proposed topology and operation strategies are presented and validated through simulation results.

Key words. nZEH, PV panels, stationary battery electric vehicle.

1. Introduction

In recent years, global efforts have focused on creating a competitive low-carbon economy to reduce greenhouse gas emissions. In the residential sector, Net-Zero Energy Houses (nZEHs) align with the goals of reducing these emissions and promoting renewable energy use.

nZEHs represent a significant advance in sustainable building design, aiming to achieve a balance between energy consumption and production through renewable sources and energy storage systems. Recent research has focused on optimizing the integration of photovoltaic (PV) systems, energy storage and smart energy management to enhance the efficiency and self-sufficiency of these houses [1]-[3].

On the other hand, the electrification of transport impacts the electrical system as both a flexibility solution and an additional load. Battery Electric Vehicles (EVs) are expected to proliferate due to advances in performance, charging times, range, and cost reduction. EV batteries as distributed storage in smart communities and homes is a current research topic [4]. Integrating electric vehicles into nZEH is crucial for enhancing the sustainability and efficiency of residential energy systems. EVs can serve as mobile energy storage units, providing flexibility and additional capacity to balance energy supply and demand within the home. This integration not only supports the self-sufficiency of nZEHs but also contributes to grid stability and the broader adoption of renewable energy sources [5]-[6].

This paper proposes control algorithms to contribute to net-zero energy flow in a house by integrating micro-renewable generation, stationary batteries, and EVs as mobile batteries. Various topologies, including independent and mixed dc/dc and ac/dc converters, are discussed. A hybrid topology is proposed for renewable generation and stationary batteries, with an independent topology for the EV charger. Control strategies aim to minimize interaction with the electrical network, allowing power flow within the home without affecting upstream of the Point of Common Coupling (PCC), enabling the house to function as a self-sufficient system or even inject surplus energy into the grid.

The paper is structured as follows: Section 2 presents the nZEH topology and section 3 details the modes of operation. Afterwards, the operation strategies for each converter are proposed in section 4. Section 5 validates the strategies through simulation tests, and the conclusions are summarized in the final section.

2. nZEH topology

The topology proposed for the nZEH is displayed in Fig. 1: This topology consists of a mixed configuration that shares a common bidirectional AC/DC converter for the PV system and the stationary battery, alongside an independent bidirectional topology for the EV off-board charger. In the mixed topology, the DC/DC converters are bidirectional for the battery and unidirectional for the renewable generation unit.

The bidirectional AC/DC converters are full-bridge voltage source inverters, while the bidirectional DC/DC converters utilize a half-bridge buck-boost topology. The unidirectional DC/DC converter is a boost converter.

The house is connected to the grid through a point of common coupling (PCC). The current demanded from the grid by the nZEH is i, with i_{EV} being the current demanded by the electric vehicle, i_B the current required by the stationary battery, i_{PV} the current injected by the photovoltaic system and i_L the current demanded by the house loads. The common bidirectional AC/DC converter current is $i_{ac/dc}$.

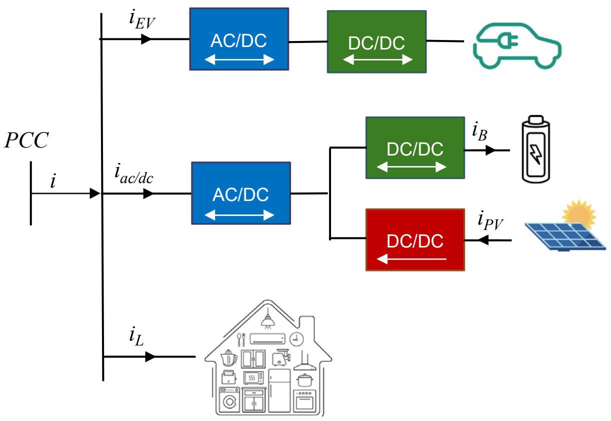

Fig.1. Topology proposed for the nZEH.

3. Modes of operation

1. Unidirectional Energy Injection from the PV System.

Four modes of operation are proposed:

- PV2H: Household demand is supplied by the PV system.
- PV2B: The stationary battery of the nZEH is charged with energy from the PV system.
- PV2V: The electric vehicle battery is charged with energy from the PV system.
- PV2G: Energy from the PV system is injected into the grid.

2. Energy Injection from the Stationary Storage System of the nZEH (Batteries)

Three modes of operation are proposed:

- B2H: Household demand is supplied by the stationary storage system.
- B2V: The electric vehicle battery is charged with energy from the stationary storage system.
- B2G: Energy from the stationary storage system is injected into the grid.

3. Energy Injection from the Mobile Storage System of the nZEH (EV)

Three modes of operation are proposed:

- V2H: Household demand is supplied by the EV batteries.
- V2B: The stationary battery of the nZEH is charged with energy from the EV batteries.
- V2G: Energy from the EV batteries is injected into the grid.

4. Energy Injection from the Smart Grid

Three modes of operation are proposed:

- G2H: Household demand is supplied by the grid.
- G2B: The stationary battery of the nZEH is charged from the grid.
- G2V: The energy of the EV batteries is charged from the grid.

The modes of operation outlined in sections 1-3 involve the flow of active power among the household elements or the injection of surplus energy into the grid. In the modes of operation described in section 4, the household elements require energy from the grid in situations where the produced or stored energy is insufficient to meet the household demand or to charge the mobile or stationary storage systems.

4. Operation strategies

Energy management strategies for the nZEH are proposed in this section, specifying the operation strategy for each power electronic converter shown in Fig. 1.

The nZEH is equipped with a central energy management system, the House Energy Manager (HEM), which continuously monitors household data such as the state of charge of the stationary battery and the battery of the EV, household demand, and the power injected from the PV system. Based on these data, demand prediction data, PV production, anticipated EV usage, electricity tariff, etc., it continuously sends active power setpoints for the stationary battery P^*_B and for the EV battery, P^*_{EV}.

Bidirectional DC/DC EV charger

The EV battery reference current i^*_{bat} is attained by adding two terms: on the one hand, the current calculated from the EV battery reference active power, P^*_{EV}, and the measured battery voltage, u_{bat}. On the other hand, this converter is responsible for assuring that the DC bus voltage u_{DC} interconnecting the dc/dc and ac/dc converters in the EV charger, meets its reference value U^*_{DC}. Therefore, the second term added corresponds to the output of a PI controller whose input is the error between the measured and reference DC bus voltage:

$$i^*_{bat} = \frac{P^*_{EV}}{u_{bat}} + PI\left(U^*_{DC} - u_{DC}\right), \qquad (1)$$

being $P^*_{EV} > 0$ when the EV battery is charging.

Bidirectional AC/DC EV charger

A Sinusoidal Current control strategy [7] is proposed for this converter with the objective of demanding a sinusoidal source current even in the case the grid voltage is distorted. This converter must comply with the active power flow in the AC and DC parts. In this way, the EV inverter reference current will be calculated as follows:

$$i_{EV}^{*} = \frac{P_{EV}^{*}}{U_{g1}^{2}} u_{g1}, \tag{2}$$

where U_{g1} is the RMS fundamental grid voltage, and u_{g1} is the fundamental grid voltage obtained by employing a single-phase Phase-locked loop (PLL) system.

Unidirectional PV DC/DC converter

The unidirectional converter operation strategy tries to extract the maximum power from the PV panels. A simple Maximum Power Point Tracking (MPPT) strategy [8] is employed. It is known that at the Maximum Power Point, it would be fulfilled this reference:

$$\left(\frac{dP_{PV}}{du_{PV}}\right)^{*} = 0, \tag{3}$$

where P_{PV} is the active power injected from the panels of the house and u_{PV} is the PV voltage. Therefore, the reference PV current, i^{*}_{PV}, is calculated as the output of a PI comparing the quotient between the variation of the measured PV active power ΔP_{PV} and the variation of the measured PV voltage Δu_{PV}, both in two consecutive control cycles, with its reference value, which following (3) is zero:

$$i_{PV}^{*} = PI\left(\frac{\Delta P_{PV}}{\Delta u_{PV}}\right). \tag{4}$$

P_{PV} is obtained as the mean value of the product of the measured PV voltage, u_{PV} times the measured PV current, i_{PV}:

$$P_{PV} = (u_{PV} \cdot i_{PV})_{mean}\,, \tag{5}$$

where the subscript *mean* means the mean value of the variable in parentheses.

By substituting (5) into (4), the reference PV current is:

$$i_{PV}^{*} = PI\left(\frac{\Delta(u_{PV} \cdot i_{PV})_{mean}}{\Delta u_{PV}}\right). \tag{6}$$

Bidirectional Battery DC/DC converter

This converter operates with the same control strategy shown for the dc/dc EV charger. So, following (1), the reference current for the stationary battery is calculated as:

$$i_{B}^{*} = \frac{P_{B}^{*}}{u_{B}} + PI\left(U_{DCB}^{*} - u_{DCB}\right), \tag{7}$$

where P^{*}_{B} is the stationary battery reference active power, u_B is the measured battery voltage, while u_{DCB} and U^{*}_{DCB} are the measured and reference DC voltage, respectively. $P^{*}_{B}>0$ when the battery is charging.

Bidirectional mixed AC/DC converter

As the global nZEH operation strategy aims minimizing its interaction with the grid, the bidirectional mixed ac/dc converter must allow inter-elements power flow inside the own house. It means that the control strategy of this converter has to be designed so that active power flow between the PV panels and the stationary battery is allowed in the DC installation of the house. Therefore, the reference active power for this converter is calculated as the stationary battery reference power minus the active power injected by the PV panels, obtained by using (5). Finally, the mixed ac/dc converter reference current is calculated by employing a Sinusoidal Current control strategy as:

$$i_{ac/dc,}^{*} = \frac{P_{B}^{*} - (u_{PV} \cdot i_{PV})_{mean}}{U_{g1}^{2}} u_{g1}. \tag{8}$$

5. Simulation results

A simulation model of the nZEH has been implemented in Matlab-Simulink, including an EV off-board charger with an Ion-Li battery pack, a PV system and a stationary Ion-Li battery.

The nZEH is connected to a single-phase low-voltage distribution grid. The nominal parameters and technical specifications are provided in Table I. The switching frequency of all electronic converters in the model is 20 kHz. The household demand is represented by the variable P_L and is modelled as a linear load with sinusoidal current, i_L, free of harmonic distortion.

Table I. – Specifications of the simulation model

PARAMETER	VALUE
Grid rated voltage (V)	230
PV system	
Rated PV power (W)	4500
Rated DC PV voltage (V)	150
Stationary Battery	
Rated power (W)	2900
Rated battery voltage (V)	115
Battery capacity (Ah)	50
Mixed ac/dc converter (PV+B)	
Rated power (W)	7360
Rated AC voltaje (V)	230
Reference DC bus voltage, U^{*}_{DCB} (V)	600
EV charger	
Type	Single-phase Type 3
Rated charger power (W)	7360
Rated AC voltaje (V)	230
Rated battery voltage (V)	250
Battery capacity (Ah)	240
Reference DC bus voltage, U_{DC}^{*} (V)	600

Different scenarios of power flow in the house are proposed in the following sections to be validated by simulation.

- Scenario 1: PV2B and V2H (PV to battery and EV to home)
  $P_{PV} = 2500$ W; $P_B^* = 2500$W
  $P_L = 3000$ W; $P_{EV}^* = -3000$ W
  The stationary battery is charged from the PV panels by means of the own DC installation. Load is fed by the EV by means of the own AC installation.

- Scenario 2: (PV+B)2(V+H) (PV+battery to EV+home).
  $P_{PV} = 2500$ W; $P_B^* = -1500$W
  $P_L = 3000$ W; $P_{EV}^* = 1000$ W
  The stationary battery and the PV panels charge the EV and take care of the consumption of the house by means of the own AC installation.

- Scenario 3: (PV+V)2(H+G) (PV+EV to home+grid)
  $P_{PV} = 3000$ W; $P_B^* = 0$ W
  $P_L = 3500$ W; $P_{EV}^* = -2000$ W
  The PV panels and the EV feed the home load, and the power surplus is injected into the grid.

Simulation results are shown in Fig. 2 - Fig. 7. For each scenario, the waveform of the current supplied or absorbed by each element of the nZEH is first presented, according to the direction indicated in Fig. 1. From top to bottom, they are shown on the left side the waveforms of the PV current, i_{PV}, the stationary battery current, i_B and the the ac/dc current, $i_{ac/dc}$. On the right side, they are displayed from top to bottom the EV battery current, i_{EV} the current demanded by the house i_L. and, finally, the nZEH current, i.

Moreover, the instantaneous power corresponding to each element is presented in the same order in the subsequent figure. The power delivered by the grid is denoted as P_S. and the power absorbed by the mixed ac/dc converter as $P_{ac/dc}$. In all cases, the active power balance can be verified as:

$$P_S + P_{PV} = P_B + P_{EV} + P_L \ , \qquad (9)$$

and the active power balance in the mixed ac/dc converter, can be calculated as:

$$P_{ac/dc} = P_B - P_{PV} \ . \qquad (10)$$

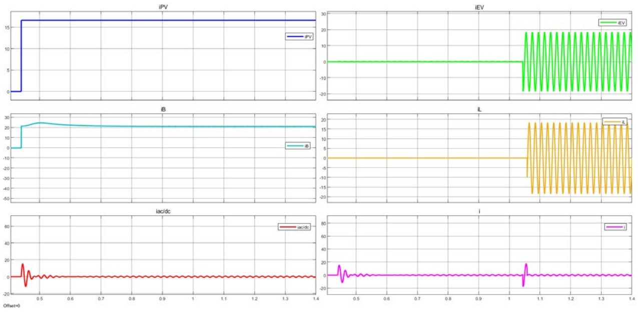

Fig.2. Current of each element of the nZEH in Scenario 1.

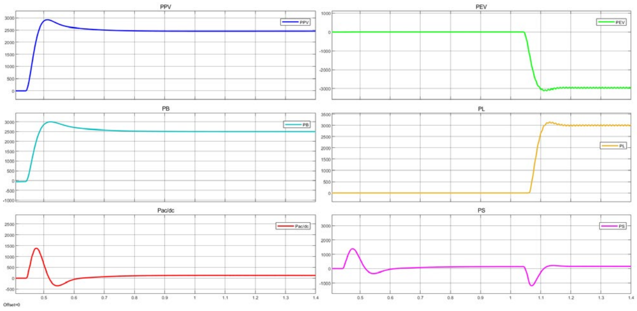

Fig.3. Instantaneous power of each element of the nZEH in Scenario 1.

In Scenario 1, at $t = 0.45$ s, the PV installation is connected to the system supplying an active power $P_{PV} = 2500$ W. Since there is no power consumption in the household at that moment, the HEM sets a power setpoint for the stationary battery $P_B^* = 2500$ W. Subsequently, at $t = 1.05$ s, the house demands an active power $P_L = 3000$ W, and given that the electric vehicle has stored energy in its battery, the HEM issues a power setpoint for the EV $P_{EV}^* = -3000$ W. The currents and instantaneous active power waveforms of the elements of the nZEH are displayed in Fig. 2 and Fig.3, respectively. Between $t = 0.45$s – 1.05 s, there is an interchange of active power between the PV system and the stationary battery in the DC installation of the house, without affecting the AC installation. After $t = 1.05$ s, no power transfer occurs on the AC side of the mixed topology nor between the household and the grid. The negligible power flow, as can be observed in the corresponding plots in Fig. 3, is attributed to power balancing adjustments required to compensate for losses in the power electronic converters.

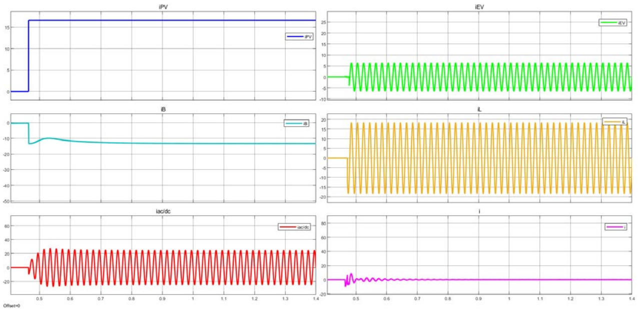

Fig.4. Current of each element of the nZEH in Scenario 2.

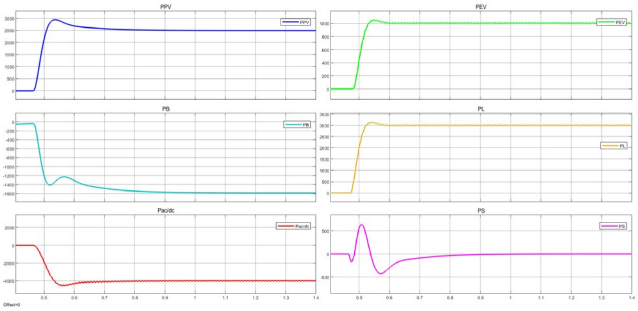

Fig.5. Instantaneous power of each element of the nZEH in Scenario 2.

In Scenario 2, at $t = 0.47$ s, the PV installation is connected to the system supplying an active power $P_{PV} = 2500$ W and the household demand is $P_L = 3000$ W. The EV begins to charge with a power setpoint $P_{EV}^* = 1000$ W. Since the stationary battery has sufficient energy to meet the household demand and EV charge together with the PV system, without the need to draw power from the grid, the HEM sets a power setpoint for the battery $P_B^* = -1500$ W. Fig. 4 and Fig. 5 show the currents and instantaneous active power waveforms in this case. One can notice that there is no power flow between the household and the grid, being the nZEH current and power negligible, operating in a self-sufficient manner. In this case, however, the mixed ac/dc converter current and power are not null, since the PV and stationary battery deliver active power to the AC installation of the house. It can be observed that the stationary battery current is negative, since it is discharging in this test. The mixed ac/dc power is also negative, in accordance with the current direction convention established for this converter in Fig. 1.

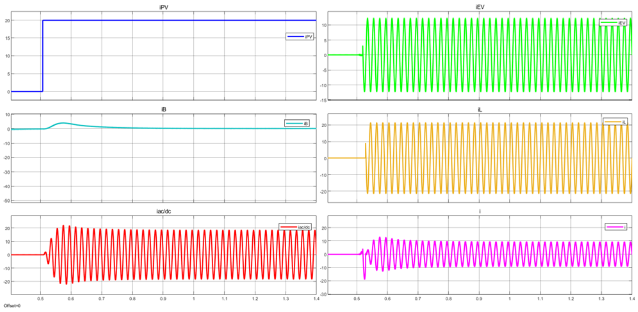

Fig.6. Current of each nZEH element in Scenario 3.

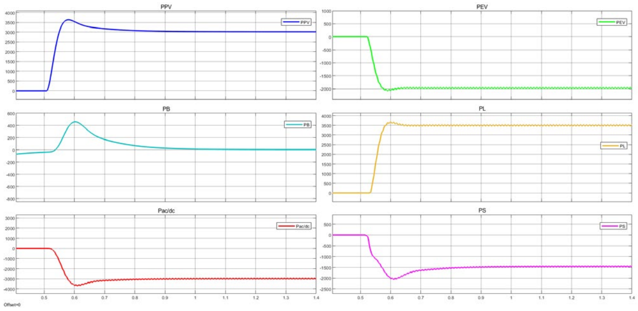

Fig.7. Instantaneous power of each nZEH element in Scenario 3.

In Scenario 3, at time $t = 0.51$ s, the household PV installation begins injecting an active power $P_{PV} = 3000$ W, while the house demands a power $P_L = 3500$ W. The EV is fully charged and is not expected to be used for the remainder of the day. Besides, the utility company offers an acceptable price for the excess generated power injected into the grid. In this situation, the HEM sends a power setpoint to the electric vehicle $P_{EV}^* = -2000$ W. The discharge of the stationary battery is scheduled for a later time; therefore, the power setpoint for this unit is $P_B^* = 0$ W. Fig. 6 and Fig. 7 show the current waveforms and the instantaneous active power profiles of the nZEH components, respectively. The power at the ac/dc converter and the power exchanged with the grid are observed to be negative, in accordance with the corresponding currents direction defined in Fig. 1.

5. Conclusions

The primary contributions of this paper include the proposal of an energy management strategy for a nZEH that minimizes grid interaction while prioritizing the flow of active power within both the DC and AC installations of the house.

The proposed topology and operation strategies have been validated through a simulation model of a house with a rooftop PV system, a stationary battery and an EV.

The simulation results demonstrate the nZEH operation under different scenarios, facilitating various interaction solutions among the stationary and mobile batteries, the PV system, the house, and the grid.

In the first and second scenario, the power flow in the own DC and AC installations of the house are validated. The nZEH is connected to the grid, but there is no interaction of energy with it. In these tests, the nZEH is self-sufficient. On the other hand, in the third scenario, there is an interaction between the nZEH and the grid. The nZEH generates or has stored more power than it needs, and the surplus is injected into the grid according to the setpoints determined by the HEM.

Currently, the authors are developing a laboratory prototype to experimentally validate the results obtained in this study.

Acknowledgement

This work was supported in part by the Spain Ministry of Science, Innovation and Universities under Grant PRX21/00265 and by the European Regional Development Fund – “A way to make Europe”, under GR24040 project.

References

[1] H. Gong, V. Rallabandi, D. M. Ionel, D. Colliver, S. Duerr and C. Ababei, "Dynamic Modeling and Optimal Design for Net Zero Energy Houses Including Hybrid Electric and Thermal Energy Storage," IEEE Transactions on Industry Applications, vol. 56, no. 4, pp. 4102-4113, July-Aug. 2020, doi: 10.1109/TIA.2020.2986325.

[2] S. B. Poore, R. E. Alden, E. S. Jones and D. M. Ionel, "Distribution System Optimal Operation of Smart Homes with Battery and Equivalent HVAC Energy Storage for Virtual Power Plant Controls," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 598-603, doi: 10.1109/ECCE53617.2023.10362535.

[3] A. Saif, S. K. Khadem, M. F. Conlon and B. Norton, "Impact of Distributed Energy Resources in Smart Homes and Community-Based Electricity Market," IEEE Transactions on Industry Applications, vol. 59, no. 1, pp. 59-69, Jan.-Feb. 2023, doi: 10.1109/TIA.2022.3202756.

[4] S. Khan, K. Sudhakar, Mohd Hazwan bin Yusof, “Building integrated photovoltaics powered electric vehicle charging with energy storage for residential building: Design, simulation, and assessment”, Journal of Energy Storage, vol. 63, 2023, 107050, ISSN 2352-152X, doi: 10.1016/j.est.2023.107050.

[5] C. Pang, P. Dutta and M. Kezunovic, "BEVs/PHEVs as Dispersed Energy Storage for V2B Uses in the Smart Grid," IEEE Transactions on Smart Grid, vol. 3, no. 1, pp. 473-482, March 2012, doi: 10.1109/TSG.2011.2172228.

[6] V. Monteiro, J. A. Afonso, J. C. Ferreira, T. J. C. Sousa and J. L. Afonso. “The Role of the Electric Vehicle in Smart Homes: Assessment and Future Perspectives”. EAI Endorsed Transactions on Energy Web. 8. 168223. 2021, doi: 10.4108/eai.25-1-2021.168223.

[7] M. I. Milanés-Montero, F. Barrero-González, J. Pando-Acedo, E. González-Romera, E. Romero-Cadaval and A. Moreno-Munoz, "Smart Community Electric Energy Micro-Storage Systems With Active Functions," IEEE Transactions on Industry Applications, vol. 54, no. 3, pp. 1975-1982, May-June 2018, doi: 10.1109/TIA.2018.2799547.

[8] V. Miñambres-Marcos, E. Romero-Cadaval, M. A. Guerrero-Martínez and M. I. Milanés-Montero, "Three-phase single stage photovoltaic inverter with active filtering capabilities," IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, QC, Canada, 2012, pp. 5253-5258, doi: 10.1109/IECON.2012.6389542.