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Hybrid Power Management and Control of PV Systems with Hybrid Energy Storage

Noor Waleed, Rakan Khalil Antar, and Ahmed A. Abdullah Al-Karakchi

Technical Engineering College of Mosul, Northern Technical University, Mosul, Iraq

rakan.antar@ntu.edu.iq

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Abstract: Photovoltaic (PV) technology is widely used in many applications. However, the PV system depends on the temperature and the amount of solar radiation. The energy produced by the PV system can have a surplus or a shortfall of electric power at demand response (DR), resulting in either loss or no energy use or service interruptions. The problem of discontinuous generation is overcome by crossbreeding. The study investigates the design and energy management of a grid-connected residential PV system with a battery and super-capacitor. The battery, super-capacitor, and PVs terminals are connected to the 311 VDC common bus using three DC-DC converters in a parallel structure. Batteries and super-capacitors are subject to strict stabilisation in boost and run modes, resulting in more precise tuning of the controller. In addition to creating a reference output current to synchronise the hybrid system with the grid using a phase closed loop (PLL), the proposed system provides and manages solar energy and an ON/OFF grid storage system, as well as a two-way connection to enable the homeowner to share the power with the grid. The proposed model was designed, simulated, and tested using MATLAB software.

Keywords: *Energy management, Renewable energy sources, Demand response, Supercapacitor, Grid system, Stand alone, Load priority.*

1 Introduction

Renewable energy sources integrated into the grid power generation systems offer a long-term and economical energy options. It is vital to preserve stability in the modern power grid by accurately balancing electricity output and demand (Iliadis et al. , 2021). However, it is difficult to maintain a stable electricity supply due to fluctuating renewable energy sources as well as uneven patterns of energy consumption around the clock, day, and season (Nengroo et al. , 2019). By storing intermittent renewable energy, energy storage system (ESS) devices can greatly help overcome these difficulties. No single ESS technology can meet all the criteria. As a result, Hybrid Energy Storage System (HESS) has become a viable option. Integrating capacity management with HESS at the system level comprises many environmental and social criteria (Abdullah , 2022). Installing battery and super-capacitors are the most widely used HESS design. Supercapacitors (SCs) help supplement and strengthen battery defects by providing high power density, extend life cycles, and increase efficiency (Panda et al. , 2020). Although batteries (BTs) power density, and low life cycle. On the other hand, SCs produce high power density and low energy capacity (Liu et al. , 2019). Combining the two storage systems is an excellent way to increase the efficiency of hybrid power systems. In the literature, different control strategies for the combination of HESS and BT-SC are discussed (Koohi-Fayegh and Rosen , 2020). This provides a review of the different types of energy storage, applications, comparisons, and recent developments. A review of BT-SC array applications for small grids and renewable energy presents a number of control strategies that have been proposed in the HESS literature (Babu et al. , 2020).

A PV system was combined with SC and BT in an off-grid and remote microgrid, and an energy management technique to accomplish coordination between these sources was suggested by (Yin et al. , 2017). Additionally, wind BT-SC HESS systems for standalone systems have been suggested and studies under challenging operation circumstances including consumer load and wind-speed step change (Shayeghi et al. , 2021). In (Manandhar et al. , 2019) a new energy management technique for a grid-connected PV system with a BT-SC hybrid energy storage system that includes both DC and AC loads

Corresponding author: Rakan Khalil ANTAR, rakan.antar@ntu.edu.iq

was developed. The writers took into account the battery's and super-capacitor's SOC restrictions. The currents of the reference BT and SC were calculated using a low-pass filter with a rate limiter. PLL was used in order to synchronise the grid. The results confirmed the battery's and the grid's effective power sharing, as well as the quick DC-bus regulation and seamless transition between operating modes. In (Cabrane et al. , 2021), authors examined various BT and SC topologies for the DC load, with the fully active parallel configuration being chosen. PI controllers were used to manage the DC-bus voltage as well as the BT and SC currents. DC-bus voltage control and filtration-based energy management techniques were used to extract the reference BT and SC currents. According to the simulation results, the combination of the super-capacitor with lowered BT usage increases filter time constants. The authors of (Singha Roy et al. , 2018) developed a low-cost ESS by evaluating reference generation algorithms for hourly dispatching solar power for 1 MW grid-connected PV arrays. A cost comparison is made between BT only, and BT with SC. According to simulation results, the HESS is the most cost-effective. In (Zeeshan Tariq et al. , 2021), An analysis was conducted on a hybrid PV-fed system with BT and ultra-capacitor in relation to grid connectivity and active power control. While the BT and ultra-capacitor are being charged, PV peak power is used to serve the load. When PV becomes idle during the night, the BT will supply the load, and the grid will remain operational to feed the load. Furthermore, Ultra-Capacitor eliminates PV’s induced system fluctuations and provides a DC link for the source side's entire system. Given the load and PV plant's momentary variations, a super capacitor with a very fast response time is also required to ensure system stability under varying operating conditions.

This paper is purposed to show how energy storage systems can help the grid to increase flexibility while supporting discontinuous renewable energy sources like solar energy. The research examines the power load management and control of hybrid energy storage systems that combine SCs and BTs when solar PV power is present with ON and OFF grid operation. A control structure based on the PI controller has been proposed to improve the super-capacitors' ramp rate.

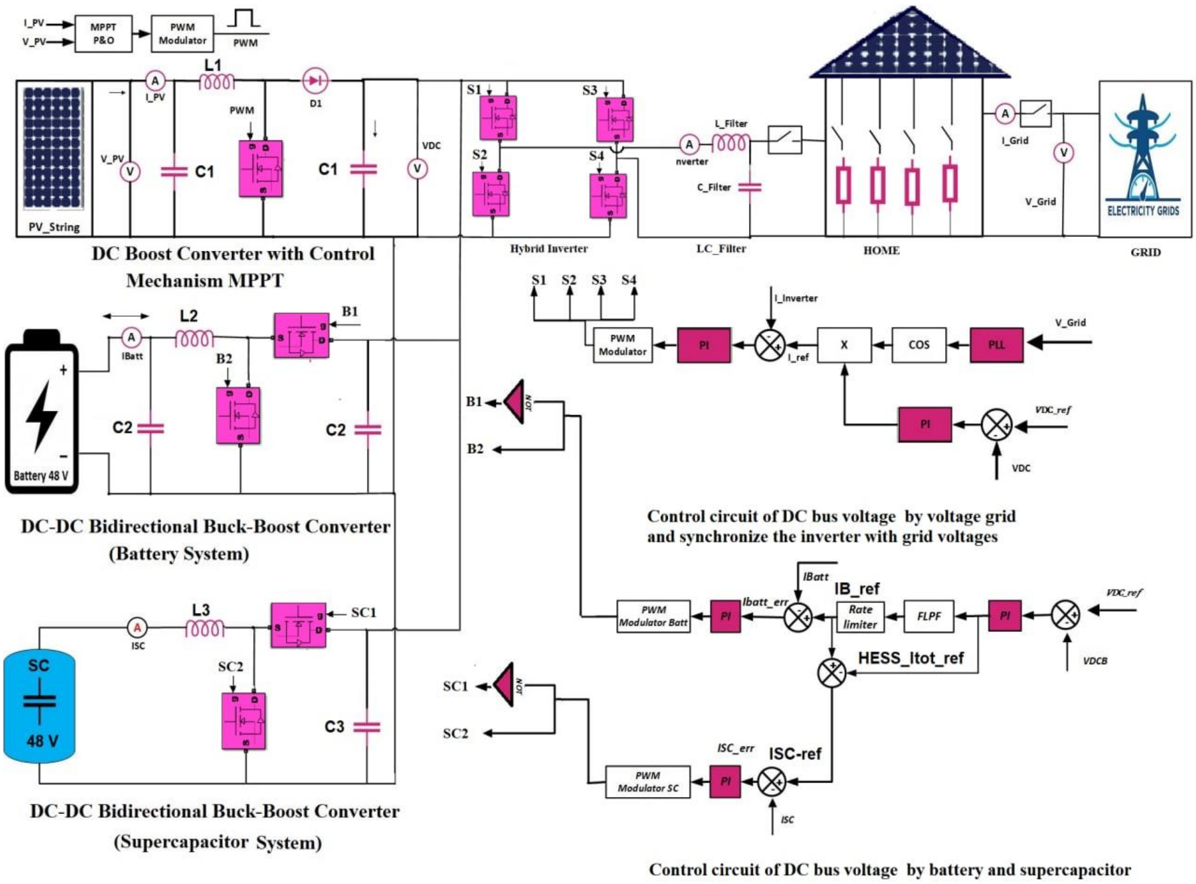


Figure 1. Hybrid system structure

2 Design System Components

In this section, the proposed hybrid structure is presented in Figure 1. The system consists of a PV system, HESS, loads, and the grid system. PVs with unidirectional DC-DC converters, HESS (charge/discharge) with bidirectional DC-DC converters, and a power inverter were combined in MATLAB/Simulink to produce the hybrid structure.

2.1 Solar PV Array

The PV array is considered as the main component of the PVs, which using the photovoltaic effect by transforming solar radiation into electricity (Mishra and Nayak , 2021). In this study, 12 PV modules of type TT400-72PM monocrystalline are connected in series and parallel. Six PV modules are connected in series to make two PV strings, which are connected in parallel to form a PV system with a voltage of 250 V and a power rating of 4800 W. The PV module parameters are listed in table 1. The level of PV generated voltage varies depending on the season and time of day, which might cause issues with inverter input. Because of this problem, a DC-DC boost converter was built to enhance the voltage to 311Vdc.

Table 1: PV module parameters

Parameters	Value
Model	TT400 72PM
Rated maximum power	400 W
Current at Pmax (Imp)	9.60 A
Voltage at Pmax (Vmp)	41.69 V
Short-circuit current	10.11 A
Open-circuit voltage	48.96 V
Efficiency	20.03 %
Operating Temperature Range	-40~85 °C

2.2 DC-DC Boost Converter with Control Mechanism

The boost converter is utilized to raise the output voltage and maximise power provided by PV systems using a certain duty cycle (Saleh and Ali, Ahmed J , 2021) . The duty cycle (D) of the maximum power point tracking (MPPT) output is used to regulate the ON/OFF states of the boost converter's Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET). The MPPT is employed as an effective strategy for making the system work within the maximum available based on perturbation and observation (P & O) algorithms (Bhan et al. , 2021). The P&O approach is used because it is simple, easy to use, and inexpensive. The boost has high efficiency due to a single switch. The inductor (L1) and capacitor (C1) of the designed boost converter are calculated using the equations below (Uthirasamy et al. , 2022). The boost converter is designed in this study to rise the input voltage (PV voltage) to constant desired value. The boost specifications are shown in table 2.

$$D = \frac{Vout - Vin}{Vout} \tag{1}$$

$$L1 = \frac{Vout(1-D)}{\Delta IL\ Fsw} \tag{2}$$

$$C1 = \frac{(1-D)}{8.\mathrm{L}(\Delta Vout/_{Vout})\ Fsw^2} \tag{3}$$

Table 2: The specifications of the DC_DC boost converter for PVs.

Parameter	Symbol	Value
Rated power	P	4800 W
Input voltage	Vin	250 V
Output voltage	Vout	311 V
Switching frequency	Fsw=1/T	3 kHz

Where ΔIL is input current ripple, for an accurate estimation of the inductor amplitude, the band should be within 30%, and ΔVout is output voltage ripple, which is often regarded as 5% of Vout (Moe, Ya, and Aung , 2020).

2.3 Hybrid Energy Storage Systems (HESS)

In theory, for any integrated energy system to be effective, an equilibrium should be achieved between what the system generates and what the demand for it is. This equilibrium can be established by putting in place a backup system. The next frontier in home energy is the battery storage system, which makes a significant contribution to higher home energy self-sufficiency and cheaper power costs. The HESS specifications are shown in table 3.

Table 3: The parameters for BT and SC are given below.

parameters	Value
Cell battery voltage	3.2 Volt
Number of batteries in series	16
Number of batteries in parallel	0
BT Voltage, Ah	48, 200
SC (Initial Voltage)	48

2.3.1 DC-DC Bidirectional Converter (Battery System)

A battery is a rechargeable device that stores energy. It provides electricity in times of high load demand and when PV cannot meet the load demand. Solar batteries are divided into three categories: maintenance-free (around 80% efficiency), lead-acid (around 90% efficiency), and lithium-ion (around 98%) (Mishra and Nayak , 2021). There are many factors which affect battery degradation, such as temperature, state of charge (SOC), depth of discharge (DOD) and maximum charging (Al-Karakchi et al. , 2019) (Abdullah Al-Karakchi, Lacey, and Putrus , 2015), The state-of-charge (SOC) is an important parameter of a battery.

The SOC is defined as the ratio of the remaining capacity to the fully charged capacity. The determination of SOC is always a necessary aspect of a battery management system, and DOD is battery's discharge depth for one cycle life, 100% depth of discharge is the worst case of discharge depth. The amount of discharge affects the degradation of the capacity and cycle life of the battery. The DOD represents the percentage of energy drawn or be usable by the load. In actual implementations, the battery charging and discharge control system must be designed based on the overall power of the system, which can be accomplished by building a DC-DC bidirectional buck-boost converter with two groups of MOSFETs (B1 and B2), inductor L2, and capacitor C2, Figure 1. These parameters can be calculated using the equations below (Jadhav et al. , 2018). Table 3.3 lists the specifications of the battery bank and the DC-DC buck-boost adaptor.

$$\mathrm{D} = \frac{BT\ voltage}{Vout * \eta} \quad (4)$$

$$L2 = \frac{D.Ts(Vout - BT\ voltage)}{\Delta IL} \quad (5)$$

$$C2 = \frac{(1-D) \times Vout \times Ts\verb|^|2}{8.\mathrm{L}.\Delta Vout} \quad (6)$$

Where ΔVout is desired output voltage ripple and usually taken as 1% of the output voltage in this converter type, η is efficiency of the converter, e.g. estimated at 90% to 95% (Jadhav et al. , 2018).

2.3.2 DC-DC Bidirectional Converter (Supercapacitor)

A super-capacitor, sometimes known as an ultra-capacitor, has high energy density, extended life, tiny size, and self-discharge. During solar system starting and heavy demand peaks, it offers rapid power. To regulate the power, a two-way DC-DC buck-boost converter is utilized, which incorporates with two groups of MOSFETs (SC1 and SC2), inductor L3, and capacitor C3 with internal resistance, Figure.1. These parameters can be calculated by equation (4-6), Figure 1. The energy storage capacity may be determined using the following formula (Zeeshan Tariq et al. , 2021):

$$\text{Energy storage capacity} = \frac{1}{2}\mathrm{C}.(\mathrm{V1}^2 - \mathrm{V2}^2) \quad (7)$$

Where V1 = the SC's cut-off voltage, V2 = SC Rated Voltage, C = stands for capacitance.

2.3.3 Control Strategy for HESS

A DC-DC bidirectional converter is employed to control the charging and discharging processes as shown in Figure 1. The basic idea of this control strategy is that the battery supports slow transients while the SC supports the fast transients of the system, as shown in Figure 1. This is accomplished through the use of voltage-constant and limited-current controllers. The voltage constant loop compares the required voltage to the measured voltage, and the result is an input of a PI controller, which is used to determine the HESS total current reference (HESS_Itot_ref). The PI controller is regulated by PI parameters that have been determined using trial and error as Kp=0.7 and Ki = 18.18.

This total current (HESS_Itot_ref) is divided into an average power component and a dynamic power component using a low-pass filter function (fLPF). The average power component is given as a reference (IB_reference) to the battery current control loop. A reference (IB-ref) is compared to the actual current value (IB) to generate control signals B1 and B2. The second control is determined by trial and error with parameters of Kp=12.93 and Ki = 13. While the dynamic power component is given as a reference (ISC_reference) to the SC current control loop. The reference (ISC-ref) is compared to the actual current value (ISC) to generate control signals SC1 and SC2. The third control is also determined by trial and error with same second PI parameters. This method keeps HESS operation within the boundaries of charging and/or discharging.

The power balance within the system and the stabilisation of the DC bus voltage can be clearly seen, as well as the effect of adding a SC to maintain current, voltage and SOC for BT, Figure 2.

2.4 Hybrid Inverter with Control

The DC-link (DC-bus) voltage of 311 V is converted to 220 Vrms at 50 Hz using a single-phase inverter. The inverter switches are derived using the PWM technique. The inverter circuit is designed with four MOSFETs with a switching frequency of 3 kHz. Due to the presence of switches used to control the output of the inverter, they contribute to increasing perturbation and the creation of harmonics (Hamoodi, Abdulla, and Kheder , 2021). The PV system cannot be connected to the grid before disruption is eliminated and optimization of the performance begins. For this purpose, a simple method of reducing inverter output harmonics uses passive filters between the inverters and AC loads to remove the harmonic content (Antar, Suliman, and Saleh , 2021) (Karaca et al. , 2019). The values of the passive filter's inductor (L_Filter) and capacitor (C_Filter) are determined by the equations bellow:

$$L\_Filter = VDC\ bus /(4*\sqrt{2}\ \Delta IL * Fsw) \quad (8)$$

$$C\_Filter = (1/l\_filter) * (10/(2 * pi * Fsw))^2 \quad (9)$$

Where:

ΔIL=20% of rated current, VDC bus =311 volt

Figure 3.a shows the inverter output voltage before the filter; Figure 3.b shows the inverter output voltage after the filter; while Figure 3.c with the fast Fourier transform (FFT). The results showed that the voltage has a peak value of (221.6-220.9) Vrms and the THD values are (1.7005-0.5939) % without and with filter respectively. While during the ON grid Figure 4.a shows the inverter output voltage before the filter; Figure 4.b shows the inverter output voltage after the filter; while Figure 4.c with the fast Fourier transform (FFT), the results showed that the maximum voltage value is (221.5177 - 220.0009) Vrms and the THD values are (2.0245-0.2282) %, receptively.

For the single-phase inverter, a voltage management approach is suggested to maintain the DC bus voltage at 311V with a control loop as shown in Figure 4. A comparison between the inverter output voltage and the grid voltage is used to fix the inverter voltage's magnitude and maintain it in synchrony with the grid. One PLL is used to regulate the angle between the inverter's AC output voltage and the grid's alternating voltage in order to align the inverter frequency with the grid frequency. The controller creates the reference grid side voltage in order to change the needed output voltage. The current controller is used to control the difference between the required and actual output currents (Waleed, Al-karakchi, and Antar , 2022).

In off-grid Figure 5.a, the inverter voltage and voltage signal were synchronized, while in on-grid Figure 5.b, the inverter voltage and grid voltages were synchronized.

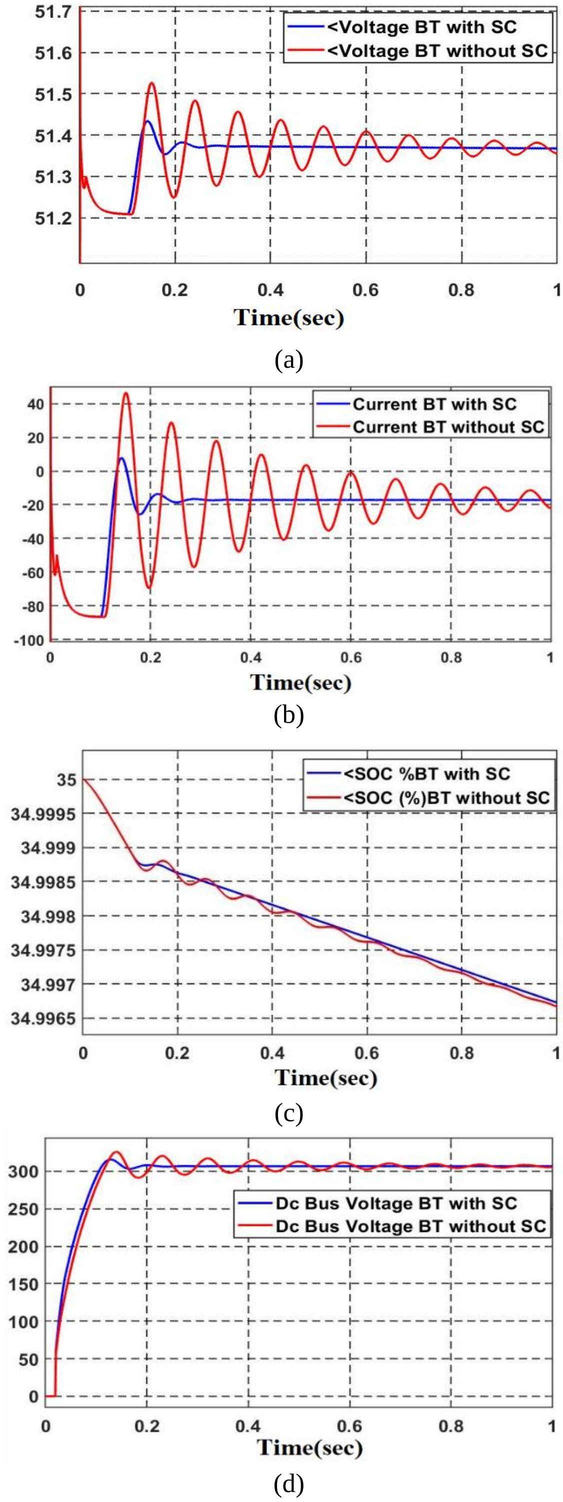
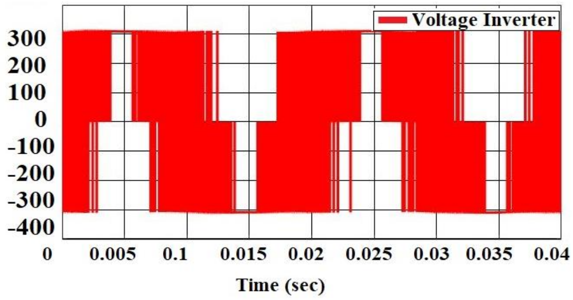


Figure 2: Battery information from (a) voltage, (b) current, and (c) SOC shows its condition with and without SC, in addition to (d) DC Bus voltage.



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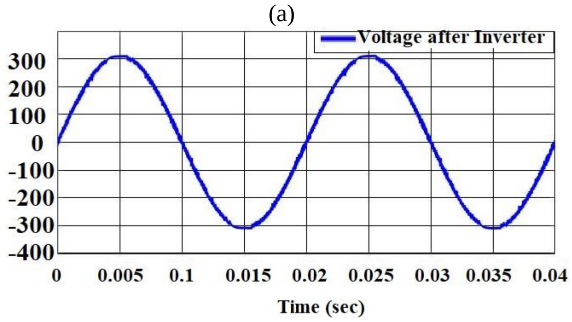

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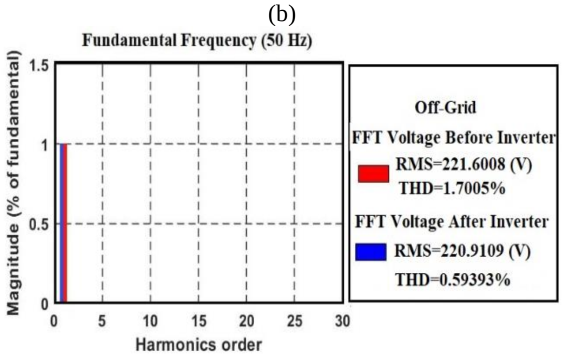
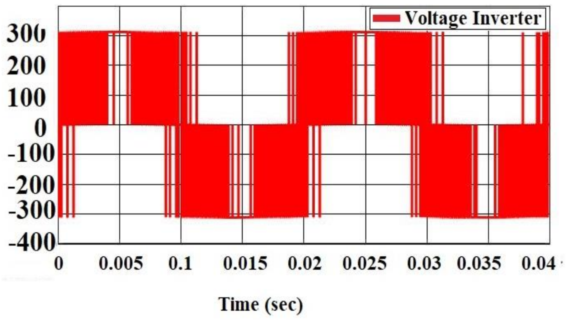


(c)

Figure 3: Inverter output voltage during Off Grid, (a) without filter, (b) with filter with, (c) FFT.



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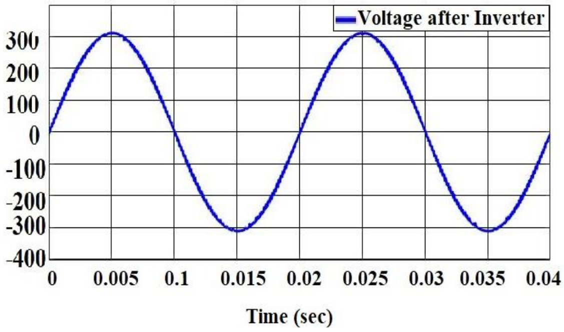

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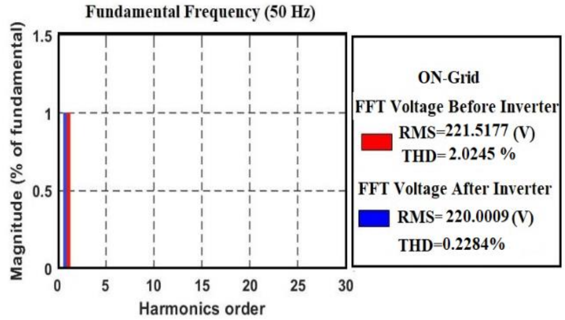
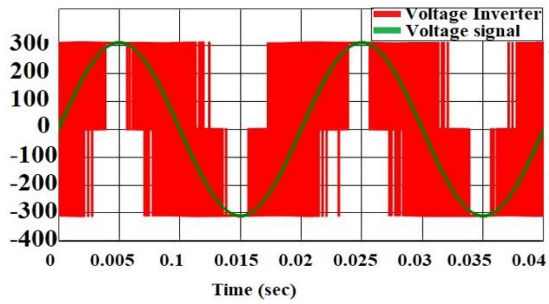


(c)

Figure 4: Inverter output voltage during ON Grid, (a) without filter, (b) with filter with, (c) FFT.



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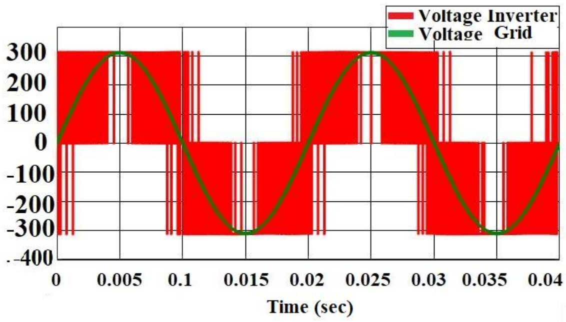


(b)

Figure 5: (a) off grid Synchronize the inverter voltage and voltages signal, (b) on grid Synchronize the inverter voltage and grid voltage

The transition between the two grid modes is done with high accuracy and fast so that the circuit remains stable, synchronized, and operates properly, as shown in Figure 6.

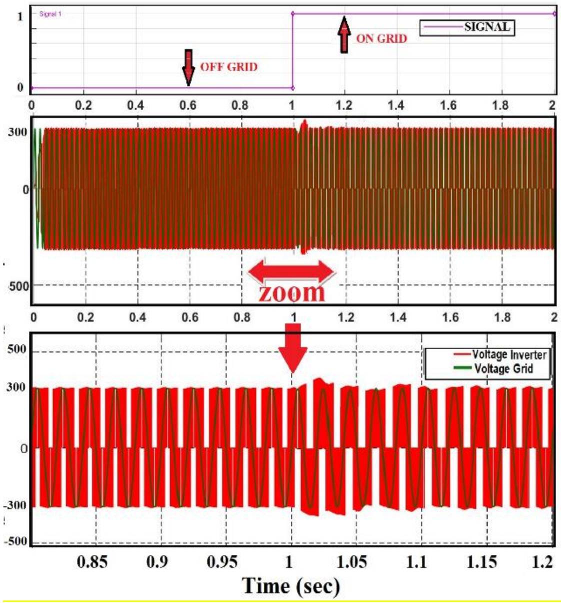


Figure 6: The control unit operates in grid mode from off to on.

2.5 Divide the Loads at Home

In order to test the home DR in the load power distribution, it is critical to understand the characteristics of household uses and load preferences (Waleed, Antar, and Al-karakchi , 2022). In this study, only loads that can be controlled, such as air conditioners, water heaters, washing machines, and refrigerators, are thought to be controlled. This is based on the priority of the device, the level of comfort, and consumer preferences. Taking into consideration the de-vices that will be included in the high-priority loads and that will be at work in the low generation conditions, namely Internet devices, cameras, and television, according to the user's preferences. First, loads are divided into four types from the viewpoint of controlling load and according to their priorities as explained in Figure 7.

2.5.1. High Priority Load (HPL)

In this study, high-priority devices such as internet devices, lighting, and television continue to operate in all conditions.

2.5.2. Medium Priority Load (MPL)

For example, refrigerator and freezer devices contain a thermostat (an element that controls the conduction of electricity according to the temperature).

2.5.3. Low Priority Load (LPL)

For instance, cooling, air conditioning, and water heaters that contain thermostats may demand a fixed level of electricity with discrete scheduling. These types start working when the temperature reaches a fixed value, and they cease working when the temperature exceeds another value.

2.5.4. Hard loads (HL)

Hard loads that can be rescheduled are included. This category, which may require a continued supply of electricity for a limited period of time, such as washing machines, dishwashers, and clothes dryers, can be delayed without impacting service.

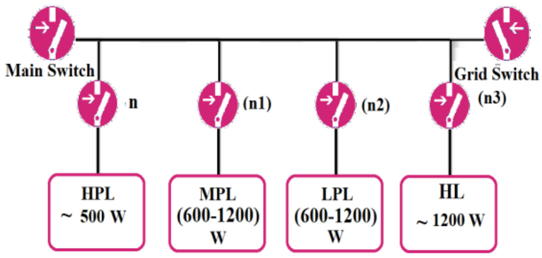


Figure 7: Consumption power value for each load type and switch number.

3 Energy Management system

The energy management strategy includes four energy sources. The management of energy sources is very important in order to increase the efficiency of the sources, use them correctly and at the lowest cost of materials, and ensure the convenience of the user. The auxiliary and reversible energy storage processes also provide energy for different loading conditions in different circumstances. The PV panels operate during the day by supplying energy to the building as well as charging HESS and sending the surplus power to the grid. During the night, the building is powered by the grid or energy stored in the HESS. In lousy weather, which has a negative effect on energy production, the energy management strategy seeks to ensure continuity of energy supply to the user for the duration of the current day. High priority loads will always run during the day. The strategy calculates the available energy for the day and then distributes it based on priority. The proposed system always seeks to maintain the available energy and efficiently manage it to operate the high priority loads in the system. For this, the system adopts strategies to monitor and control load operations. The available energy is estimated by calculating the energy produced and the battery level, taking into consideration the grid status in addition to the load priority. To calculate the energy generated in real time, an equation was adopted to estimate the maximum power generated by the PVs, which is calculated as (Liu et al.,2019):

$$PPV=(GHI)\times\eta\ PV \times APV \quad \dots (10)$$

Where (GHI), PV, and APV are the global horizontal irradiation, the efficiency of the PV panel, and the PV active surface in m2. In this study, two PV system scenarios are studied, as indicated in Figure 8. Scenario (A) has a simple PV module connected to the grid that can feed the desired load charges the HESS. But, scenario (B) has PV modules and HESS that can feed the desired load.

3.1. Scenario A (ON-Grid)

When the grid is available, if the generated power from PVs is higher than the DR and the battery SOC is less than 80%, the system will compare it. The system will send the surplus generated from the PVs to the battery. To avoid overcharging the battery, the PV array is unplugged from the battery when the SOC surpasses 95%, and the opposite will send the excess power to the grid. If the PV power is less than the DR, the controller will be sent to the grid to share the DR according to priority and charge the battery. According to this scenario, the total required load current is 18.6135A while the inverter current generated by the PVs is 21.6819 A. The current, 5.98A, is drawn from the grid as shown in Figure 9.a, so the system makes up for the shortfall from the grid to charge the HESS and to use this storage during grid off or when the generation of PVs is low. Figure 9.b explained that the load current is supported by the PV system and grid. In addition to that, in this case, the maximum current harmonics is less than 3%, as explained in Figure 9.c.

3.2. Scenario B (OFF-Grid)

After estimating the maximum Ppv and then subtracting from it the power consumed for the high priority loads, and after calculating the unused power, whether that power is available to add additional loads or not, the system will compare the battery SOC if it is less than 50%. The system will operate the high priority load and then it will operate the loads one after the other according to priority and PVs the generated power only (i.e., operating according to available power and without battery involvement) and send the remaining power to charge the battery as shown in Figure 10.a&b. Basically, the load from the battery will be disconnected when the battery SOC drops below 20%, so that deep discharge is prevented.

But if the battery charge is more than 50%, the system will allow the battery to be shared to add more load according to priority as shown in Figure 11. In addition, as mentioned previously, some devices enter sleep mode (still in service/usage). The system converts this energy and exploits it to run an additional load during this period only when the battery charge is higher than 50%. When the three loads (HPL, MPL, and LPL) are turned on, the total current of the loads is 13.2A, and after transferring some devices MPL and LPL from the load (during service or use), the current to each load is reduced from (5.45 to 2.73 A). This will transfer the free energy from these devices to run HL during this time, as shown in Figure 12.

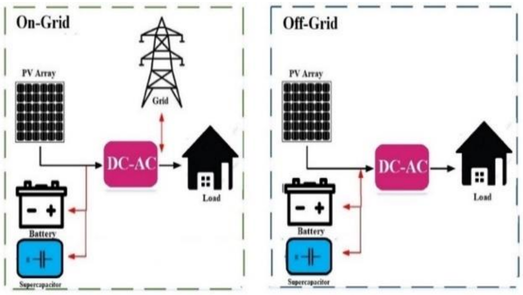
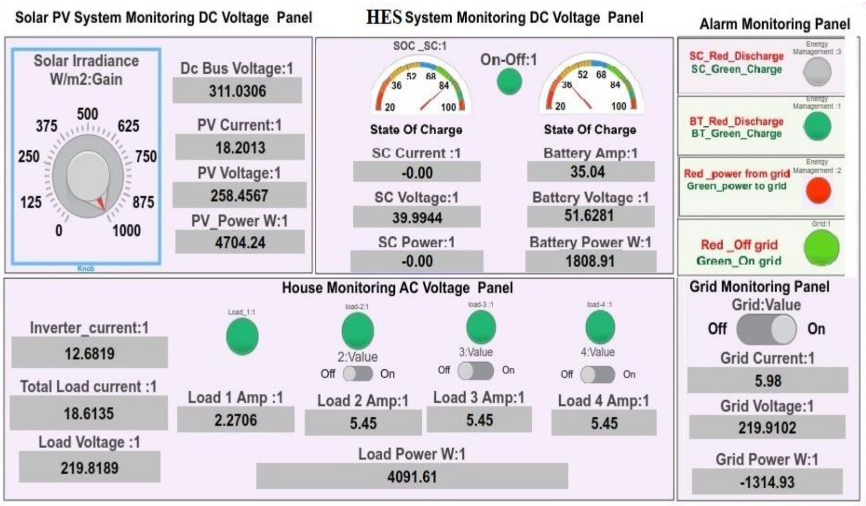


Figure 8: The control schematic Proposed System: On/Off Grid



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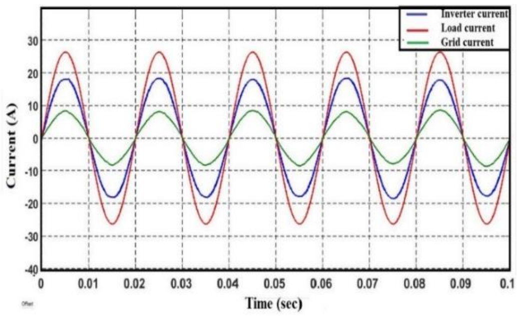

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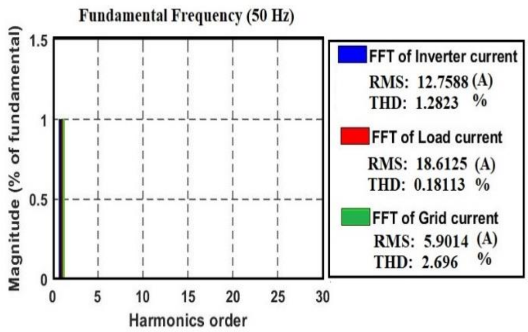
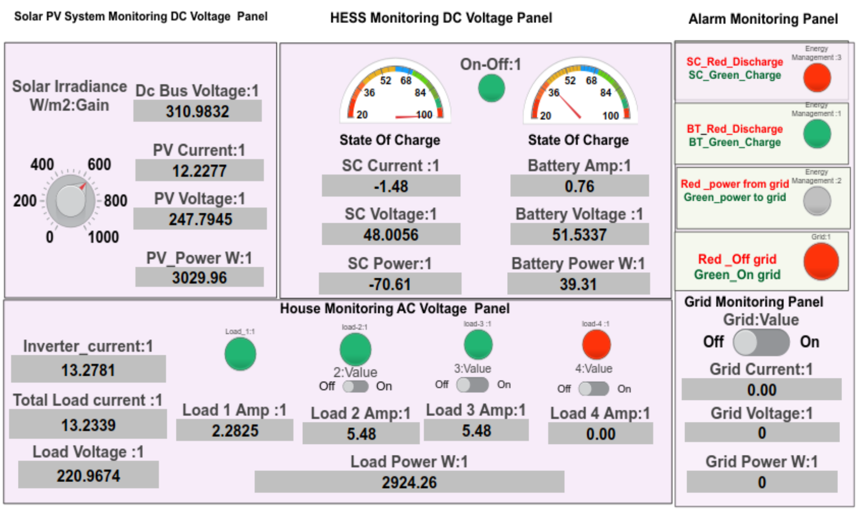


(c)

Figure 9: The PV-Battery-Grid (a) meters, (b) their currents (c) FFT analysis.



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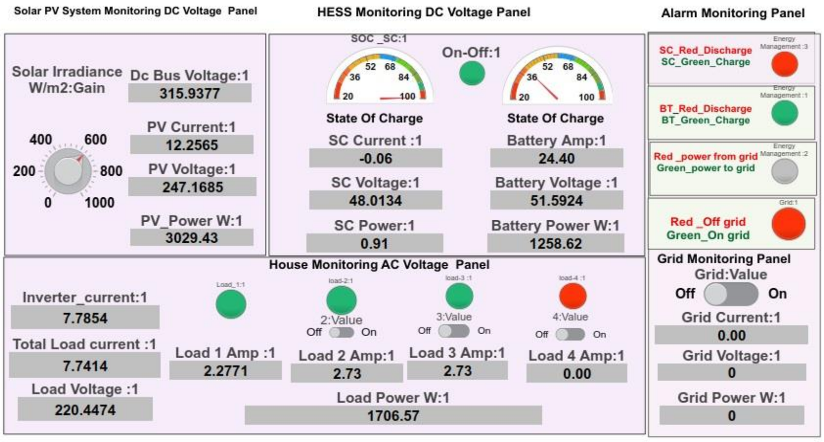

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Figure 10: The PV-Battery and SOC less 50%.

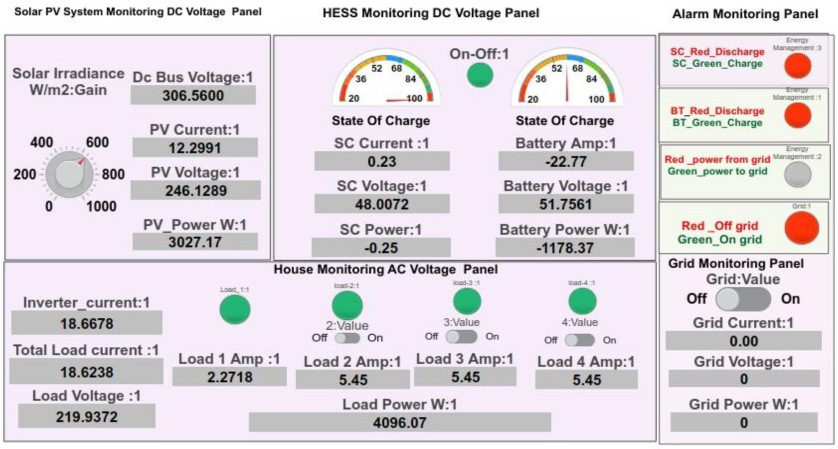

Figure 11: The PV-Battery and SOC more than 50%.

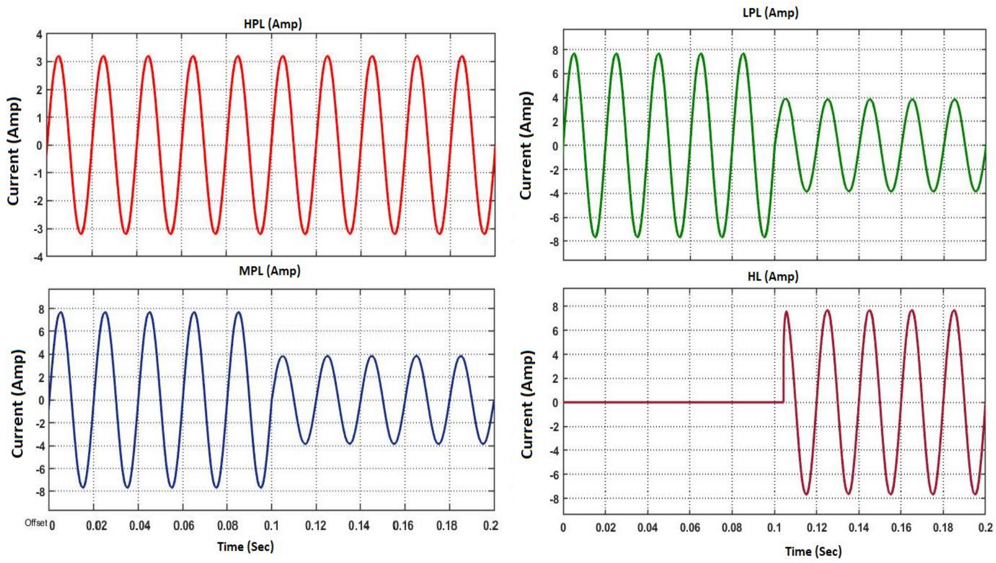

Figure 12: Exploiting the free power of devices that contain thermostats to turn on another load.

4 Conclusions

The proposed system has been designed to keep available energy power at load terminals and to manage the system efficiently in order to keep high-priority loads operational. As a result, the system employs strategies to monitor and control load operation while maintaining high power quality and limiting THD to less than 3%. The available energy has been estimated by calculating the energy produced by PVs and the battery level. The weather conditions and the amount of solar energy produced have been considered. Power generated by the PVsystem is first used to meet load demands. When the PV energy exceeds the load demand, the excess PV energy is injected into the batteries or the grid. As a result, the goal of this hybrid system is to meet the load demand at the lowest possible cost. In addition, the SC and BT manage and control the power flow because they are connected in parallel on the 311 V DC bus (PV converter output) through two bidirectional DC-DC converters. The control strategy ensures that the life of the BT is extended by keeping the variation in SOC, current, and voltage constant. A control strategy with HESS handles transient events much better than a system using only BT.

To ensure the user's comfort and non-interruption during the operation of a particular load, additional switches have been placed for the purpose of forcing the load to operate even if it is outside the priority operating rules. When the energy of some loads changes (during service or use), the system converts this energy and uses it to power additional loads. Alternatively, it can be stored in the form of heat or cooling. Loads classification ensures the user's comfort in operating high-importance loads almost always during periods of low generation and grid absence.

Finally, these measures reduce the pull of electricity from the grid, and thus reduce the cost and peak times of the electricity grid because, the maximum generation of the solar system coincides with the peak times of the grid and the demand for the load.

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Corresponding author: Rakan Khalil ANTAR, rakan.antar@ntu.edu.iq

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Noor Waleed Ramdhan earned her B.Sc. in 2009 from the Technical Engineering College/Mosul, Northern Technical University, Iraq. She currently works as an engineer for the Ministry of Electricity/State Company of Electricity Distribution for North / Nineveh Electricity Distribution, Iraq. She can be contacted at email: (noor.ramdhan@ntu.edu.iq)

Asst. Prof. Dr. Rakan Khalil Antar got his B.Sc., M.Sc. and Ph. D. degrees from University of Mosul, Iraq in 2002, 2005 and 2013 respectively. Now, he is a lecturer at Technical Engineering College, Northern Technical University, Iraq. He is concerned in power electronics, power quality, power converters and drives, and renewable energies. (rakan.antar@ntu.edu.iq)

Dr. Ahmed A. Abdullah Al-Karakchi obtained his B.Sc. in 2001 from Al-Mustansiriyah University, M.SC in 2004 from University of Technology, and Ph.D. in (2018) from Northumbria University, UK. Currently. He had a titular as lecturer from 2019. He is working in the Electrical Engineering Specializing in Electrical Power Techniques Engineering Department at Northern Technical University (NTU), Technical College of Engineering/Mosul-Iraq. He can be contacted at email: (ahmedalkarakchi@ntu.edu.iq)