Towards a Near-Zero Energy Building using a Building-Integrated Photovoltaic System with Smart Energy Management Capabilities

A Kh Abbas 1, A A Obed 2 and A J Abid 3
1,3Middle Technical University, Baghdad, Iraq

Abstract. Renewable energy resources, despite their advantages, it is uncertain due to the fluctuations in the weather. Clouds, dust, rain, and heat will negatively affect photovoltaic panels' production, which leads to the problem of power supply interruption and a decline in reliability. For that, it is required a standalone photovoltaic system with a smart energy management strategy. On the other hand, the load's reactive power decreased the system's efficiency and caused an overcurrent fault. So, it requires the adopt a mechanism to correct the power factor to enhance efficiency. The proposed system adopted two strategies: the first adopt an energy consumption management that determines the schedule's consumption loads. This strategy includes the predicted supplied power for the current day and two days ahead according to the available energy based on the forecast of solar radiation and the batteries' energy to update and correct the expected values. Moreover, three operating modes are presented according to the battery state of charge (SoC). The second strategy is adopting an automatic power factor correction (APFC) unit. A capacitor bank is used, where the system adds one or more capacitors to enhance the power factor. The proposed system also offers an Internet of Things (IoT) technology to communicate between system components and implement remote monitoring and control. The simulation results showed an integrated system capable of saving energy and relying on a limited renewable energy source. Such a promised system will lead to near-zero energy buildings (NZEB) without affecting life quality.

Keywords. Near-zero energy building (NZEB); Automatic power factor correction (APFC); Renewable energy uncertainty; Internet of Things (IoT).

1. Introduction
Reducing energy consumption in buildings ensures that future energy and climate goals are met. The near-zero energy building (NZEB) concept was adopted, which provides an opportunity to optimize the consumed energy [1]. NZEB is defined as energy-saving buildings in which the annual supplied energy is equal or less than the renewable energy produced from the site [2]. In other words as buildings that require a small amount of energy supplied from buildings renewable sources itself or nearby its sites [3]. Therefore it was counted on Renewable energy resources. However, despite the advantages of renewable sources, there are associated defects with them due to their impact on weather conditions. Dust, birds drop, and clouds are factors that lead to blocking the sun's rays from the photovoltaic panels, which reduce the produced energy and system efficiency and that, such as high temperature [4, 5]. Furthermore, inductive loads are considered another problem that held a portion of the supplied energy in the devices' magnetic field and then returned it to the source. Additionally, inductive loads
cause the current lags the voltage at an angle called theta or impedance angle. As this angle increases, the power factor decreases, leading to increased current drawn from the source, which requires additional costs, including an increase in the inverter rated current. Therefore, capacitors are used to balance the reactive power, reduce the effect of inductive loads, and raise the power factor, enhancing the system efficiency [6] and reducing unnecessary overcurrent faults.

Several smart strategies have been adopted to manage energy mitigation and reduce production fluctuations to ensure reliable PV systems [6, 7]. Many researchers worked to improve the efficiency of the solar system by tracking the sun[8-11] Also, detect faults and monitor the system [12, 13] and smart energy monitoring system [14].

Many previous studies are related to energy management in photovoltaic. Systems published, such as; For model, the writer used mathematical models for all single elements to a continuous power supply to the load for a standalone PV system in [15]. A multi-loop strategy to battery support and maintain the power balance for a standalone PV system [16]. Moreover, optimization of reducing battery replacement and shading of the load to improve reliability and cost reduction for a standalone PV system is presented [17]. Investigators adopted the Algorithm of load priority control to fulfill user requirements and improve the standalone PV system reliability [18].

In contrast, MPPT techniques synchronize with a battery bank to improve the PV system's performance suggested in [19]. In [20], the authors presented a Fuzzy logic to economic advantage and steady operation for a standalone PV system. The writer inserts Fuzzy logic to increase reliability for a standalone PV system [21]. Moreover, redefine the daily optimum weight values and Linear Programming optimization for a standalone PV system within zero energy building [22]. Others relied on building designs within the concept of autonomous zero-energy buildings AZEB, where the energy consumed equals the generated energy [23].

In our previous works [24, 25], we have presented a strategy to manage energy consumption based on the standalone PV system's available energy. The photovoltaic system's produced energy is calculated based on the weather conditions for the next two days with the energy of the batteries to estimate the available energy. The load profile is adjusted to increase the system reliability, as well as adopting the strategy of correcting the automatic power factor to raise efficiency.

In this work, the system fully controlled remotely using the Internet of Things (IoT) Technology. Energy management strategy EMS is adopted to create a high-reliability system and contribute change towards zero energy buildings ZEB. EMS reduces the daily consumption and regulates it for the current day and the next two days, depending on the forecast of solar radiation and correcting the expected production values. Moreover, a strategy for an Automatic Power Factor Correcting APFC is adopted to increase its efficiency. A diesel generator has been added to the system, which works in an emergency when photovoltaics generation is not available. The charge in the batteries falls below the permissible limit.

2. Proposed System

The proposed system guarantees high-priority loads for three days in the absence of the necessary generation. The energy consumed is determined according to the available energy estimated from the photovoltaic panels' energy produced. (EPpv) as in Equation (1) and the maximum energy stored in the batteries (MESbattery) as in Equation (2). The system manages, monitors, and controls all components according to energy management strategies, corrects the power factor, and as in figure 1, which shows the system's components and the connections between them.

\[ EP_{pv} = \sum_{n=0}^{N} V_{pv}(T_{sunset} + nT_0) \times I_{pv}(T_{sunset} + nT_0) \times T_0 \]  

where N = \left[ \frac{\text{sunset time} - \text{sunrise time}}{T_0} \right], T_0 = \text{equal 3 minute}

\[ MES_{battery} = \text{battery amper. hour} \times \text{battery voltage} \times \% \text{deep of discharge} \]  

\[ (2) \]
The system offered remote monitoring and control based on IoT Technology. Components operation and communication are managed by Visual Basic software in the main PC server and C++ for microcontroller ESP32.

2.1 System Circuitry

The prototype consists of interconnected components to implement the strategies by monitoring, controlling, and managing loads, as shown below.

- Personal computer (PC): Its function as a main server monitors and controls operations, analyzes and processes data
- Microcontroller: Acts as a client who receives information from sensors and sends it to (PC), executes requests and requests, and controls loads.
- Alternating power sensor: It measures the load's voltage, current, frequency, magnitude, power factor, and power.
- Multiplexer: It passes the load data from the power sensors to the microcontroller in sequentially.
- The relays module: it turns on and off the loads according to single from microcontroller and activates the contactors
- Contractors: it connects the capacitors with the primary power supply source.
- Capacitor bank: It contains a group of capacitors with different values for power factor correction.
- Router: forwards data between different network nodes using a Wi-Fi signal.
- Inductive loads: These are the main loads represented by three inductive motors and with a set of low power resistive loads.

3. Technical Design

The proposed system works according to two strategies, energy consumption management, and automatic power factor correction. Different modes of operation are adopted in energy management based on the battery state of charge (SoC) and the produced energy. A backup plan is also considered to switching to the auxiliary power source or the diesel generator when SoC drops below 50%. The available energy is calculated based on the stored energy and the predictive produced power. Therefore, the consumed energy is managed, and the building is dependent on its energy sources as much as possible. The system determined the appropriate capacitive loads that need to be injected into
the grid to enhance the load power factor. Figure 2 illustrates the process of identifying operation modes and correcting the power factor.

3.1 Energy Consumption Management Strategy

Energy Consumption management performs several tasks to reduce consumption according to energy availability.

- According to their importance to the user, the loads classify into three classes, high, medium, and low priority.
- Create a daily load schedule that shows each device's operating time, the number of working hours, and the type of load.
- Operation is according to three modes automatic and one manual. The automatic modes depend on the SoC; when SoC is greater than 70%, high-performance mode (HPM) is adopted, which allows the operation of all load classes. While when SoC is 60-70%, regulated power mode (RPM) is adopted, allowing high and medium priority operation loads. When SoC is 50-60%, power-saving mode (PSM) is adopted. It enables the operation loads of high priority only, as shown in Table 1.
- When the SoC drops below 50%, the diesel generator will start and switch to manual operation. The diesel generator will charge the batteries and supply the power to the loads; when SoC reaches 70%, the diesel generator will stop and switch to automatic operation.
- The available energy is calculated for three days, depending on the energy produced from the PV panels and the batteries' energy. The energy produced is calculated based on the predictive global horizontal irradiation (GHI). The produced energy values are corrected depending on the average error factor correction factor, calculated from the previous days' actual and expected data.
- A new daily load schedule is created according to the available energy, and it is updated daily and specifies it the operation modes. Figure 3 shows the calculation of available energy and the mechanism for distributing it to the loads.

| Auto operation modes  | High performance mode (HPM) | Regulated power mode (RPM) | Power saving mode (PSM) |
|-----------------------|----------------------------|---------------------------|------------------------|
| Operating range       | SoC > 70%                  | SoC (60 – 70)%            | SoC (50 – 60)%         |
| according to battery  |                            |                           |                        |
| SoC%                  |                            |                           |                        |
| Class of Working      | High, medium and low       | High and medium            | High                   |
| Devices               |                            |                           |                        |

Table 1. Auto Operation Mode
The loads’ consumption schedules are formed in three stages; the first is to determine whether the high-priority loads can work or not for the current day, tomorrow, and after tomorrow using the energy produced from the panels for each day energy of the batteries. The second stage is to calculate the working of the medium priority loads for the current day, tomorrow, and the after tomorrow, using the unused energy and the remaining battery energy from the first stage. The same process is for the third stage, which determines the work of low priority loads.

Figure 2. System main flowchart
3.2 Automatic Power Factor Correction Strategy

The system calculates the total reactive power \( Q_0 \) resulting from running the inductive loads. And then calculates the value of the reactive power \( Q_1 \) corresponding power factor equal to 0.9. From these two values, calculates the injected reactive power \( Q_{\text{injected}} \) resulting from the insertion of appropriate capacitors in the system, as in equation 5.

\[
Q_{\text{injected}} \text{ in (VAR)} = Q_0 - Q_1 \quad (3)
\]

Additional load impedance \( (XC) \) in \( \Omega = V^2 \text{(volt)} / Q_{\text{injected}} \text{ (var)} \quad (4)
\]

Additional capacitor \( C \) (farad) = \( 1 / (2\pi f XC) \) \quad (5)

4. Result and Discussion

The results include building a prototype to test the system in switching between operating modes, activating power factor correction. Moreover, a graphical user interface established to monitor, control, and receive data. In addition to established a daily load schedule according to the available energy.

**Figure 3.** Energy consumption management flowchart
4.1 System Prototype

A prototype had been built to test the system performance and ensure all used communications protocols between the branch electrical circuits. Three potentiometers were added to simulate both SoC, current, and voltage of the PV panels, as shown in figure 4.

![Prototype diagram](image)

**Figure 4.** The prototype of the suggested monitoring and control system

4.2 System Operation Modes Results

Figure 5a shows that high-performance mode (HPM) @ the battery SoC equal 76% adopted, allowing all load classes to operate. While In figure 5b at battery SoC equal 64%, regulated power mode (RPM) adopted as it enables high and medium priority loads to run. Figure 5c at battery SoC equal 57%, power-saving mode (PSM) is used to allow only high priority loads to run. While in the state of emergency, when SoC falls below 50%, as in figure 5d, the diesel generator will run to supply the loads and charge the batteries. In the three operation modes, When APFC is activated, both the system’s total current and apparent power will decrease, and the power factor will increase. Table 2 shows a comparison between the three operation modes, and Table 3 shows the APFC effect.
Figure 5. The Four Operation Modes and APFC, (a) HPM APFC no Backup required, (b) RPM APFC no Backup required, (c) PSM APFC no Backup required, (d) PSM with backup generator.
Table 2. Three Operation Modes

| Operation Mode                             | HPM | RPM               | PSM  |
|--------------------------------------------|-----|------------------|------|
| SoC %                                       | 76  | 64               | 56   |
| Class of Working Devices                   | High, medium, and low | High and medium | High |
| Number of Devices On                       | 8   | 5                | 2    |
| Number of Devices Off                      | 0   | 3                | 6    |
| Generated Power (W)                        | 455 | 427              | 413  |
| Consumed Power (W)                         | 372 | 242              | 99   |
| Net Power for Charging the Batteries (W)   | 82  | 184              | 313  |
| Total reactive power(Q) of the system (VAR)| 1018| 645              | 261  |

Table 3. Applied APFC

| Operation Mode                             | HPM | RPM     | PSM  |
|--------------------------------------------|-----|---------|------|
| Injected reactive power(Q) (VAR)           | 961 | 531     | 194  |
| Net reactive power(Q) (VAR)                | 57  | 113     | 67   |
| Power factor before applied APFC           | 0.36| 0.39    | 0.44 |
| Power factor after applied APFC            | 0.90| 0.95    | 0.94 |
| Apparent power(V.A.) before applied APFC   | 1128| 711     | 287  |
| Apparent power(V.A.) after applied APFC    | 441 | 256     | 109  |
| Total current (A) before applied APFC      | 5.01| 3.09    | 1.17 |
| Total current (A) after applied APFC       | 1.98| 1.26    | 0.54 |

4.3 Results of Response to Fluctuation of Global Horizontal Irradiation (GHI)

The results include the change in GHI from the standard rate for three consecutive days and the system's response to these changes, considering correcting predictive values and rescheduling loads daily, as in Figure 6. In Table 4, a comparison between three days in terms of the GHI change has listed Shows the difference in the produced energy and the system's response to it by reducing consumption, rescheduling the daily loads, and correcting the predictive values of production.
**Tabel 4.** The fluctuation of power output and system response to corrected values

| Date       | 26/1/2019 | 27/1/2019 | 28/1/2019 |
|------------|-----------|-----------|-----------|
|            | Before correcting | After correcting | Before correcting | After correcting | Before correcting | After correcting |
| The energy produced by P.V. system (kW)/day | 0.701 | 0.639 | 0.062 | 0.056 | 0 | 0 |
| Battery (kWh) | 0.6 | 0.6 | 0.515 | 0.515 | 0.377 | 0.371 |
| Available energy (kW)/day | 1.301 | 1.239 | 0.577 | 0.571 | 0.377 | 0.371 |
| Class of devices ON | High | High medium | High | High | High | High |
| Power consumed (kW)/day | 0.615 | 0.615 | 0.2 | 0.2 | 0.2 | 0.2 |
Figure 6. Reformulate the Daily Load Schedule
5. Conclusion

In this work, an energy consumption management system is designed and implemented for the standalone PV building to efficiently monitor and control available energy. The system operates according to a daily energy consumption schedule. The loads are classified according to their priority high, medium, and low priority. The system adopts three operating modes; HPM, RPM, and PSM that determine the amount of energy consumed for each mode and within a specified level of SoC. The system calculates the available energy. On its basis, it reformulates the daily load schedule to achieve a balance between production and consumption. It also adopts a strategy to automatically enhance the load power factor and raise system efficiency by reducing inductive loads' negative impact by using a capacitor bank. The results show a promised integrated system that can reschedule the load according to the available energy and the stored energy. Reliance on self-renewable energy sources for the building, which contributes to achieving the goals of NZEB. Moreover, the system could monitor and control the loads via IoT technology, which leads to an increase in system reliability and the continuity of supplied energy. Two main issues are solved in this design; the first is the overcurrent problem mainly caused by the high inductive loads. Moreover, the second is the emergency plan that allows the system to energized the generator as required.

References

[1] D'Agostino D and Mazzarella L, "What is a Nearly zero energy building? Overview, implementation and comparison of definitions," Journal of Building Engineering, vol. 21, pp. 200-212, 2019.
[2] ENERGY U S D O E E E A R. A Common Definition for Zero Energy Buildings. Available: https://www.energy.gov/sites/prod/files/2015/09/t26/A%20Common%20Definition%20for%20Zero%20Energy%20Buildings.pdf
[3] Union O J o t E. REGULATIONS COMMISSION DELEGATED REGULATION (EU) No 244/2012 of 16 January 201, Available: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:081:0018:0036:EN:PDF
[4] Ramli M A, Prasetyono E, Wicaksana R W, Windarko N A, Sedraoui K, and Al-Turki Y A, "On the investigation of photovoltaic output power reduction due to dust accumulation and weather conditions," Renewable Energy, vol. 99, pp. 836-844, 2016.
[5] Bouraiou A, Hamouda M, Chaker A, Mostefaoui M, Lachtar S, Sadok M, Boutassetta N, Othmani M, Issam A, and Management, "Analysis and evaluation of the impact of climatic conditions on the photovoltaic modules performance in the desert environment," Energy Conversion and Management, vol. 106, pp. 1345-1355, 2015.
[6] Wan C, Zhao J, Song Y, Xu Z, Lin J, Hu Z, and Systems E, "Photovoltaic and solar power forecasting for smart grid energy management," CSEE Journal of Power and Energy Systems, vol. 1, no. 4, pp. 38-46, 2015.
[7] Shivashankar S, Mekhilef S, Mokhlis H, and Karimi M, "Mitigating methods of power fluctuation of photovoltaic (PV) sources–A review," Renewable and Sustainable Energy Reviews, vol. 59, pp. 1170-1184, 2016.
[8] Abid A J, "Arduino based blind solar tracking controller," International Journal of Open Information Technologies, vol. 5, no. 10, pp. 24-29, 2017.
[9] Al-Naima F M, Ali R S, and Abid A J, "Design and implementation of a smart dual axis sun tracker based on astronomical equations," The European Workshop on Renewable Energy Systems, Antalya, TURKEY, vol. 1, pp. 1-6, 2012.
[10] Al-Naima F, Ali r, and Abid A, "Design of a control and data acquisition system for a multi-mode solar tracking farm," in The European Workshop on Renewable Energy Systems, 2012.
[11] Al-Naima F M, Ali R S, and Abid A J, "Solar tracking system: design based on GPS and astronomical equations," in IT-DREPS Conf. Exhib, 2013, pp. 1-6.
[12] Abid A J, Obed A A, and Al-Naima F M, "Web-Based System Design to Monitor and Control the Mismatching Effects in a Vast Solar Farm," International Energy Journal, vol. 18, no. 4, 2018.
[13] Abid A, Obed A, Al-Naima F, and Technology, "Detection and control of power loss due to soiling and faults in photovoltaic solar farms via wireless sensor network," International Journal of Engineering & Technology, vol. 7, no. 2, pp. 718-724, 2018.
[14] Abid A J and Ali A H, "Smart monitoring of the consumption of home electrical energy," International Journal of ComputerTrends and Technology(IJCTT), vol. 47, no. 2, pp. 142-148, 2017.
[15] Kebaili S and Betka A, "Design and simulation of stand alone photovoltaic systems," WSEAS transactions on power systems, vol. 6, no. 4, pp. 89-99, 2011.
[16] Mahmood H, Michaelson D, and Jiang J, "Control strategy for a standalone PV/battery hybrid system," in IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society, 2012, pp. 3412-3418: IEEE.

[17] Semaoui S, Arab A H, Bacha S, and Azoui B, "Optimal sizing of a stand-alone photovoltaic system with energy management in isolated areas," Energy Procedia, vol. 36, pp. 358-368, 2013.

[18] Faxas-Guzmán J, García-Valverde R, Serrano-Luján L, and Urbina A, "Priority load control algorithm for optimal energy management in stand-alone photovoltaic systems," Renewable Energy, vol. 68, pp. 156-162, 2014.

[19] Jyothi V M and Muni T V, "An optimal energy management system for pv/battery standalone system," International Journal of Electrical and Computer Engineering (IJECE), vol. 6, no. 6, p. 2538, 2016.

[20] Musilek P, Krömer P, Martins R, and Hesse H C, "Optimal energy management of residential PV/HESS using evolutionary fuzzy control," in 2017 IEEE Congress on Evolutionary Computation (CEC), 2017, pp. 2094-2101: IEEE.

[21] Ozden T, Kesler S, and Okumus H, "A fuzzy logic embedded energy management software with multi-agent system for a stand-alone PV power plant," International Journal of Environmental Science and Technology, vol. 16, no. 9, pp. 5197-5204, 2019.

[22] Georgiou G S, Christodoulides P, and Kalogirou S A, "Optimizing the energy storage schedule of a battery in a PV grid-connected nZEB using linear programming," Energy, p. 118177, 2020.

[23] Taherahmadi J, Noorollahi Y, and Panahi M, "Toward comprehensive zero energy building definitions: a literature review and recommendations," International Journal of Sustainable Energy, pp. 1-29, 2020.

[24] Abbas A K, Obed A A, and Abid A J, "Comprehensive Modelling of an Optimized Energy Management System for Photovoltaic Standalone Building," Technology Reports of Kansai University, vol. 62, no. 4, pp. 1989-2007.

[25] Abbas A K, Obed A A, and Abid A J, "Design of a Smart Energy Management System for Photovoltaic Stand-Alone Building," in IOP Conference Series: Materials Science and Engineering, 2020, vol. 881, no. 1, p. 012158: IOP Publishing.