

Application of Solar Energy Technology in Green Healthcare Camps for Fighting COVID-19 Outbreak in Saudi Arabia

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ABSTRACT

The healthcare facilities sector is an energy-intensive organization especially at a time of spreading dangerous infectious viruses, such as new Coronavirus, or what is known as COVID-19. Recently, many countries have opened several mobile field quarantine hospitals provided with the required technical equipment to prevent the COVID-19 outbreak in these countries. Unfortunately, most of these healthcare camps are lacking in the application of the necessary sustainability principles and health standards to become green healthcare facilities. Solar energy can be used for various purposes in green healthcare facilities, such as power generation and other sterilized applications. Therefore, in the present paper, a new design for the mobile, quick built, and solar-powered green healthcare camp, in safe and effective 24 hours a day services, is introduced. The proposed green healthcare camp is built using modern building technologies for rapid constructions, in which the building design is proposed to incorporate the photovoltaic power generation consideration. Photovoltaic systems are designed according to the loads required for the operation of the designed model of the green healthcare camp. Moreover, the total cost of a solar-powered green healthcare camp is estimated according to local conditions and standards in Saudi Arabia. The practical recommendations are presented with the designed photovoltaic system to attain the overcurrent and overvoltage protection. The photovoltaic designed system is proposed under the condition of ascertaining the service continuity of the photovoltaic power system during the electric faults in the photovoltaic strings. This is achieved by incorporating series diodes at the terminals of each photovoltaic string. The performance of a 50-kW PV system simulated using Matlab/Simulink is evaluated for the fault disturbance to enhance the service continuity.

1. Introduction

Recently, the sustainability concept has become an important strategy for the achievement of the Saudi Arabia 2030 vision. Energy-efficient buildings are an essential objective for the planned sustainable future [1]. Therefore, great attention has been given to achieve green building standards in a way that is appropriate with the privacy and principles of Saudi society. The impacts

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of green healthcare camps in terms of design, construction, operation, and management on the environment and surrounding community as well as patients' health are, due to the current COVID-19 crisis, mandatory.

As per the World Health Organization (WHO), several viral diseases are currently emerging and representing important issues to public health over the world. A comprehensive review of the most dangerous viruses and epidemics that have threatened humans over the past decade and their harmful effects can be found in [2, 3]. Among these pathogen viruses spread at the end of last year is the new coronavirus, which became known as COVID-19. This virus is considered as the most dangerous one than other previous infectious viruses [4]. The current greatest concern of all countries over the world is how to prevent or limit the virus outbreak and to significantly reduce the number of infected people with this virus, as an indication of the decline of the disease. The challenge during such a process is the long incubation period of this virus that might reach 14 days [5] and possibly 24 days after onset, as recently indicated [6].

Many countries have taken appropriate preventive measures and precautions as the current strategy to limit the COVID-19 outbreak so that the number of infected people does not exceed the maximum capacity of the health care system [7]. Such preventive strategies are focused on the patient's isolation and careful infection control, including suitable measures to be applied during the diagnosis and the provision of clinical care to an infected patient [8]. Accordingly, healthcare facilities, particularly those in low-resource settings, will be put under considerable pressure by the COVID-19 extreme outbreak.

Recently, new proposed healthcare facilities are widely spread and known as green hospitals or green healthcare camps. This is considered as one of the four initiatives of the Hospital 2020 movement worldwide. The green healthcare camp is defined as a healthcare camp that has taken the initiative to have one or more of the required elements for green healthcare buildings. These elements are starting from choosing an environmentally friendly site, utilizing sustainable and efficient designs, using green building materials, and applying renewable energy systems [9, 10]. In general, a green healthcare camp is an energy-efficient building constructed around a facility that recycles, reuses materials, reduces waste, and produces cleaner air [11].

Based on the previous investigations, many technologies based on renewable energy sources can be applied in healthcare camps. For example, solar energy technologies can be applied in heating and cooling applications and providing energy needs for equipment and other healthcare services [12]. It is known that the application of solar energy technology in green healthcare camps requires more investment costs and complicated structure. Unfortunately, dust accumulation is one of the challenges for solar applications in Saudi Arabia, as it is a desert area. Therefore, cleaning techniques are associated with photovoltaic power systems [13, 14]. However, renewable energy technology generally results in lower carbon dioxide emissions which lead to sustainable development [15-17]. This is in line with the goals and strategies of Saudi Arabia's 2030 vision to achieve sustainability in all aspects of life.

Applying the renewable energy suppliers for healthcare centers in the rural regions became attractive as reported in [18, 19]. They considered optimal design of hybrid energy system combination of photovoltaic (PV), wind and battery storage system to obtain sustainable energize healthcare considering the off-grid state. However, these studies did not consider the mobility conditions of healthcare camps.

In case of epidemic spread in any country, the need for large-scale and rapid healthcare facilities with certain specifications is considered a vital topic that cannot be delayed. In this case of the need for rapid construction, steel structures seem to be suitable due to many advantages [20]. In addition to their fast execution, these types of structures can cover large spans as well as resist

live and dead loads, especially external loads such as winds in an open area. Finally, these structures can be dismantled and reused in other projects reducing construction cost in the long run.

Smart applications have recently become essential to improve service popularity and system quality. Accordingly, the healthcare centers attracted and gained smart system applications. In [21], the healthcare performance was monitored and evaluated with the aid of automated weighted indicators. The system was studied toward energy management and cybersecurity considerations, and machine learning was utilized to automatically attain the healthcare functions using widely distributed indicators. In [22-24], the internet of things (IoT) was also applied to automatically monitor the healthcare to enhance the system quality and overcome the technical challenges. Accordingly, the patient condition monitoring was proposed to smartly assess the patients' health considering medical measurements such as blood pressure, temperature, etc. Also, healthcare performance was assessed widely. However, all these smart systems for the healthcare centers are not efficient without the electric energy service continuity.

In the present paper, a simple and robust design for the quick built and mobile healthcare camp is introduced and its initial cost is estimated. The proposed designed healthcare camp is powered with PV solar arrays that are connected to a battery storage system to assure the 24 hours daily service for the healthcare camp. The area of the camp and the other associated systems are considered to be suitable for 50 patients. The performance analysis of the designed 50 kW-solar power system is performed by using Matlab/Simulink and some important results are illustrated. Moreover, the total cost of the complete designed healthcare camp is estimated according to the available price in the Saudi Arabia market.

2. Structure Building of Mobile Healthcare Camp

To construct a healthcare camp unit covering 50 beds, it is proposed to use a structure building based on frame steel structures (10 m width, 60 m length, and 5 m height) as shown in Figure 1.

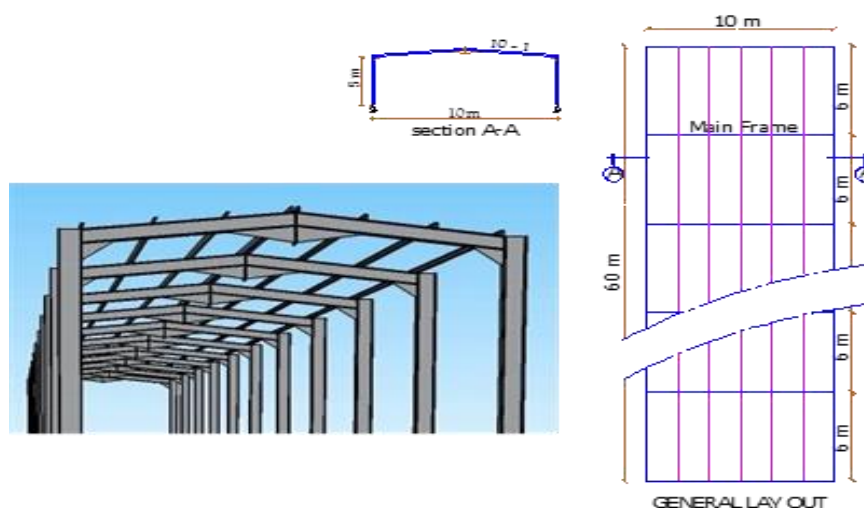


Fig. 1. The proposed representation of the healthcare camp

The proposed structure was completely designed for the purpose of cost estimation. All structure elements were designed such as foundations, steel frames all elements. Furthermore, all execution activities were identified to calculate the cost such as cut, fill, plain and reinforced concretes, steel fixing, and finishing work based on medical specifications and standards. Due to the

soil variation from place to place, the selection of site should take into consideration the soil type. Soil type affects the type and sections of foundations as well as cut, fill, and insulation activities [25]. The cost calculation was determined on bearing soil capacity of 1.00 kg/cm^2 which represents the common bearing capacity in KSA. Based on the last data, the estimated total cost including indirect cost is 175,000 \$.

3. Electrical Loading Evaluation of Mobile Healthcare Camp

The healthcare services mainly depend on continuous energy service with attaining the energy characteristics in the form of the highest reliability, affordability, and sustainability. These high conditions of the service continuity at a low price are required to care for the patient and his life-saving. It means that the patient servicing in the healthcare and life-saving is ascertained based on the energy service continuity. The energy service in healthcare and human life is directly presented using electricity. The electricity is for powering medical and non-medical equipment essential for the patient treatment and his living standards.

The electrical service of healthcare loads is mandatory and should be completely covered. The healthcare loads are mainly medical and non-medical types. The medical equipments are such as suctions, sterilizer, pulse oximetry, reverse-osmosis water purifier, X-ray machine, mechanical ventilator, ultrasound scanner, electrocardiogram (ECG), and Nebulizer, etc. The medical laboratory equipments are such as vaccine refrigerator (165 L), microscopes, centrifuge, spectrophotometer, blood chemistry analyzer, haematology analyzer, and arterial blood gas (ABG) analyzer, etc. The non-medical equipments are such as lighting, thermal heating, air conditioning; water pumping, electricity pin-out plugs, controllers, computers, and ceiling fans, etc. The following Table 1 summarizes the electrical loads of the equipment. This table is redrawn and modified based on the one given data in [12]. The modification is to consider the service of ten patients. From the results in Table 1, the non-medical and medical loads are close in their energy size. Under the condition of more patients greater than ten, the multiple of ten patients is considered. For example, if the design is for fifty patients, the load presented in Table 1 is multiplied by five, and so on. The electrical load of one hundred patients (as an example) is less than ten times the electrical load of ten patients because the laboratory equipments are expected to not be repeated but its consuming time may be increased.

To energize the mobile healthcare camp, there are several types of generation units such as diesel generators, solar systems, wind energy, fuel cell, wind turbines, etc. However, the diesel generator is not recommended in this study due to noise and emission pollutions as well as maintenance requirements. The hybrid renewable energy generation system especially of the solar, fuel cell, and wind is better than utilizing one of them alone. However, wind turbines need maintenance and hard to transfer from one place to another. Consequently, the solar energy is only considered in the design; however, the fuel cell can be utilized for energy storage supporting the battery system. However, this study does not include the fuel cell to practically simplify the source energizing the mobile healthcare camp. Accordingly, the solar system is the base system for generating electricity energizing the mobile healthcare camp.

Regarding the energy storage system, there are several types including mechanical storage systems such as flywheels and compressed air, electrochemical storage systems such as batteries, and electrical storage systems such as supercapacitors and superconducting magnetic systems. The most famous and commercial one is the battery storage system. Accordingly, it is considered in this study especially with the off-grid PV system. For on-grid PV system, the batteries are used as a backup for the emergency electric services.

In order to attain the PV ratings to energize the mobile healthcare camp, the global horizontal irradiance (GHI) of Saudi Arabia is to be estimated in accordance with the load energy summarized in Table 1. Therefore, solar radiation is evaluated for different measuring places in Saudi Arabia as discussed in the following section. This is to estimate the efficiency of the Saudi Kingdom country to develop the healthcare camp electrification based on the solar system and also to determine the PV system rating in order to energize the mobile healthcare camps.

Table 1

Modified electrical load data for ten patients per day using data presented in [12]

Type	Equipment	Power/Hours/Energy (W/h/Wh)	Qty	Energy per day (Wh/day)
Non-medical	Lighting (fluorescent)	11/6/66	15	1000
	Conditioning system	30-100/10/300-1000	5	1500-5000
	Electricity plug	20-50/8/160-400	5	800-2000
	Computers	15-200/4/60-800	2	100-1600
	Water pump	100/6/600	2	1200
	Heater	1000-1500/4/4000-6000	2	8000-12000
Total				12600-22800
Medical	Sterilizer (steam)	500-1550/2/1000-3100	2	2000-6200
	Suction	25/10/250	2	500
	Pulse oximetry	25/2/50	2	100
	Reverse-osmosis water purifier	250-600/8/2000-4800	1	2000-4800
	Mechanical ventilator	200/10/2000	2	4000
	Ultrasound scanner	75/2-3/150-225	2	300-450
	Electrocardiogram	50-100/0.5/25-50	2	50-100
	Nebulizer	200/3-5/600-1000	2	1200-2000
Total				10150-18150
Laboratory	Vaccine refrigerator	50-500/4/200-2000	1	200-2000
	Microscopes	50/2/100	1	100
	Centrifuge	600/2/1200	1	1200
	Spectrophotometer	100/1/100	1	100
	Blood chemistry analyzer	50/2/100	1	100
	Hematology analyzer	250/2/500	1	500
	Arterial blood gas (ABG) analyzer	250/0.8/200	1	200
Total				2400-4200
All totals				25150-45150

4. Solar Energy Measurements throughout the Kingdom

In this section, the solar energy parameters are evaluated for different places in Saudi Arabia in order to attain the most efficient solar irradiation exposable locations and then estimate the PV system rating to energize the mobile healthcare centre. The following results were collected under the preparation done by King Abdullah City for Atomic and Renewable Energy, as part of the Renewable Resource Monitoring and Mapping (RRMM) Program. Toward the statistical records of the renewable resources throughout the kingdom, one of the renewable resources recorded are the solar resources using satellite maps. Distributed stations for recording solar components are installed where there are more than fifty stations installed in the Kingdom. These solar components, related to solar radiation, are direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and global horizontal irradiance (GHI) plus related meteorological and dust parameters. In [26], the solar measurement parameters such as DNI and GHI are illustrated and summarized as follows. The direct normal irradiance (DNI) relatively indicates the solar radiation

amount perpendicularly received to the solar energy conversion device (the solar system), and GHI indicates the global horizontal irradiance after considering the DHI effect [26].

4.1 Statistical Study of Irradiation Measured Parameters

As aforementioned, there are more than fifty recording stations throughout the kingdom. Six places are selected for these stations to illustrate the recorded direct normal irradiation (DNI), as shown in Figure 2. The selected cities under study are Dammam – IAFU (the station is at Imam Abdulrahman Bin Faisal University), Jeddah – KAU (the station is at King Abdulaziz University), Madinah (the station is at Taibah University), Qassim (the station is at Qassim University), Riyadh – KSU (the station is at King Saud University), and Taif (the station is at Taif University). These six cities are selected to consider important cities as well as geographically widespread throughout the Kingdom. As shown in Figure 2, the irradiation records were from January 2016 until August 2018 (one and a half years). This record period is considered as it is available free of charge.

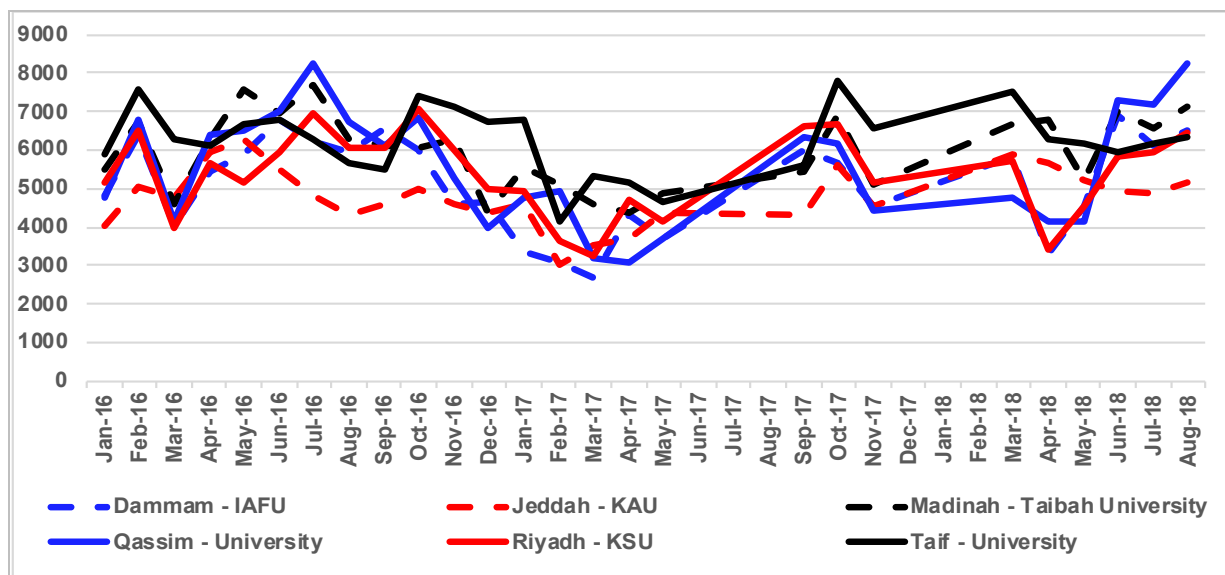


Fig. 2. DNI measurements for different cities as measured and tabulated in [26]

Through the recording period, Figure 3 shows the statistical parameters of the DNI using the boxplot shapes designed based on the probability density function concerning the normal distribution of measured data for each city individually. Using the boxplot, the box indicates the interquartile range, and the red line is the median value. From the comparison between the selected cities in Figure 3, Taif city has the highest median irradiation value of 6258 Wh/m² with a low quartile of the distribution DNI irradiation. Jeddah city has the lowest median of 4778 Wh/m². The GHI measurements at Taif city are slightly reduced as shown in Figure 4. However, all cities under study have the ability of solar energy generation where their global horizontal irradiances are greater than 6000 Wh/m². Under the operation of the solar energy conversion system, the gained irradiances are expectedly increased using the maximum power tracking system [27].

From Figure 4, the mean of GHI is between 6000 to 6800 Wh/m² per day in Saudi Arabia considering the selected cities under study. This GHI value is competitive to good places such as Haiti with range of 5000 to 7000 Wh/m², Rwanda with maximum value of 5400 Wh/m², and Zambia between 5500 and 6300 Wh/m². These countries are considered as sunny countries and have a high average day time. Although Germany has only a GHI range of 2700 to 3300 Wh/m², however, it can be also considered, in the comparison point of view, as one of the leading countries in installing PV

systems. By comparing the GHI measured in Saudi Arabia and these countries, Saudi Arabia has two times the GHI value of Germany country that has many successful solar-based energy projects. This ensures energy generation capability using solar systems in Saudi Arabia.

Concerning the GHI measurements shown in Figure 4, Taif city as an example has GHI mean value equal to 6300 Wh/m² per day. Unfortunately, the GHI is not completely transformed into electric energy using the solar PV system; however, there is an efficiency coefficient. This efficiency coefficient is less than 25 % for commercial solar panels, although the research is in progress and enhances the efficiency coefficient at 50 %. Accordingly, it is commercially difficult to attain the efficiency value of the purchased solar panel. On the other hand, efficiency affects the panel size.

To overcome the uncertainty of the efficiency of the commercial solar panels, the rating addressed for the commercial solar panel is utilized as a reference for the electric power generation. For example, if the purchased solar panel power is 280 W, its generated energy multiplied by the light hours of the city. However, the solar panel power does not continuously generate rated power energy. Accordingly, there is an equivalent light hour value multiplied by the panel rating, in which this multiplication is equal to the total generated energy of the panel throughout the day. For Taif city, the equivalent light hour is five hours. For example, the 280 W solar panel products energy of $280 \times 5 = 1400$ Wh per day.

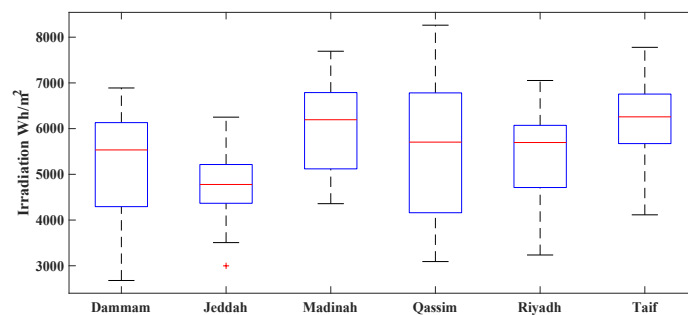


Fig. 3. Statistical distribution parameters of the DNI measurements [26]

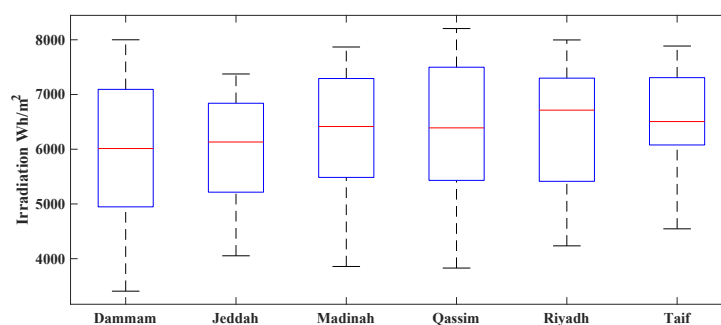


Fig. 4. GHI measurements [26]

5. Design Principles of Solar Powering Mobile Healthcare Camp

Based on the above study, solar energy is available throughout the kingdom, especially Taif city. The required energy to energize the healthcare camp depends on the number of patients and the healthcare team. From the previous study in section 3, every ten patients consume 45 kWh/day during the maximum consuming power consideration. The design principles are as follows:

- i. As the ten patients consume 45 kWh/day and assuming the average sun time is five hours per day at Taif city, the photovoltaic power plant to develop the energy is $45 / 5 = 9$ kW. That is concerned with 10 kW due to considering factors for the reliability of the service continuity against the intermittent energy generation.
- ii. The 10-kW photovoltaic power generation (PPG) unit is considered the base generation unit. The 10-kW PV system is considered to attain small power conversion systems instead of a large conversion system as it will be discussed in subsection 6.1. Then, this generation unit is repeated when a further load is found. This suggestion facilitates the mobility action, transferring the equipment to another project, and distributing the equipment based on the government directions.
- iii. For the reliable operation of the PV system, the batteries are associated with the PPG units. Furthermore, grid connection availability is exploited. The battery-based system and the on-grid interconnection enhance system's energization reliability and service continuity.
- iv. For the off-grid PV system, the reliability is also increased by reserving a further 10 to 15 % of the healthcare camp power size of the PV system. For example, if the camp power size is 100 kW, a further 10 kW is considered as spare. In other words, ten PPG units are in the operation mode to energize the healthcare camp, while the further units are in spare status. This spare is utilized for any fault cases in the PV system.
- v. Smart supervisory and control system is developed to monitor the PV system operation and attain continuous service continuity.

From the above discussion, the 10-kW PV system is to energize and electrify the electric service of ten patients. As the design base of the structure building discussed in section 2 is for fifty patients, the 50-kW PV system is a suitable size for energizing the infrastructure of the green healthcare camp. This PV system size (50-kW) is ascertained in detail concerning the PV structure layout, cost, and simulation-based performance evaluation at fault conditions as discussed follows.

6. Photovoltaic Energy Conversion Systems

6.1 Photovoltaic System Integration Layouts

There are different PV system interconnections, in which they can be achieved for on-grid and off-grid considerations. One of the configurations is that the complete PV system is connected as a single energy bulk using a single inverter. However, the other system layout is interconnected using multi-inverter plants. The following discussion is under the consideration that the inverter is associated with DC/DC boost converter including the algorithm of maximum power point tracking. Also, there is an associated charge/discharge converter to attain battery energy management.

By comparing these two system interconnections, the second PV configuration is appropriate for the mobile healthcare camp as the mobile healthcare size is adaptive based on the number of patients which is not controllable and as the mobile healthcare can be moved from one place to several places or from several places to a single place. This means that the multi-inverter configuration is appropriate for mobile healthcare camps. Furthermore, the multi-inverter PV system can be implemented in a decentralized configuration by making further buildings associated with the healthcare camp elongation. For example, if the camp is implemented for 150 patients and under the conditions of further patients' consideration, the building extension and electrification is for 50 patients as the design base is for 50 patients. Also, the fault in any inverter separately reduces the generated power as the faulted inverter is only disconnected.

On the other hand, any fault in the PV string such as shadow or electrical fault affects the operation of the corresponding inverter only. A further advantage of the multi-inverter PV system is

that the distributed generation and distributed loads are attained. This can reduce the losses in the energy distribution system. Finally, the multi-inverter system topology provides the advantage of the adaptive system size following the mobile healthcare centre load size. Accordingly, the three-phase multi-inverter system is considered for energizing mobile healthcare where the base value of the 50-kW PV system is utilized.

Following the decentralized electrification system, further decentralized consideration is done that the multi-DC/DC converter topology is applied for each inverter in the multi-inverter system configuration. This consideration attains multi-MPPT algorithms, where such implementation attains and enhances the PV-based system electrifications.

As the multi-inverter system is better than the single-inverter system, the base system that is used for performing the multi-inverter system is suggested 50-kW for the 50 patients as discussed previously. Then, each 50-kW inverter includes five 10-kW DC/DC converters to individually attain the maximum power point tracking operating separately. Referring to Figure 5, the 50-kW PV power generation (PPG) unit has five 10-kW DC/DC boost converters individually achieving the maximum power point tracking to continuously attain the available maximum energy gained from the PV system. Also, it includes DC/DC converter to attain charging and discharging energy management with the battery system. In the figure, there is DC/AC inverter to convert from DC power to AC power suitable for energizing loads of the mobile healthcare camp. The inverter controller should attain important characteristics such as pure AC sinusoidal waveforms, a low value of the total harmonic distortion, a unity power factor, etc. As aforementioned, the system is shown in Figure 5 is associated with the building structure discussed in section 2 and it is repeated with the structure when the patients are greater than fifty persons.

The battery system as an energy storage system is essential to be installed following the PV system; especially the on-grid operation may be interrupted due to disturbances. This is to reserve the energy during the day time and then utilize the stored energy during the evening and night times until the next day. Also, the battery system enhances performance during the day time as it facilitates the energy utilization with the loads. The battery system provides stability against the fluctuated differences between the PV generation and the daily load demand curve. Accordingly, a reliable and stable energy source is attained to energize the healthcare camp based on an integrated PV-battery energy source system.

As the battery is an electrochemical device, their types are several. They are categorized based on energy storage technology such as lead-acid, sodium, lithium, and nickel batteries. The factors differentiating between these battery types are energy density that affects the battery volume, discharge time, safety, lifetime, maintenance, and price. More discussion and comparison between these types are addressed in [12].

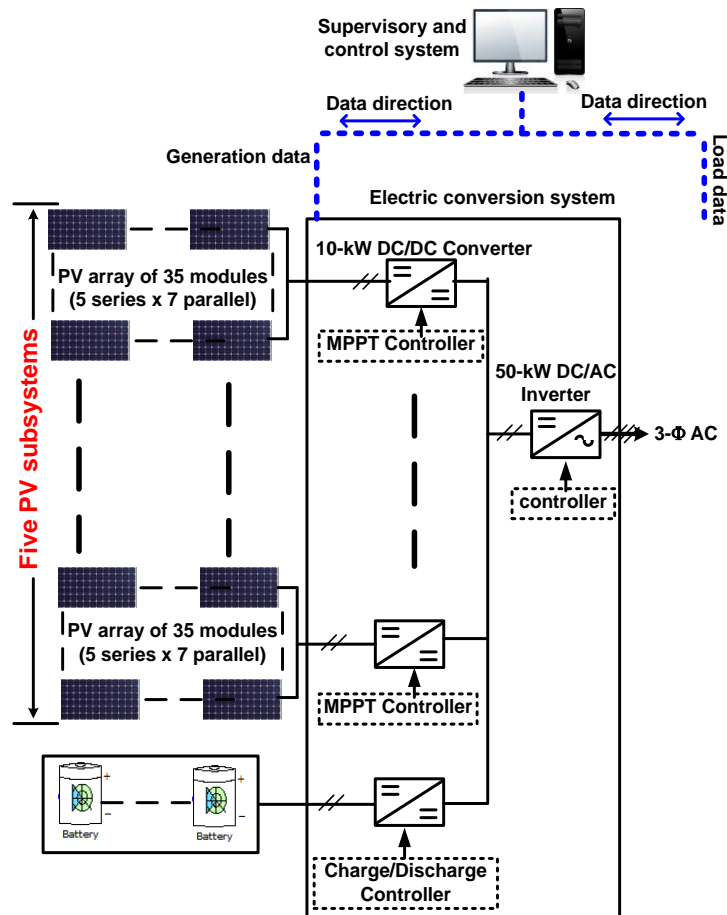


Fig. 5. The 50-kW PV power generation unit base designed for building a structure of fifty patients

6.2 More Design Issues for the Multi-Inverter PV System

In this subsection, further options are considered and discussed during the design stage concerning the multi-inverter system and considering the multi-MPPT DC/DC converters shown in Figure 5 as discussed as follows.

6.2.1 Smart supervisory and control system

As depicted in Figure 5, there is a smart supervisory and control system. This system communicates with the DC/DC boost converters, DC/DC charge/discharge converters, DC/AC inverters, load points, and measuring devices. Accordingly, this supervisory system with the aid of supervisory and control software facilitates to monitor and control of the system terminals. The supervisory and control system can utilize energy management software for optimal energy management operation, in which the supervisory system can communicate with the controllers of the distributed DC/DC converters, DC/AC inverters, remote switches, and accessible loads. Accordingly, it provides the optimal operation for the system devices [28]. Furthermore, this supervisory system successfully operates either on-grid or off-grid PV mode services. Under the energy shortages, the supervisory system communicates with loads to manage the loading process according to the circumstanced shortage of energy. Finally, the supervisory and control system can include fault detection algorithm by monitoring the distributed currents either in the DC side or the

AC side and also by monitoring the operations of the DC/DC converters, DC/AC converters, batteries, and protection system.

6.2.2 Overvoltage protection

For the PV system as the considered example in Figure 5, overvoltage stress is probable due to lightning strokes. Accordingly, overvoltage protection is to be added. One of the overvoltage protection devices is the surge arrester, which has advantages such as high reliability and smooth clipping operation. The important places to install the surge arrester are at the AC busbar. As the load area has the characteristics of the low voltage level, the low voltage surge arrester is installed. An example installed in the low voltage level to protect against overvoltage transients is addressed in [29]. However, this arrester device protects only the AC side including the AC loads.

For the PV system and attaining overvoltage protection in the PV domain especially against lightning strokes, air terminations (lightning rods) are fixed and distributed following the PV panels. The tall length of the air termination determines the area protected over the PV panels, in which the protected area is increased by increasing the air termination height.

6.2.3 Grounding system

Either the surge arrester or the air termination overvoltage protection systems should be connected to the grounding system. Practically, two vertical electrodes of length 3 m and interspace 6 m are the construction of the grounding system. However, the grounding system design depends on the earth structure where the PV system is going to be installed. Considering Taif city, Saudi Arabia, the soil resistivity is high as the ground is a rock type. Accordingly, further research efforts are required to attain a low grounding resistance system appropriate for protecting the PV system, especially against over voltages due to the lightning strokes. The grounding system can be a vertical electrode or several vertical electrodes; however, it is designed as a grid for the high resistivity soil to attain low grounding system resistance. Toward further reducing the grounding system resistance, the vertical electrodes can be added and associated with the grounding grid. In [30], the grounding system design is recently addressed for PV installed at Taif city, in which a grounding grid dimension of 15 × 20 m is suggested. Although this grounding system increases the installation costs, it is essential to protect the system against lightning as Taif city is frequently subjected to lightning strokes.

6.2.4 Overcurrent protection

There is a possibility for fault occurrences in the system during the system operation. The most dangerous faults are the shunt faults either in the DC side or on AC side. This fault type produces high currents leading to damages and accordingly further cost and downtime, which is not allowed for the mobile healthcare camp. Accordingly, the overcurrent protection devices are to be installed at the AC side and DC side especially using miniature circuit breakers with rating depends on the inverter rating, converter rating, and load points.

Regarding the PV strings, it is proposed in this paper to add two diodes in each PV string (a diode at each terminal of the string). The diodes attain the current in one direction that is not changed during the in-service time. These diodes completely prevent the current to reverse due to the faults in PV strings. Therefore, they participate in interrupting the PV string fault currents.

6.3 PV Cost Analysis

The multi-inverter PV system is considered, and each PV converter system includes multi-DC/DC converters as shown in Figure 5. Each distributed PV power generation unit including multi-DC/DC is suggested to be 50-kW, and each DC/DC converter is considered 10-kW. The PV panel technology of considering bypass diodes is to be recommended. Table 2 illustrates the items of the base PV generation unit of a 10-kW PV system; however, the inverter is 50-kW to include five MPPTs. The prices listed in Table 2 are approximately estimated to be searching on the well-known purchase website in Ref. [31]. The cost information in Table 2 does not include the transportation and installation expenses. However, this net cost is reduced when the loads are DC load types, in which there is no need for the DC/AC inverter under this condition.

For the design stage and then cost estimation, the selected photovoltaic panel is 315 W, and accordingly, 35 panels are utilized to build the 10-kW PV system. The PV panel electric characteristics include 6.14 A short circuit current, 64.6 V open-circuit voltage, 315 W maximum power, 54.7 V voltage at the maximum power, and 5.76 A current at the maximum power as reported in [32]. Further characteristics are that the panel efficiency rate is up to 18.6%, the panel frame dimension is 156 × 104 × 4.6 cm, and therefore the panel area is 1.62 m². Then, the total area of 10-kW, 35 PV panels is 56.8 m², and therefore the area of 50-kW is 284 m² that is less than the half area of the building top-roof of the mobile healthcare camp as the roof has a tent shape as shown in Figure 1. The 35 panels are distributed to construct each string of five series modules to build the voltage up to 5 × 64.6 = 323 V, and seven parallel strings to build the current up to 7 × 6.14 = 42.98 A. The total PV panels price is around 4200 \$ as presented in Table 2.

Table 2

Cost of the PV generation unit excluding the transportation and installation expenses

#	Descriptions	Price (U\$)	Qty	Total price (U\$)
1	Solar panels 315 [25]	120	35	4200
2	Batteries, Deep Cycle Gel	200	30	6000
3	Accessories, DC cables, AC cables, steel structure, and others.	2500	--	2500
Summation concerning 10-kW PV				12700
4	Conversion system, 50-kW, including MPP tracking systems and charge/discharge battery controllers	6500	1	6500
Net summation of 50-kW PV system				70000

Regarding the batteries, the deep cycle gel battery is suggested, where its ratings are 12 V and 200 Ah. The energy stored in the battery is considered 24 kWh per day concerning around 50 % of the 10-kW PV power generated energy per day. Considering the depth of discharge factor of 0.5 [33], the total battery capacity equals 24 kWh / 12 V / 50% = 4 kAh. Then, the number of batteries is 4 kAh / 200 Ah = 20 batteries. Considering the safety factor of 50 % extra batteries, the final number of total batteries associated with the 10-kW PV generation unit is 30 batteries. Accordingly, the total price of the battery system is 6000 U\$ as shown in Table 2. From Table 2, there are more expenses including accessories, DC cables, AC cables, steel structures, and others, in which their cost is close to 2500 U\$. Therefore, the total price of the base 10-kW PV system excluding the conversion system (as it is 50-kW) is 12700 U\$.

Regarding the inverter, its rating is 50-kW that can be selected to service both the on-grid and off-grid operation modes. The energy conversion system includes the DC/AC inverter and DC/DC converters, and it has the advantages of smart metering and communicating with the supervisory and control system with delivering information about the inverter, converters, PV string currents,

PV voltage, etc. The electric energy conversion system price is expected around 6500 U\$. Therefore, the net total cost is around 70000 U\$ for the 50-kW PV system.

The cost presented in Table 2 is only for the 50-kW PV generation unit, which is considered as the base generation unit for building the electric circuit energizing the mobile healthcare camp using five distributed 10-kW PV generation units. For example, if the healthcare camp is designed for 150 patients, the required PV generation power system is 150-kW that is three times the 50-kW PV generation units. Accordingly, the price is expected to be around 210000\$. This cost can be reduced by the grid connection implementation as the battery size can be reduced, where the most expensive item in the list is the battery system.

7. Simulation-Based Performance Evaluation

Based on the options discussed in section 5, the grid-connected PV system is considered for the service continuity, in which the distributed concept is implemented. The 50-kW PV system shown in Figure 5 is implemented using the five distributed PV subsystems, and each subsystem is around 10-kW connected by MPPT DC/DC converter. The five MPPT DC/DC converters are collected to support the 50-kW DC/AC inverter to energize the load and interconnect with the network under the supervise and control system. A further condition that is proposed in this study and evaluated in this section is that two diodes are connected in each PV string to increase the system service continuity. One of these two diodes is connected in series of each string terminals to prevent the reverse current as declared by the following performance evaluation. The corresponding Matlab/Simulink simulated circuit is shown in Figure 6. This model is modified using the available built-in model in Matlab/Simulink.

As shown in Figure 6, the DC/DC converters are used to attain the maximum power operation of the 10-kW PV subsystem, where the MPPT controller is implemented based on the Perturb and Observe algorithm principles. The DC/DC converter contains a parallel capacitor and series inductor operating as a boost converter. The 50-kW DC/AC inverter is operated as a voltage source converter (VSC) to provide the power to the AC side at voltage level 400 V, 60 Hz as in the low level Saudi standard operation.

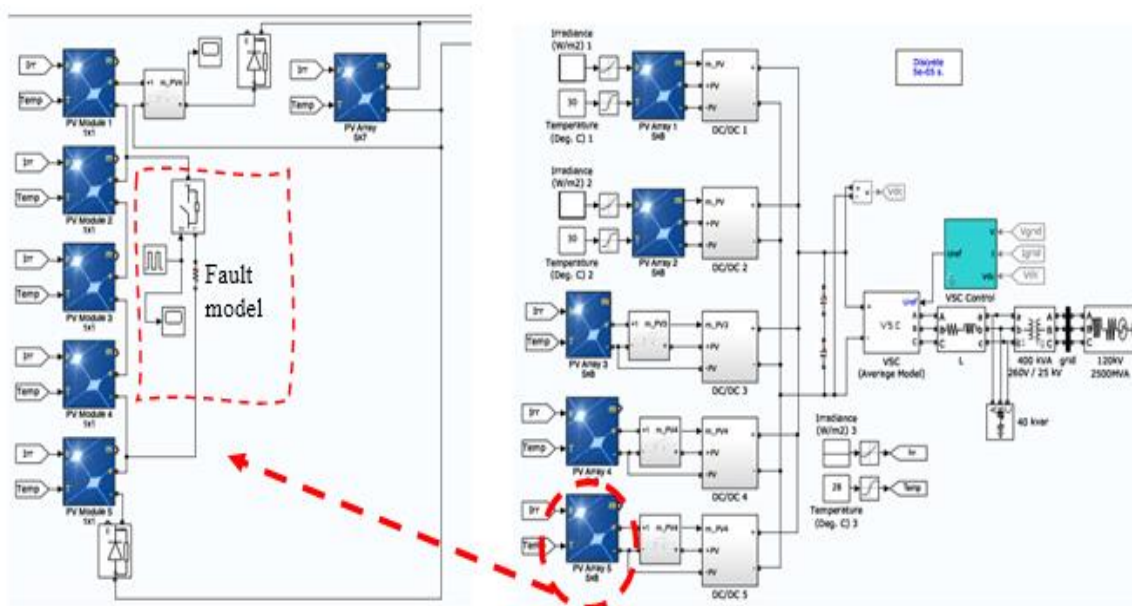


Fig. 6. Simulated system using Matlab/Simulink

Figure 7 and 8 show the time-domain performance of the PV simulated system during a string fault through four PV modules in the faulted string indicated in the simulated system in Figure 6. The fault resistance is assumed to be close to zero as it is the worst fault condition. The results show the performance of the faulted PV system without considering the series diodes and considering the series diodes within each string. The fault period is considered from 0.35 to 0.85 s.

As shown in Figure 7(a), the faulted string current is reversed and increased due to the fault and reached more than 100 A when the system is free of diodes. This current value is high as the PV string rated current is close to 6 A. Of course, the protection series fuse operates to isolate the fault, and this protection is not involved in the simulation as it is expected. However, there is a period of high reverse currents that increase the fault point damage. On the other hand, the fault current becomes zero when the distributed diodes are installed. This performance ensures the value of installing diodes in series with each string. In Figure 7(b), the faulted string voltage associated with the diodes is lower than the faulted string voltage free of diodes. This performance makes the diodes of the faulted string to be in reverse made operation.

Figure 8 shows the performance of the PV subsystem (PV array) that includes the faulted string. During the fault period, the PV subsystem current is reserved for the free-diode system while its current is reduced with the diode-based consideration as indicated in Figure 8(a). The reduced current value is due to the outage of the faulted string by the diode reverse mode operation during the fault period. Accordingly, the PV subsystem voltage is stable with considering the distributed diodes as depicted in Figure 8(b).

From these results in Figure 7 and 8, the diodes enhanced the service continuity of the PV energy system where the faulted string is only out of service. The next step is that a detection algorithm will be proposed in a work to follow.

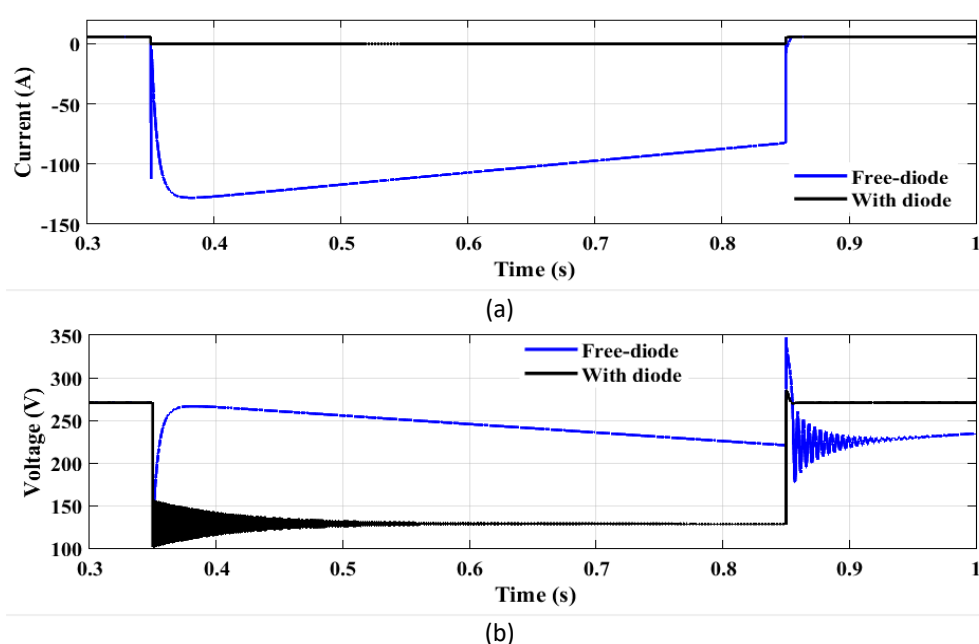


Fig. 7. Faulted PV string performance (a) Currents (b) Voltage

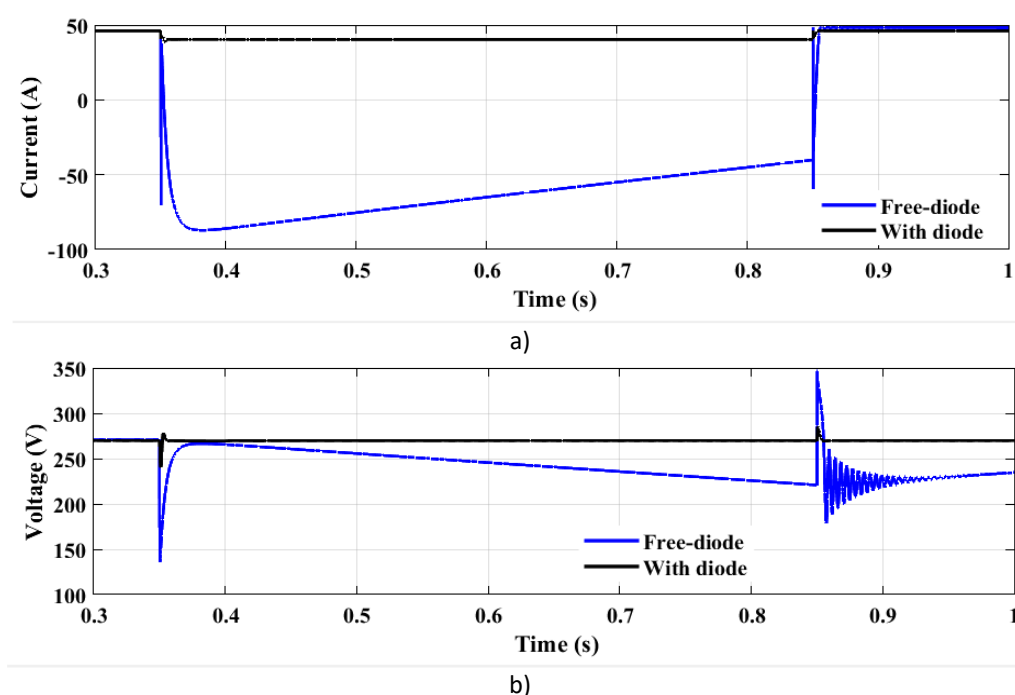


Fig. 8. Faulted PV subsystem performance (a) Currents (b) Voltage

8. Conclusions

The present paper deals with the applications of solar energy in the green healthcare camps in Saudi Arabia. The main objectives of such applications are to provide clean energy and high quality internal health conditions as well. The obtained healthy conditions in the healthcare camps can fight the outbreak of different dangerous viruses such as the current COVID-19 pandemic. The proposed green healthcare camp unit is constructed by applying modern building technologies for rapid constructions. The solar energy power system is designed to cover the electrical load required for serving 50 patients in safe and effective 24 hours a day service. The designed PV system is proposed in the form of the possibility to be transmitted to other places of the mobile healthcare camps. Accordingly, the multi-inverter PV system was proposed and each inverter was considered for multi-DC/DC converters. The evaluation of the performance of the 50-kW PV system using Matlab/Simulink has been implemented for the multi DC/DC conversion system that enhanced the service continuity, where the faulted string is only isolated using the dynamic effect of the series diodes. Then, the supervisory system would be responsible for alarming the string out of service.

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