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Optimization of Solar Energy Utilization, System Reliability and Utility Savings using a New Framework

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Abstract: *The relevance of focusing on SPV systems with storage to meet the user specific requirement is discussed}. Existing Solar Photovoltaic (SPV) systems are studied and the need for introducing new classification based on the interaction with utility grid, solar module and battery backup, based on load types and end user application is proposed. In order to represent the entire SPV systems a generic framework is introduced known as the three-switch model. All the SPV systems under the new classification can be represented using the framework by changing the switch states. Using this framework, a method to convert existing backup systems into a grid-interactive system is proposed. The ways to enhance maximum solar utilization, utility savings and system reliability are discussed. The states of the grid-interactive systems are discussed and simulated using Typhoon HIL 600.*

Keywords: *Solar Photovoltaic systems, Grid-interactive systems, Three-switch model, Solar energy utilization, System reliability, Utility savings.*

I. INTRODUCTION

Electricity prices are increasing over the last decade in all over the world. The Energy Information Administration forecast the increase in residential electricity price by an additional 1.8 percent in 2020 (1). Commercial sector electricity price increased by 0.5 percent in 2019 and it is predicted to rise another 0.1 percent by 2020 (2). According to the study conducted by BP Energy, the energy consumption of India would grow by 4.2 percent per year faster than all major economies in the world. Grid unreliability issues are addressed by providing diesel generators and battery storage which will increase pollution and reduce efficiency respectively (3).

Most of the consumers end up paying a minimum charge for the grid supply even without making the best use of it since supplies are absent in most productive hours (4).

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Affordable users buy Uninterrupted Power Supply (UPS) and batteries creating a boom in that market; whereas others try to be content with cheaper solutions such as solar lanterns (5).

India alone sells 6.5mn battery inverter and uninterrupted power supplies (UPS) per annum (6; 7; 8). The battery inverter system market is growing at a Compound Annual Growth Rate (CAGR) of 9.33% and UPS market is growing at 11.93%. The world- wide market for the battery inverter storage is expected to reach $40Bn by 2025 (9). It is estimated that 145mn battery inverter storage systems will be deployed in APAC countries and 280mn systems world over (10). Nearly all the 1.37 billion people who gained access since 2000, 70 percent are connected to the utility grid which is powered from fossil fuels (11).

Renewables will become the second largest source of domestic energy production overtaking gas and then oil by 2020 (12; 13). Governments in both developed and developing countries are encouraging the process of transiting from a high carbon-intensive sources to less carbon-intensive electricity sources (14). Renewables generally require a higher degree of flexibility from the network to compensate for their intermittency (15). Hence, providing reliable, affordable and efficient supply of electricity is a major challenge. Mostly energy consumption is high during early morning and late evening; i.e during non-solar hours (16; 17). Generally natural gas, coal or diesel-based energy sources are used to meet the evening load requirement. Based on levelized cost of electricity (LCOE) coupled with the experience curve approach, a grid parity model is studied in detail to understand the concept (18). The rapid growth in PV deployment is largely policy driven. Unless government continue to expand financial incentives and policy mandates, as well as address regulatory and market barriers (19) such growth would not be sustainable. Spinning reserves are needed to handle the variance in renewable generation (20).

In short, this research is taken up to address the problems faced by people due to unreliable electricity and unutilized solar energy. The challenge is addressed by proposing a solution by providing electricity with a combination of solar energy, utility grid and battery backup (21). Most of the UPS users have already invested in the power electronics and storage to provide backup during utility power outage, sags and swells (22). These same power backup systems can be used to evacuate solar PV if they are converted to solar power compatible.

Even if 1.5KWp solar module is connected on average to 25% of these systems, 100GW can be evacuated through the existing infrastructure in a seamless fashion. The paper describes a method for converting existing battery-based UPS systems into solar power systems. By choosing solar energy, the research is aligned in the direction of promoting clean technology.

To maximize the solar energy utilization; storage back up is used to support the evening energy consumption, which is charged using solar energy. The cost of solar PV is down to 0.10 dollar per KwH compared to the cost of electricity generation based on fossil fuels which is falling in the range of 0.05 to 0.17 dollars per KwH (23). Hence the research focuses on maximizing solar energy utilization, providing backup and increasing utility savings.

The various sections of the paper are as follows: Section II gives the background study of the SPV systems. The need for introducing a new classification was identified and proposed. The section also discusses the novelty of the paper by introducing a universal framework called three-switch model for representing all the classified SPV systems. The most suitable SPV model for converting the existing battery-based systems to solar compatible is discussed in section III. Various states of the model are also discussed using the three-switch framework in this section. The proposed system is modelled using Typhoon HIL 600 simulator and different states are also simulated in section IV. In order to achieve the proposed solution an algorithm is discussed in section V using different switch states of the proposed model. The paper is concluded in section VI by discussing the future work.

II. BACKGROUND

Most of the large installations in solar PV systems are grid-tie as the per watt installation cost is much lesser than other systems. However, when solar energy is inadequate either conventional energy sources or storage units are need to handle the energy consumption (24). Eventually solar energy along with storage will win the energy war as the natural resources are depleting and even if available, global warming will prevent us from harnessing all those resources in a conventional way (25). All the evidence available in literature points to the fact that the only way out for human race is to couple renewable energy sources along with energy storage (26). Due to these reasons, it is important to make sure the following three fundamental and yet conflicting requirements are to be met when using renewable energy, especially SPV systems along with energy storage.

- If a user prefers higher reliability there should a provision for accommodating higher storage capacity compared to a user demanding lower reliability at a lesser cost. In other words, system reliability should be on user's demand.
- The two type of costs involved are CAPEX and OPEX. Generally, CAPEX cost of renewable energy sources is high, and they pay off over a longer period of time. Hence, the system should be designed to maximize solar energy utilization.
- Most utilities use time of day metering to discourage energy usage during peak demand period. Hence, OPEX cost can be reduced if the renewable energy is utilized during peak hours resulting in utility savings. This is achieved by storing the generated solar energy for non-solar hours.

These requirements are conflicting and also the variables will keep on changing. For example, solar insolation will change from day to day or season to season. Energy consumption pattern will change as per the day of the week, time of the day and also has a seasonal behavior. Finding a solution to optimize all the above variables i.e. deciding when to store, when to release the energy from storage and when to charge from utility grid or when to support the load using utility grid for revenue maximization is a challenge. The existing SPV systems are studied to understand the most suitable model for achieving the proposed solution.

A. Existing Literature on SPV Systems

This section investigates the entire space of SPV systems in detail to find out an appropriate classification. In paper (27) SPV systems are mainly classified as grid-tie and stand-alone systems based on system's functional and operational constraints, configuration parameters of the components and end use. The authors classified the systems as thermal systems, hybrid photovoltaic thermal systems, photovoltaic systems and thermoelectric systems based on the concentrated solar irradiance. (28) Suggests another classification category based on emerging technologies: solar PV based water pumping, home lighting systems, desalination plant, thermal, space technology, building integrated SPV systems and concentrated SPV systems. In (29) SPV systems are broadly classified as grid- connected and stand-alone systems and sub-classified based on consumer and non-consumer applications. Based on the energy generation (30) classified PV systems as concentrating PV systems, PV systems with sun tracking and fixed at PV systems. The authors of (31) classified the power tracking of PV systems based on different MPPT techniques. Only two types of solar energy systems are mentioned by authors in (32): stand-alone systems and solar-hybrid systems. One or more renewable energy sources are considered in the hybrid systems. Different off-grid hybrid systems such as PV-wind, PV-diesel-battery, PV-wind-diesel, and PV-fuel cell systems are discussed in (33). The authors of (34) classified o_-grid systems as conventional, non-conventional and hybrid micro-grid. Different grid-connected PV concepts such as central converter, string converter and module-integrated converter concept are discussed in (35). The authors discussed different types of solar technologies in (36) and classified the SPV systems as on-grid and off-grid systems. The work (37) discusses two main categories of PV systems, stand - alone and grid-connected systems. Based on the scale, the grid-connected systems are classified as small, medium and utility scale systems. The authors of (38) introduces new classification category for grid-connected system based on storage availability. However, the basic SPV systems were classified as stand-alone and grid-connected systems by the authors. The author made an attempt in (39) to classify SPV systems as grid-connected, hybrid and off-grid systems based on user application and storage availability. The term `grid-interactive systems' is used instead of grid hybrid systems with energy storage in this study.

However, none of the above classification categorize the entire SPV systems based on their application, technology, load-type and user requirement under one structure. Thus, a need to categorize all SPV systems based on utility and energy consumption interface, magnitude of solar energy generation, storage availability, load types and end user application was identified.

B. Proposed SPV Classification

SPV systems are classified as off-grid, grid-tie and grid-interactive systems based on the availability of storage and utility grid. Off-grid systems are not connected to utility grid. It can be classified into DC and AC systems based on the load type. Depending upon the end user applications, DC systems are further classified as lighting system, sensor and gadgets and microgrid. In grid-tie systems, generated solar energy gets directly exported to the grid. There is no external storage available in these systems except the grid acting as the pseudo storage. The system will stop working during grid failure. Normally an auxiliary power supply like a diesel generator is used to mimic a grid during power failure. Grid-interactive system is a combination of off-grid and grid-tie system. It has solar energy, battery backup and utility grid to support the load. They are also classified as DC and AC systems based on load type. AC systems are further divided based on user applications as solar UPS, hybrid systems and AC microgrid, where solar energy gets stored into the battery, exported back to the grid and used to support user load respectively. Depending on the user application, home lighting systems and DC microgrid are the two types of DC systems under grid-interactive systems. The different variants of SPV systems are illustrated in (Figure 1)

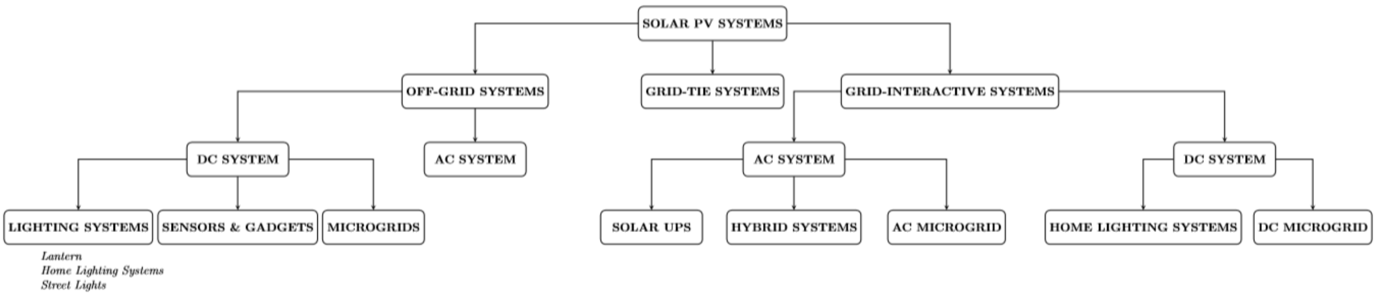


Fig. 1. Classification of Solar PV Systems

C. Universal Framework for SPV System Representation

SPV systems classification proposed in section 2.2 can be represented using a universal framework, called three-switch model. The model is shown in the Figure 2. Switch S1 indicates the presence of solar energy. Switch S2 indicates the presence of battery storage system. Switch S3 indicates the presence of the utility grid. All the systems given in Figure 1 can be represented using this three-switch model.

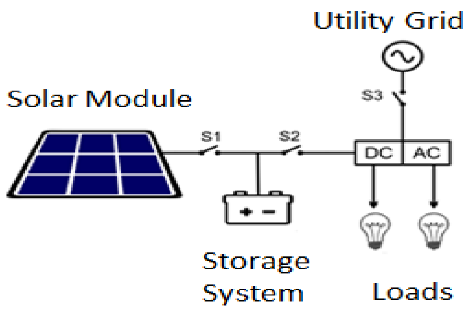


Fig. 2. Generic Three Switch Framework

Table 1 illustrates the various systems that can be represented using this generic framework. Normal utility connected systems have only S3 switch. UPS systems have both S2 and S3 switches. Grid-tie systems have S1 and S3 switches; whereas S1 and S2 switches are used for representing off-grid systems. Systems having interface between solar modules, storage, utility grid and UPS, classified as grid-interactive systems, have all the three switches present.

Table 1: Different System Representation Using Three-Switch Framework

S1 State	S2 State	S3 State	System Type
0	0	1	Utility Connected Systems
0	1	1	UPS Systems
1	0	1	Grid-tie Systems
1	1	0	Off-grid Systems
1	1	1	Grid-interactive Systems

III. PROPOSED SYSTEM

In section 1, it was discussed that about 6.5mn battery UPS are being sold in India per annum. The importance to focus on renewables; specifically, solar energy (40), to reduce the gap between energy demand and supply was also discussed in section 1. In order to replace the battery UPS into solar compatible UPS, a huge capex cost is needed. But, with the framework proposed in section 2.3 the existing systems can be converted into solar compatible systems at lower CAPEX investments. The existing systems comes under the classification of UPS systems which has S2 and S3 switches. By adding S1 to the topology the existing UPS system can be converted into grid-interactive systems as illustrated in Table 1. Studies have found that batteries improve the efficiency of storage based SPV systems.

The solution becomes more profitable if the price of electricity increases (41). It is found that battery usage is more effective than Demand Side Management (DSM) programs for promoting self-consumption (42). Moreover, the user is able to time shift the usage of locally generated energy during peak hours (43). Hence, the study focuses on converting the existing systems into grid-interactive systems than any other systems. Figure 3 shows a grid-interactive system which has solar module, storage, UPS and utility grid to support the load. Battery overcharging is regulated by the charge controller.

Figure 4 shows three switch representation of the grid-interactive system. Solar switch controls the delivery of solar energy to the DC Bus, battery switch controls interconnecting the DC Bus to the load or the utility grid and mains relay is used for forcefully turning off the utility grid, so that the energy consumption is supported by the solar energy generated and the battery. System efficiency is affected by variables such as solar irradiance, load pattern, available AH capacity of the battery at the user site, availability and quality of utility grid and user preference for maximum backup over solar utilization (44). The variation in these dynamic variables can be addressed using the three-switch model. The model provides a provision to expand or reduce the system size based on the energy consumption and future applications. Variation in load usage and solar insolation also get addressed in this framework by providing the required SPV modules and storage capacity. Thus, the framework has the capability to provide residential, commercial and industrial users over a degree of magnitude in energy consumption on either side during weekdays, weekends and holidays with varying load pattern. By controlling the switches in the model, the system is capable of taking a decision to provide an optimized solution for maximizing solar energy utilization, system reliability and utility savings.

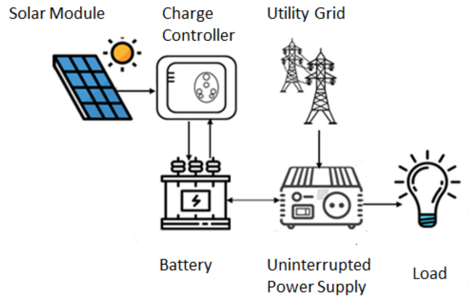


Fig. 3. Grid-interactive systems

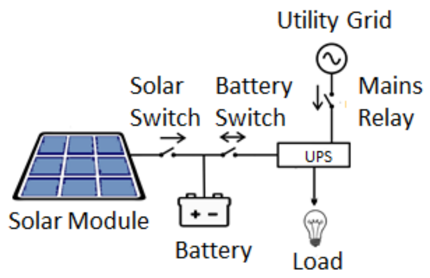


Fig. 4. Three-switch Representation of Grid-interactive systems

A. Different states of grid-interactive systems

Based on the position of three switches in the order S1, S2 and S3, the system can operate in eight different states. State 1, where all switches are OFF and State 5 where only S1 is ON are not feasible, hence not discussed in this section. The system can transit into any of the six states depending on certain parameters explained in section 5. In this section the various states of the grid-interactive system are explained. This section also explains the attribute of each state i.e the contribution of the state towards solar utilization, backup and utility savings.

A. State 2 - Inhibition state

When the solar switch and battery switch are OFF and mains relay is ON, the system is said to be in state 2. The battery charging is inhibited in this state. Hence it is also termed as inhibition state. The load is supported by the utility grid. Since, the battery charging from mains is inhibited, it contributes towards utility savings.

B. State 3 - Force trip state

When the solar switch and mains relay are OFF and battery switch is ON, the system is said to be in state 3. The load is transferred to the battery by forcefully tripping the mains relay. Hence the state is termed as force trip state. This state contributes towards utility savings as the load get supported by battery bypassing the mains supply.

C. State 4 - UPS state

When the solar switch is OFF, battery switch and mains relay are ON, the system is said to be in state 4. In this state, the system operates as a normal UPS system. Hence, termed as UPS state. Depending on the utility grid availability, the battery is either charged or discharged. It contributes towards the system reliability.

D. State 6 - Solar charging mode

When the solar switch and mains relay are ON and battery switch is OFF the system is said to be in state

6. The load is supported by mains and battery is charged using solar energy. This state is termed as solar charging mode. Since, the battery is charged using solar and mains charging is inhibited, it contributes towards solar utilization and utility savings.

E. State 7 - Solar assisted force trip state

When the solar switch and battery switch are ON and mains relay is OFF, the system is said to be in state 7. The load is supported by both battery and solar by forcefully tripping the mains relay. Hence, it is termed as solar assisted force trip state. This state contributes towards solar utilization and utility savings.

F. State 8 - Solar assisted power failure

When all the three switches are ON, the system is in state 8. During this state, if the utility grid is unavailable; the battery along with solar energy is used to support the load. Hence, the state is termed as solar assisted power failure. This state contributes towards reliability and solar utilization.

The various states mentioned above are consolidated in the table 2. The grid-interactive system is modelled and the states mentioned above are simulated and presented in section 4.

Table 2: Different Switch States of Grid-interactive Systems

State Number	S1 State	S2 State	S3 State	State Mode
1	0	0	0	Not feasible
2	0	0	1	Inhibition
3	0	1	0	Force Trip
4	0	1	1	UPS
5	1	0	0	Not feasible
6	1	0	1	Solar Charging
7	1	1	0	Solar Assisted Force Trip
8	1	1	1	Solar Assisted Power Failure

IV. COMPUTERIZED SIMULATION IN TYPHOON HIL 600

The six states mentioned is section 3.1 are simulated using Typhoon HIL 600. For the simulation, the different entities of the grid-interactive system are modelled. The section 4.1 explains the different entities that are modelled and the section 4.2 explains the simulation results of various states that are modelled. Parameters like solar voltage, solar current, battery voltage, battery current, UPS voltages and load voltage for each state are simulated and presented in this section. The purpose of the simulation

is to understand the parameter values in each state in detail.

A. Simulation Model

The grid-interactive system consists of solar module, battery, UPS, load and utility grid. In order to simulate the states, the above-mentioned entities are modelled. The complete model is classified into four section.

1. Solar module, battery and sensing section
2. AC/DC converter model of UPS
3. DC/AC converter model of UPS
4. Utility and sensing section

Each section is individually modelled and the sub components are put together to build the grid-interactive PV system.

A. Solar Module, Battery and Measurement System

The PV array model available in Typhoon library is used for modelling the solar module. The solar irradiance and external temperature values given for simulating the module are 1000 W and 30 degree Celsius respectively. The solar voltage and solar current are measured using voltage and current measurement blocks. When the solar switch is closed the voltage of the solar panel will be equal to battery voltage.

Lead-acid battery module available is chosen for simulating the battery component. The battery parameters are given as 150 AH and 12V. The initial state of charge (SoC) of the battery is given as 80%. The battery current of the circuit is measured using a current sensor. The solar and battery model along with its measuring sensors, solar and battery switches can be seen in Figure 5

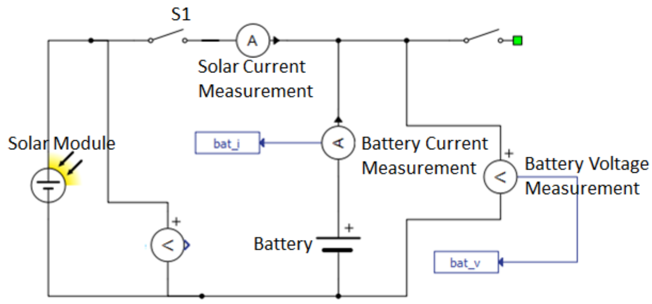


Fig. 5. Solar and Battery Measurement System

B. UPS Modeling

The entity which needs more attention when modelling is the UPS. The UPS can either work as an AC/DC converter charging the battery or as a DC/AC converter supporting the load, based on the requirement. Hence the UPS has to be modelled as two entities.

1. Rectifier model of UPS - The UPS charges the battery rectifying the utility grid. The charging profiles of the battery is based on the manufacturer of UPS. When the utility fails, the battery is used to support the load. In order to mimic this, a controlled voltage source is used. The controlled voltage source is connected to the battery via a single pole double throw relay. When the utility grid fails, the battery is connected to the DC equivalent AC load. The control is based on the availability of the utility grid and battery voltage. The minimum battery voltage till which the system can operate without any issues is 10.8V and maximum voltage till the battery can get charged is 14.4V. Figure 6 shows the rectifier model of UPS. In this simulation, it is assumed that if the battery voltage is 10.8V the output of the converter will be 11.2V and if the battery voltage is 14.4V the corresponding converter voltage will be 14.4V. A linear curve is fit between the above mentioned battery voltage and UPS voltage forming the equation 1 which gives the charging profile used in the simulation.

Converter voltage = 0.9 x battery voltage + 1.6 (1)

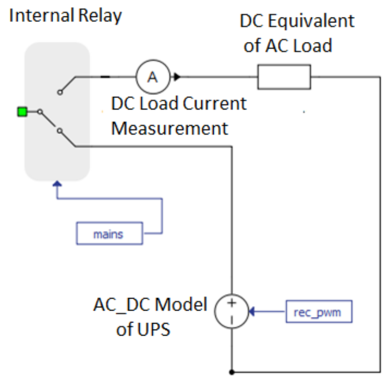


Fig. 6. DC side of the UPS circuit

2. Inverter model of UPS - When utility grid is available, the load is met using the utility grid. When utility fails, a PWM is generated to operate the inverter for supporting the load. The inverter is modelled using a controlled voltage source. The control voltage is a sine reference, which is active when the utility grid fails.

The control signal to the controlled voltage source depends on utility availability and battery voltage. A relay is used inside the UPS to transfer load between the mains and UPS. Whenever the battery voltage goes critical or the utility grid is available, the control signal becomes zero and the output voltage will be zero. If the utility grid becomes unavailable or the battery voltage is above the critical value, then the controlled voltage source generates a sinusoidal AC signal of 230V RMS and 50Hz. Figure 7 shows the inverter model of UPS.

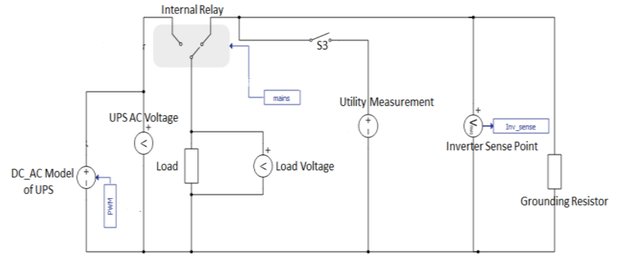


Fig. 7. AC side UPS model

C. Load and utility grid

The load is simulated as a series RLC branch. A constant load of 100 is used for simulation. The utility grid is modelled as a controlled voltage source instead of using an AC voltage source. The control signal to the voltage source is provided such that it generates 230V RMS at 50Hz. A constant block is used to toggle between utility grid availability. If a unit value is given to the constant block, 230V sinusoidal signal gets generated and 0V is generated if the constant block is given zero value.

The state transitions are controlled by solar mosfet, battery mosfet and the mains relay. Solar mosfet is used to control the delivery of solar energy to the DC Bus. Battery mosfet interconnects the DC Bus to the load or the utility grid. The mains relay is used to forcefully turn off the utility grid, so that load is transferred to both generated solar energy and the battery or battery based on the system state. The complete circuit of a grid-interactive PV system can be seen in Figure 8

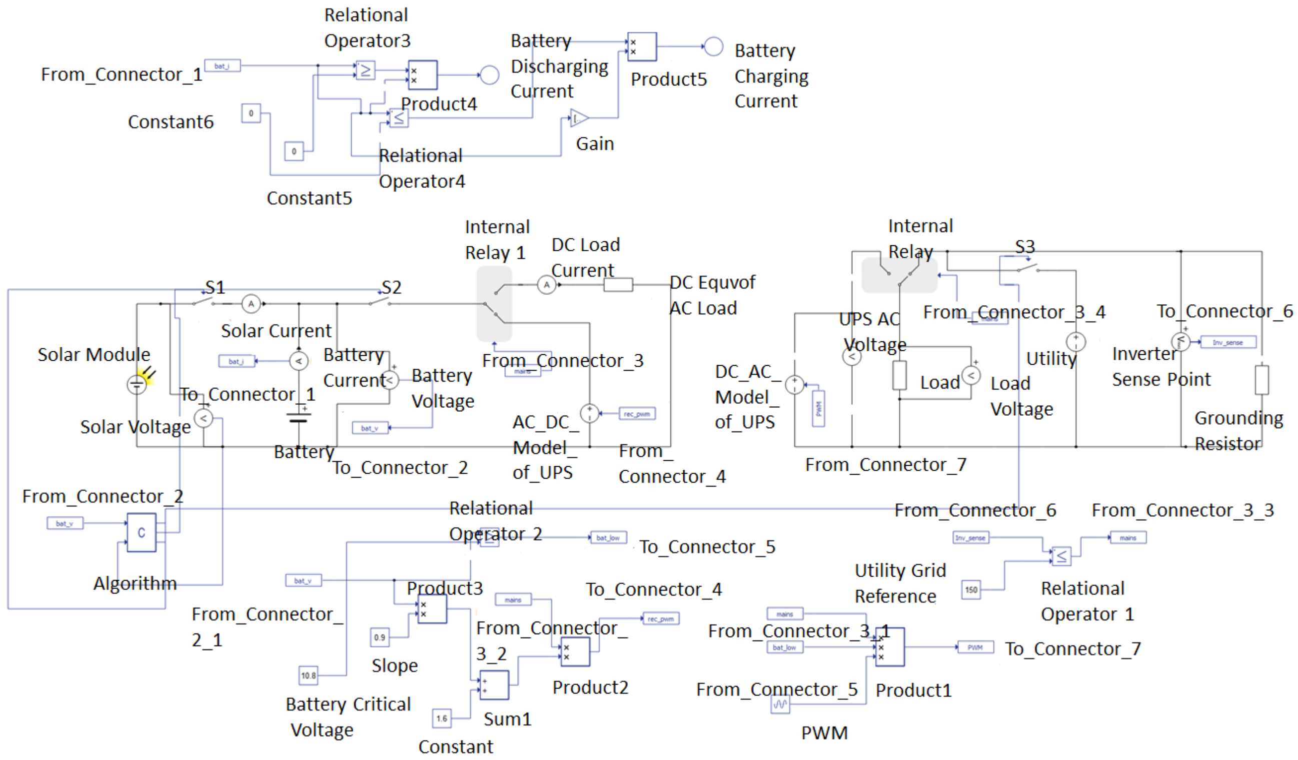


Fig. 8. Model of Grid-interactive System

B. Simulation Result

A. State 2 - Inhibition State

As mentioned in section 3.1.1 this state contributes towards, utility savings. It can be seen from Figure 9 that the charging current of the battery is zero. The load voltage and utility voltage are the same. Since the utility grid is available, the UPS voltage is zero and rectifier voltage tallies with equation 1. Figure 9 shows that only the load gets supported by the mains. Figure 10 validates the fact that both battery charging and discharging currents are zero. It can be seen from Figure 11 that the load voltage is equal to mains voltage and the UPS is not providing any voltage to support the load.

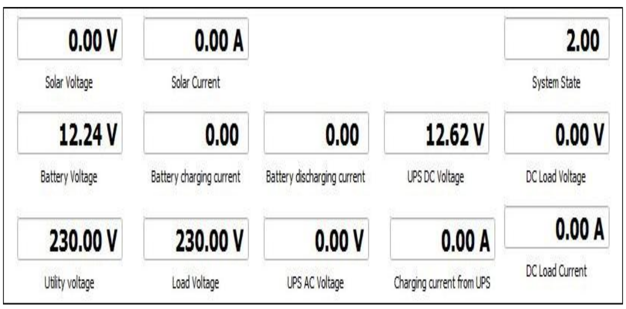


Fig. 9. Sensor measurements during State 2

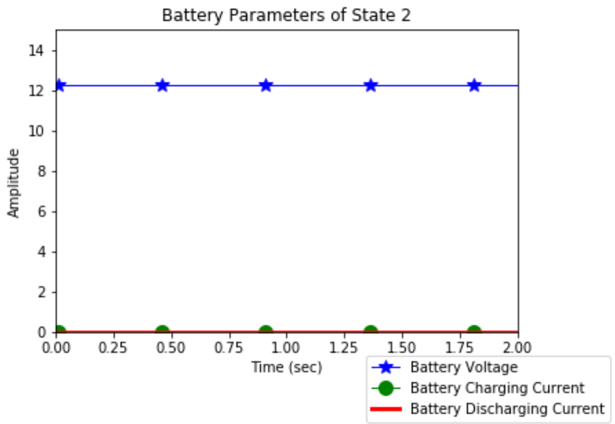


Fig. 10. Battery Measurements in State 2

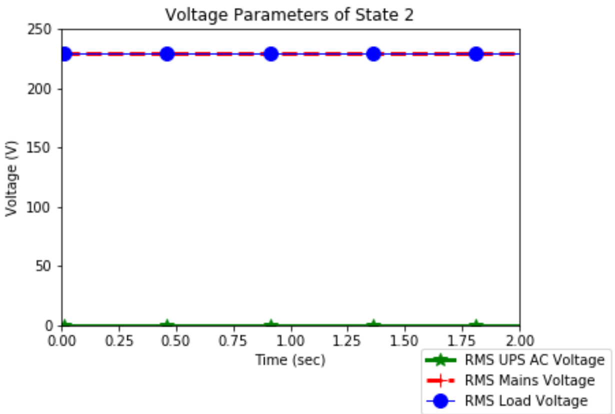


Fig. 11. Load Measurements in State 2

B. State 3 - Force Trip State

As mentioned in 3.1.2 this state contributes to utility savings. From Figure 12, we can see that the DC load current is equal to battery discharge current, 9.55 A which implies that the load is supported by the battery. Only battery discharging is happening in State 3 which is illustrated in Figure 13. From Figure 14 it can be seen that load voltage is equal to ups ac voltage, which confirms the fact that the load is transferred from utility grid to UPS even when the grid is available. This is achieved by turning OFF mains relay.

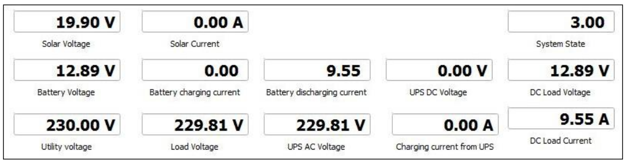


Fig. 12. Sensor measurements during State 3

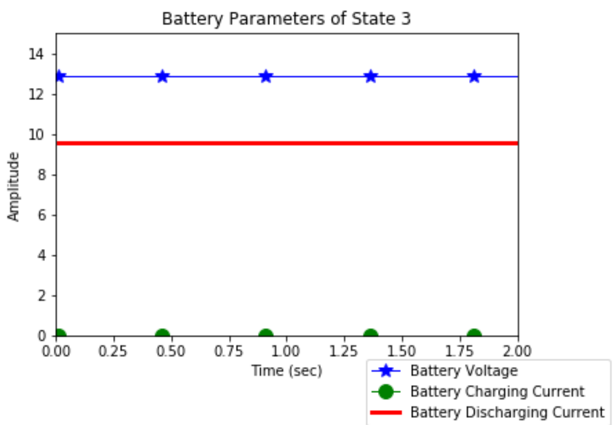


Fig. 13. Battery measurements in State 3

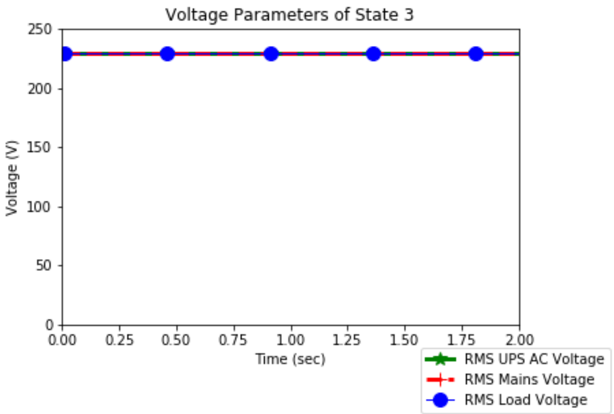


Fig. 14. Load measurements in State 3

C. State 4 - UPS State

System reliability is achieved in this state as mention in section 3.1.3. It can be seen from Figure 15 that the battery voltage is below the critical voltage and is getting charged from the utility grid. The load is supported by the mains. Both Figures 16 and 17 shows the battery and load measurements when the device is in UPS mode.

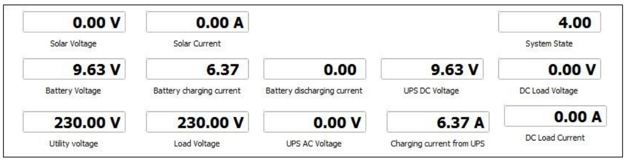


Fig. 15. Sensor measurements during State 4

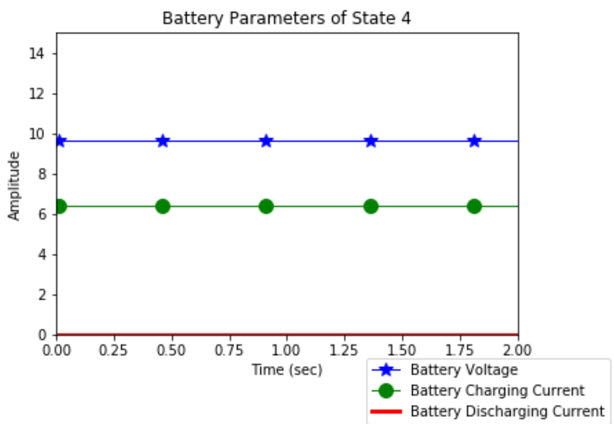


Fig. 16. Battery measurements in State 4

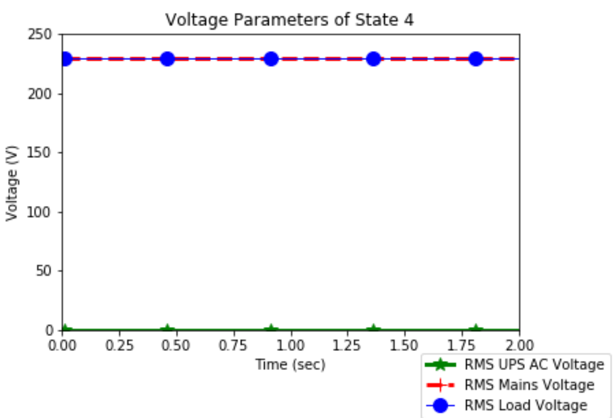


Fig. 17. Load measurements in State 4

D. State 6 - Solar Charging State

Solar energy utilization and utility savings are the two contributions of this state as mentioned in section 3.1.4. It can be seen that only solar current is used to charge the battery. The load is supported by utility grid, Figure 18. The battery charging current, load voltage and solar measurements can be seen in Figures 19, 20 and 21 respectively.

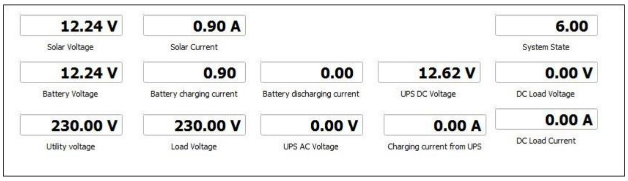


Fig. 18. Sensor measurements during State 6

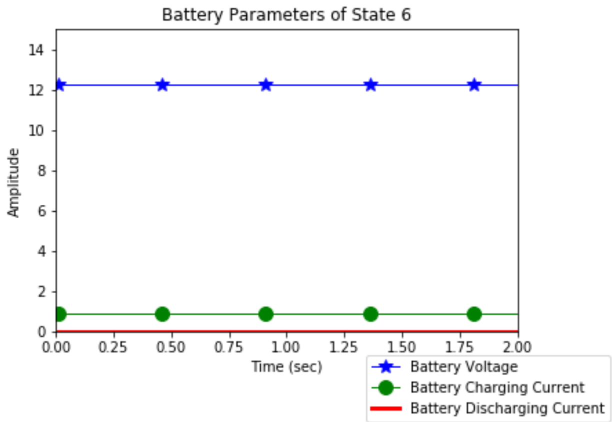


Fig. 19. Battery measurements in State 6

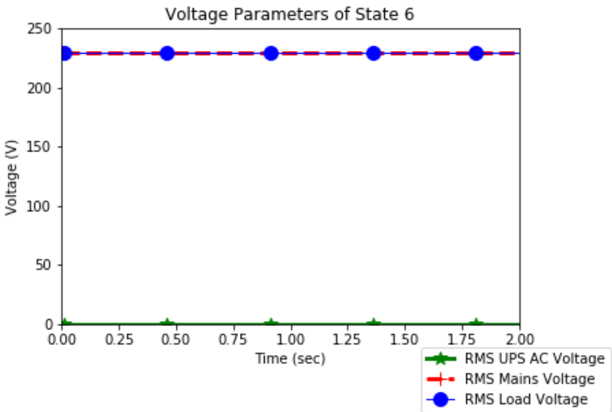


Fig. 20. Load measurements in State 6

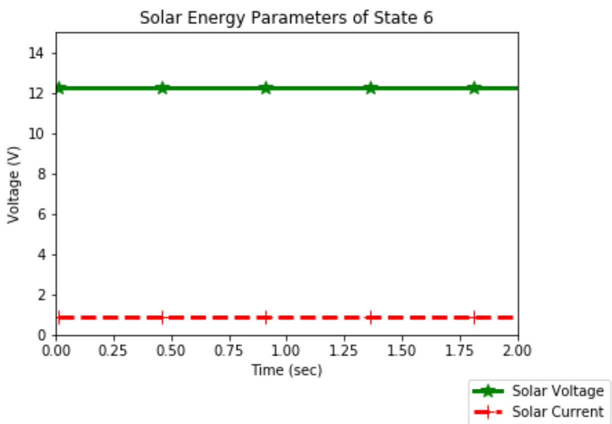


Fig. 21. Solar measurements in State 6

E. State 7 - Solar Assisted Force Trip State

As mentioned in section 3.1.5, both solar energy utilization and utility savings are achieved when the device is in state 7. Figure 22 shows that the DC load current is the sum of the solar current (Figure 23) and battery discharge current (Figure 24). The load is supported by the UPS which can be seen in Figure 25.

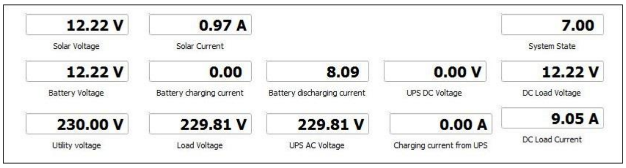


Fig. 22. Sensor measurements during State 7

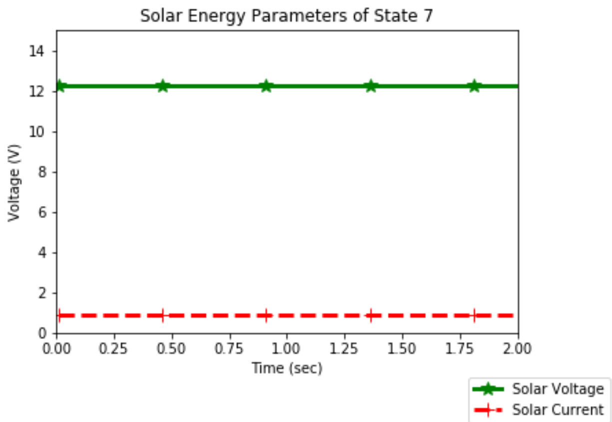


Fig. 23. Solar measurements in State 7

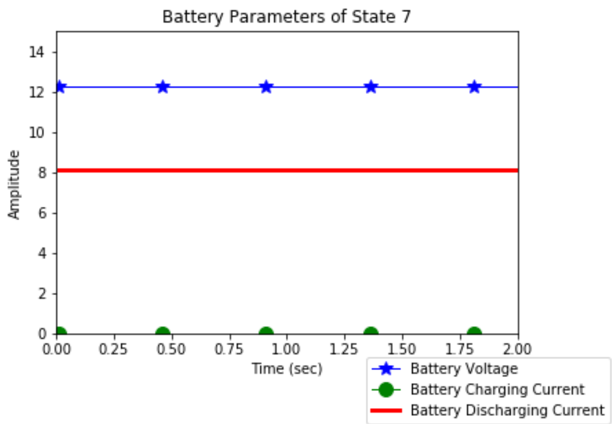


Fig. 24. Battery Measurements in State 7

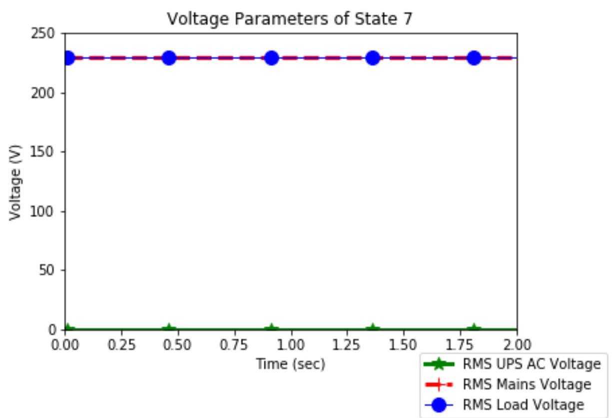


Fig. 25. Load measurements in State 7

F. State 8 - Solar Assisted Power Failure State

All the three switches are turned ON when the system is in state 8. System reliability and solar utilization are achieved during this state as mentioned in section 3.1.6. The load is supported by utility grid which is shown in Figure 26. Figure 27 shows a scenario when there is sufficient battery backup and utility grid failure occurs. It can be seen that the load gets transferred to the UPS, without affecting the system reliability.

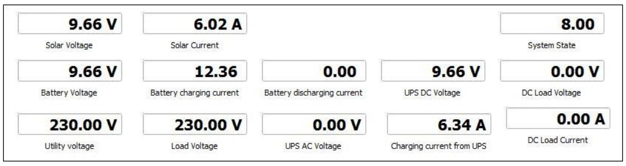


Fig. 26. Sensor measurements during State 8

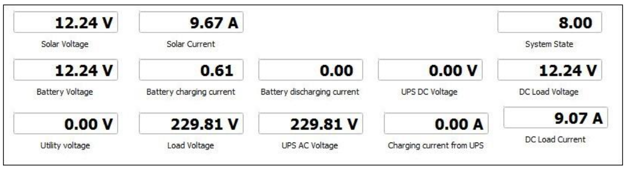


Fig. 27. Sensor measurements during Mains Failure in State 8

As discussed in section 3 and 4 each state of the system contributes towards at least one of the three fundamental requirements mentioned in section 2. Since these requirements are conflicting, the optimization of these requirements can be achieved by operating the system in these states based on the requirement. The following section 5 proposes and discusses an algorithm using which this optimization can be achieved.

V. ALGORITHM

Various dynamic variables such as solar irradiance, load pattern, available AH capacity of the battery at the user site, availability and quality of utility grid and user preference need to be considered to achieve the optimal solution discussed in section 2. This section explains an algorithm for optimizing solar utilization, backup availability and utility savings by transiting the system to any one of the states mentioned in section 3.

The default state in the algorithm will be UPS state. It is from this state, the device will transit to other state based on the solar energy, battery energy and utility availability. The following are the terms used in the algorithm.

1. Battery full voltage - Maximum allowable voltage up to which the battery can be charged. This is provided by the manufacturer.

2. Solar connectivity voltage - The minimum voltage below which the solar switch cannot be turned ON.

Below this voltage, if the battery is turned on reverse current from the battery can ow into the solar module damaging it.

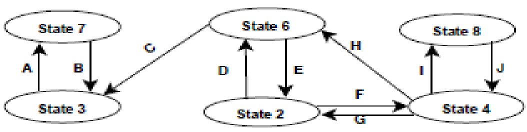
3. Battery critical voltage - Battery voltage below which the whole system operation stops.

4. Force trip exit voltage - Battery voltage till which the system can stay in force trip state (either solar assisted force trip or normal force trip state)

In the proposed algorithm, the battery is primarily charged from solar energy and utility grid acts as a backup source. The battery gets charged, whenever solar energy is available and battery is not full. Only when the battery voltage is less than the battery critical voltage, mains charging is permitted. When battery full voltage is reached, the device transits to inhibition state. This is done to protect the battery from overcharging. If solar energy is available when battery full voltage is reached, the device transits to force trip state. Once the battery voltage, falls to force trip exit voltage the device enters UPS state. If solar energy is available the device then transits to solar charging mode.

During night time the system enters State 2 where load gets supported by utility grid. In addition, battery charging is inhibited contributing to utility savings. The system transits from State 2 to State 4 during night time if there is a power failure. However, if the battery voltage goes below the set critical value, it is charged back to full using State 4. Utility grid provides both load support and battery charging just like a normal UPS system. This ensures system reliability to handle any unexpected power cuts. If the device stays in State 4 due to power failure and solar voltage becomes greater than solar connectivity voltage, the device transits to State 8 contributing to solar utilization. When utility grid becomes available, the device transits to State 6 if the battery voltage is greater than battery critical voltage. If the battery voltage falls below the critical voltage during power failure, device transits to State 4 and charges back the battery to full capacity. This is done to ensure reliability.

When the device is in State 6 and battery full voltage is reached, it transits to State 3. The load is transferred from mains to battery during this state. When the battery voltage falls below solar connectivity voltage, the device transits to State 7. If excess solar energy gets generated, both load support and battery charging are done using solar energy. If the load consumption is high, both battery and solar energy are used for supporting the same. Both states contribute to utility savings and solar energy utilization. However, when the battery voltage reaches force trip exit voltage, the device transits to State 6. Only solar energy is used for charging the battery back to full. State transition of grid-interactive systems can be seen in Figure 28.



A: Solar energy is available I battery is not full
B: Battery is full and system enters *Force Trip* if load is less than UPS capacity
C: Same as B
D: Solar voltage is above connectivity voltage
E: Solar voltage is below connectivity voltage
F:Utility grid failure
G:Utility grid available
H:Solar voltage is above connectivity voltage
I: Both utility grid and solar energy are available
J: Only utility grid is available

Fig. 28. State transitions of Grid-interactive systems

Thus, by choosing various switch combination as proposed in section 5 it is possible to optimize solar utilization, backup reliability and utility savings as mentioned in section 3.

VI. CONCLUSION

Off-grid deployment is only 4% of total SPV install of 31.69 GW in India (45; 46; 47). However, it is difficult to convince the user to put in the initial cost for solar solution due to its high CAPEX and longer pay back periods (48). Moreover, there is a maintenance cost involved to make sure the balance of systems is properly equipped to give the maximum yield (49). Thus, a solution to convert UPS systems into grid-interactive system is proposed in this paper. Also, when grid extension catches up, grid-interactive SPV systems do not become redundant. In order to achieve this, a new type of SPV classification was proposed. The proposed classification, was made into a generic framework called a three-switch model. The conversion of the system and different states involved in the systems are explained. Each state and its attributes were discussed and simulated. The paper was concluded proposing an algorithm which can be used to optimize solar utilization, reliability and utility savings. However, it is important to validate the proposed algorithm using real-time experiments. Validating the model using HIL and conducting a field test using actual hardware with a three-switch architecture is being proposed as part of future work.

REFERENCES

1. A. D. Pasternak, *Global energy futures and human development: a framework for analysis, US Department of Energy*, OakRidge (2000).
2. D. In_eld, L. Freris, *Renewable energy in power systems*, John Wiley & Sons, 2020.
3. B. Shen, G. Ghatikar, Z. Lei, J. Li, G. Wikler, P. Martin, The role of regulatory reforms, market changes, and technology development to make demand response a viable resource in meeting energy challenges, *Applied Energy* 130 (2014) 814{823.
4. K. E. Kanyarusoke, J. Gryzagoridis, G. Oliver, Re-mapping subsahara africa for equipment selection to photo electrify energy poor homes, *Applied Energy* 175 (2016) 240{250.
5. E. Gra_y, S. Kihm, Does disruptive competition mean a death spiral for electric utilities, *Energy LJ* 35 (2014) 1.
6. S. K. Sahoo, Renewable and sustainable energy reviews solar photovoltaic energy progress in india: A review, *Renewable and Sustainable Energy Reviews* 59 (2016) 927{939.
7. H. Kanchwala, *Luminous inverter/ups review* 2019, https://www.bijlibachao.com/inverters/luminous-inverter-ups-review.html(2019).
8. J. Linssen, P. Stenzel, J. Fleer, Techno-economic analysis of photovoltaic battery systems and the inuence of different consumer load profiles, *Applied Energy* 185 (2017) 2019{2025.
9. Adroit Market Research, *Energy storage battery inverter market to hit 40 billion dollars by 2025 - global industry analysis by, size, share, trends, strategy and statistics: Adroit market research*, https://www.globenewswire.com/news-release/2019/04/18/1806357/0/en/Energy-Storage-Battery-Inverter-Market-to-Hit-40-Billion-by-2025-Global-Industry-Analysis-by-Size-ShareTrends-Strategy-and-Statistics-Adroit-Market-Research.html (2018).
10. T. R. Ran Fu, R. Margolis, Utility-scale photovoltaics plus energy storage system costs benchmark, nREL,Technical Report (2018).
11. C. Breyer, A. Gerlach, Global overview on grid-parity, *Progress in Photovoltaics: Research and Applications* 21 (1) (2013) 121-136.
12. BP Energy, *Bp energy outlook*, https://www.bp.com/energyoutlook/(2018).
13. B. Chen, J. Li, X. Wu, M. Han, L. Zeng, Z. Li, G. Chen, Global energy flows embodied in international trade: a combination of environmentally extended input-output analysis and complex network analysis, *Applied energy* 210 (2018) 98-107.
14. D. G. Ockwell, J. Watson, G. MacKerron, P. Pal, F. Yamin, Key policy considerations for facilitating low carbon technology transfer to developing countries, *Energy Policy* 36 (11) (2008) 4104-4115.
15. J. Kim, Y. Suharto, T. U. Daim, Evaluation of electrical energy storage (ees) technologies for renewable energy: A case fromthe us pacific northwest, *Journal of Energy Storage* 11 (2017) 25-54.
16. J. Torriti, Understanding the timing of energy demand through time use data: Time of the day dependence of social practices, *Energy research & social science* 25 (2017) 37-47.
17. C. H. Miller, Optimized energy management system, *US Patent* 7,274,975 (Sep. 25 2007).
18. M. Beaudin, H. Zareipour, A. Schellenberglabe, W. Rosehart, Energy storage for mitigating the variability of renewable electricity sources: An updated review, *Energy for sustainable development* 14 (4) (2010) 302-314.
19. C.-J. Yang, *Reconsidering solar grid parity*, Energy policy 38 (7) (2010) 3270-3273.
20. J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. PortilloGuisado, M. M. Prats, J. I. Leon, N. Moreno-Alfonso, Power-electronic systems for the grid integration of renewable energy sources: A survey, *IEEE Transactions on industrial electronics* 53 (4) (2006) 1002-1016.
21. D. Masa-Bote, M. Castillo-Cagigal, E. Matallanas, E. Caamano-Martin, A. Gutierrez, F. Monasterio-Huelin, J. Jimenez-Leube, Improving photovoltaics grid integration through short time forecasting and self-consumption, *Applied Energy* 125 (2014) 103-113.
22. S. Swaminathan, R. K. Sen, *Review of power quality applications of energy storage systems* (1998).
23. D. Dudley, *Renewable energy will be consistently cheaper than fossil fuels by 2020, report claims* (2018). URL https://www.forbes.com/sites/dominicdudley/2018/01/13/renewable-energy-cost-effective-fossil-fuels-2020/#7a62a1044ff2
24. O. Palizban, K. Kauhaniemi, Energy storage systems in modern grids-matrix of technologies and applications, *Journal of Energy Storage* 6 (2016) 248-259.
25. C. Ogbonnaya, A. Turan, C. Abeykoon, Energy and exergy efficiencies enhancement analysis of integrated photovoltaic-based energy systems, *Journal of Energy Storage* 26 (2019) 101029.
26. F. C. Robert, G. S. Sisodia, S. Gopalan, *A critical review on the utilization of storage and demand response for the implementation of renewable energy microgrids, Sustainable cities and society* 40 (2018) 735-745.
27. A. Pandey, N. Rahim, M. Hasanuzzaman, P. Pant, V. Tyagi, Solar photovoltaics (pv): A sustainable solution to solve energy crisis, in: Green Technologies and Environmental Sustainability, *Springer*, 2017, pp. 157-178.
28. A. Pandey, V. Tyagi, A. Jeyraj, L. Selvaraj, N. Rahim, S. Tyagi, Recent advances in solar photovoltaic systems for emerging trends and advanced applications, *Renewable and Sustainable Energy Reviews* 53 (2016) 859-884.
29. A. McEvoy, T. Markvart, L. Casta~ner, T. Markvart, L. Castaner, Practical handbook of photovoltaics: fundamentals and applications, *Elsevier*, 2003.
30. M. E. Ya'acob, H. Hizam, T. Khatib, M. A. M. Radzi, *A comparative study of three types of grid connected photovoltaic systems based on actual performance, Energy Conversion and Management* 78 (2014) 8-13.
31. N. Karami, N. Moubayed, R. Outbib, General review and classification of different mppt techniques, *Renewable and Sustainable Energy Reviews* 68 (2017) 1-18.
32. R. K. Akikur, R. Saidur, H. W. Ping, K. R. Ullah, Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review, *Renewable and Sustainable Energy Reviews* 27 (2013) 738-752.
33. A. M. Aris, B. Shabani, *Sustainable power supply solutions for off-grid base stations*, Energies 8 (10) (2015) 10904-10941.
34. S. Mandelli, J. Barbieri, R. Mereu, E. Colombo, Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review, *Renewable and Sustainable Energy Reviews* 58 (2016) 1621-1646.
35. M. Meinhardt, G. Cramer, Past, present and future of grid connected photovoltaic-and hybrid-power-systems, in: 2000 *Power Engineering Society Summer Meeting* (Cat. No. 00CH37134), Vol. 2, IEEE, 2000, pp. 1283-1288.
36. Y. Chu, P. Meisen, *Review and comparison of different solar energy technologies*, Global Energy Network Institute (GENI), San Diego, CA (2011).

37. S. Mirhassani, H. C. Ong, W. Chong, K. Leong, Advances and challenges in grid tied photovoltaic systems, *Renewable and Sustainable Energy Reviews* 49 (2015) 121-131.
38. C. Lupangu, R. Bansal, A review of technical issues on the development of solar photovoltaic systems, *Renewable and Sustainable Energy Reviews* 73 (2017) 950-965.
39. K. Zipp, *What are some common types of solar pv and storage installations?* (2015). URL https://www.solarpowerworldonline.com/2015/10/what-are-some-common-types-of-solar-pv-and-storage-installations/
40. R. Gupta, M. C. Soini, M. K. Patel, D. Parra, Levelized cost of solar photovoltaics and wind supported by storage technologies to supply firm electricity, *Journal of Energy Storage* 27 (2020) 101027.
41. R. Luthander, J. Wid_en, D. Nilsson, J. Palm, Photovoltaic self-consumption in buildings: A review, *Applied Energy* 142 (2015) 80-94.
42. J. Widen, Improved photovoltaic self-consumption with appliance scheduling in 200 single-family buildings, *Applied Energy* 126 (2014) 199-212.
43. A. Bruce-Konuah, R. Gupta, Using smart energy storage to increase self-consumption of solar-generated electricity and reduce peak grid load at household and community level, in: *ECEEsummer study proceedings*, 2017, pp. 1019-1029.
44. T. Bocklisch, Hybrid energy storage approach for renewable energy applications, *Journal of Energy Storage* 8 (2016) 311-319.
45. R. Pradeep, H. Menon, S. Vijayaraghavan, R. Mohan, V. Gopal, Low acceptance of solar pv solutions to meet rural electricity demand: A case study, in: 2017 *International Conference on Technological Advancements in Power and Energy (TAP Energy), IEEE*, 2017, pp. 1-6.
46. A. Jhunjhunwala, A. Lolla, P. Kaur, Solar-dc microgrid for Indian homes: A transforming power scenario, *IEEE Electrification Magazine* 4 (2) (2016) 10-19.
47. B. Shyam, P. Kanakasabapathy, Large scale electrical energy storage systems in india-current status and future prospects, *Journal of Energy Storage* 18 (2018) 112-120.
48. F. C. Robert, S. Gopalan, *Low cost, highly reliable rural electrification through a combination of grid extension and local renewable energy generation*, Sustainable Cities and Society 42 (2018) 344-354.
49. C.-J. Yang, *Reconsidering solar grid parity*, Energy policy 38 (7) (2010) 3270-3273.

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