Energy Management System in Smart Micro-Grid

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Abstract: This paper focuses on discussing an energy management system (EMS) for a smart microgrid integrating multiple renewable sources. The task of the EMS is to efficiently balance power generation and consumption by controlling various energy sources, including photovoltaic systems, energy storage units, engine generator set and the utility grid. An EMS optimizes power flow between the microgrid components and keeps the micro-grid stable, by using different control strategies. In this microgrid, the PV system serves as the primary energy source, while the other sources of electrical energy act as backups. The energy management system prioritizes supplying load demand from either the PV system or the other sources, with load shedding during peak hours if the supplied energy is insufficient. The approaches based on StateMachine and StateFlow are discussed in this paper for enhancing the energy management system's performance.

Keywords: Energy Management System (EMS), Smart Micro-Grid (SMG) , Stateflow (SF), StateMachine (SM)

1. INTRODUCTION

Microgrids are compact electricity distribution networks that can stand alone or run connected to the main power grid. They typically consist of Distributed Generation Resources (DER), Energy Storage Systems (ESS) and various types of electrical loads [1], [2]. Microgrid can be considered a single element with respect to the main grid. The DERs in the Microgrid may be micro turbines, fuel cells, solar cells, wind turbine, or any conventional or renewable power sources [3]. Microgrids may function in an islanded or grid-connected mode, which means they either are linked to or unlinked from the large scale grid [4], [1]. Due to their capacity to offer dependable and sustainable power, especially in isolated or off-grid places, they are growing in popularity.

An Enhanced Energy Management System (EMS) in a microgrid can provide valuable real-time data and enable more accurate and effective control and management of the grid. Here are some ways an EMS can be enhanced through the use grid optimization and control. The acquired data can be used to optimize the operation of the microgrid, improve energy efficiency, and maximize renewable energy utilization. The EMS can analyze the phasor measurements to determine optimal power dispatch strategies, manage energy storage systems, and optimize the integration of distributed energy resources (DERs) such as solar panels and wind turbines.

2. ENERGY MANAGEMENT SYSTEM

Energy Management (EM) involves the proactive, structured, and systematic coordination of energy purchase, conversion, distribution, and consumption to meet requirements while considering environmental and economic objectives. The term Energy Management System (EMS) refers to a suite of power network applications that includes generation control, scheduling, and monitoring functions. It is often implemented through a computer system designed for the automated control and monitoring of energy-intensive equipment in buildings, such as heating, ventilation, and lighting systems. EMS can be deployed in various settings, from single structures to complex networks of buildings like universities, office complexes, retail stores, or industries. These systems typically include metering capabilities for electricity, gas, and water, enabling self-diagnosis, optimization, trend analysis, and annual consumption estimates.

There are several reasons why energy management plans and strategies are needed:

- ✓ They are effective in influencing daily operations and behavioral patterns.
- ✓ They have a low implementation cost.
- ✓ They can lead to significant energy and maintenance cost savings.
- ✓ They contribute to occupant satisfaction.
- ✓ They can be integrated into long-term and sustainable strategies.

However, there are challenges associated with implementing EMS, including:

- ✓ The need for support from top management and the establishment of an appropriate organizational structure.
- ✓ Training and awareness challenges.
- ✓ Resource constraints, such as staffing shortages and budget cuts.

- ✓ The capital required to renovate buildings for improved energy efficiency.
- ✓ Potential equipment failures or poor equipment performance.
- ✓ Ensuring satisfaction and support from occupants at all levels.

2.1 Smart Micro-Grid Components

Smart Micro-Grids **(SMG)** are Hybrid systems with more than one source of power. The most common type of Smart Micro-Grids contains gas or diesel-powered engine generator with PV system and energy storage unit (DG-PV-ESU). Another hybrid approach is a PV/wind system.
Figure 1 shows PV system with energy storage unit powering AC loads. This system is connected to utility power supply or diesel generator and having battery storage for backup.

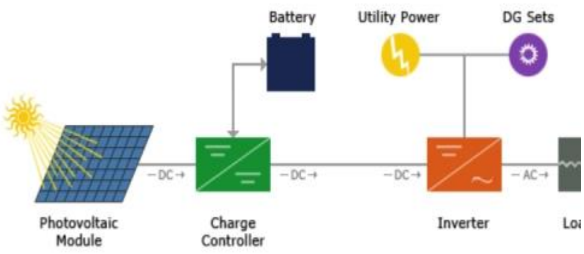

Figure .1: DG-PV-ESU Hybrid system [5]

Photovoltaic cell: The photovoltaic cell is the basic element of solar panel. It is composed of two semiconductors (usually Silicone) whose PN junction is exposed to sunlight. It utilizes the photovoltaic effect to convert light energy into electrical energy.
The PV cell is composed of a P-type semiconductor and an N-type semiconductor. The sunlight hitting the cell produces two types of electrons, negatively and positively charged electrons (holes) in the semiconductors. Electrons (-) gather around the N-type layer while holes (+) gather around the P-type layer resulting an electric current flow, when the PV cell is connected to an electrical load as shown in figure 2.

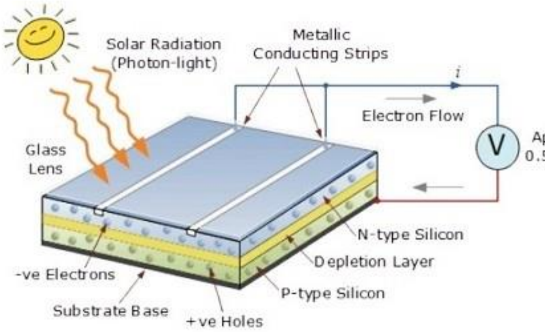

Figure. 2: Photovoltaic cell diagram [2]

Regardless of size, a typical silicon PV cell produces about 0.5 – 0.6 volt DC under open circuit, no-load conditions. The current (and power) output of a PV cell depends on its efficiency and size (surface area), and is proportional to the intensity of sunlight striking the surface of the cell. For example, under peak sunlight conditions, a typical commercial PV cell with a surface area of 160 cm^2 will produce about 2 watts peak power. If the sunlight intensity were 40 percent of peak, this cell would produce about 0.8 watt. [3]
The basic element of solar panel is composed of two semiconductors (usually Silicone) whose PN junction which is exposed to sunlight. It utilizes the photovoltaic effect to convert light energy into electrical energy.

Batteries: batteries are included to store the excess electric energy in order to use it whenever the solar energy is insufficient (during night or in cloudy days).
The batteries for PV applications are to be designed to meet the following characteristics [6]: Low cost, high energy efficiency, long life time, low maintenance, robust construction, good reliability and less self discharge, wide operating temperature.
Two types of batteries that are most common to solar energy systems such as Lead-acid batteries and Lithium-ion batteries (li-ion) that can operate over a wide temperature range and have a long cycle life which makes them more suitable for PV system. One of the disadvantages of li-ion is that they have a moderately high initial cost [7].
Property of batteries which is important in EMS is State Of Charge (SOC). It is a measurement of the amount of energy available in a battery at a specific point in time expressed as a percentage (0% = empty, 100% = full).

DC to DC converters: they are power electronic circuits that convert a dc voltage to a different voltage level. There are different types of DC to DC converter that are widely used in renewable energy systems, among them boost converter. The boost converter as shown in figure 3 consists of power switch, diode, inductor, capacitors and load.

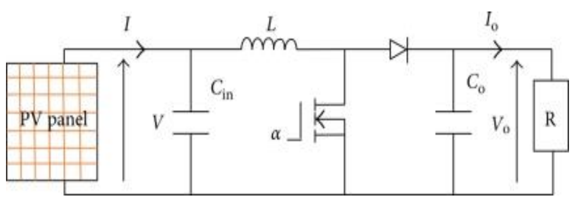

Figure .3: Boost Converter in PV System [8]

Inverter: An inverter is a key part of any solar photovoltaic system, as it converts DC power of PV module or the storage to AC power.

Maximum power point tracking (MPPT): The MPPT algorithms can be used with charge controllers which are DC-DC converter working as shown in figure 4 or with the inverter. They try to match the system load impedance with the system source impedance for transferring as much power as possible from the system source to the system load. [9]

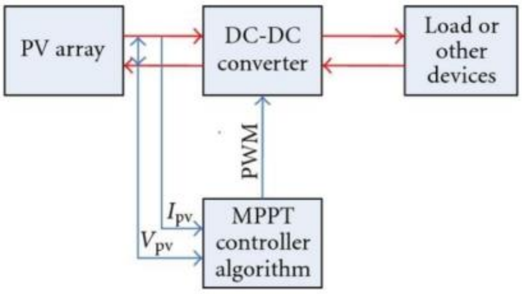

Figure. 4: MPPT system diagram [10]

The "Perturb & Observe (P&O)" algorithm is a popular and widely used MPPT due to its simplicity as illustrated in figure 5. However, there are two key concerns related with this algorithm: "stability" and "dynamics" [11, 12]. P&O algorithm works by introducing a perturbation (offset) in the Duty cycle; it compares the calculated power of PV module with the previous one. And then, the voltage with the previous value in the same method and controls the Duty cycle to track the maximum power point.

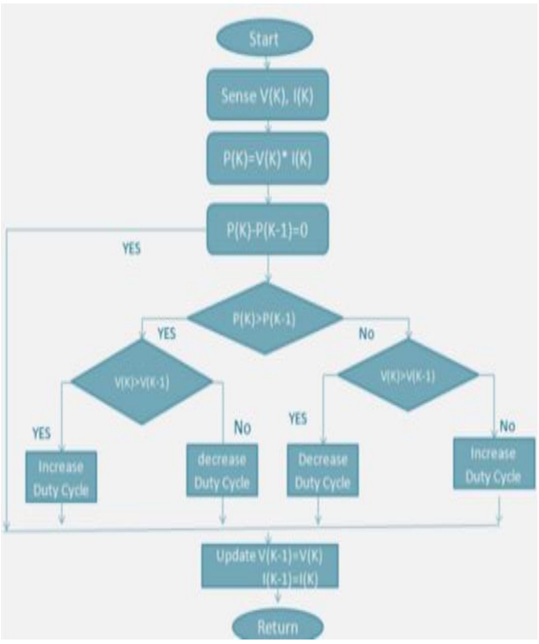

Figure .4: Flowchart of the P & O method [13]

3. State-Flow and State-Machine Based EMS in a microgrid

Supervisory control in a microgrid can be implemented through Stateflow/Statemachine, a tool within MATLAB/Simulink, to minimize reliance on backup sources. Stateflow/Statemachine allows for the design and simulation of control logic and state machines.

To minimize reliance on backup sources, the supervisory control system using Stateflow/Statemachine can follow a set of rules and algorithms to prioritize power generation sources. The control system continuously monitors the energy generation and demand within the microgrid and makes decisions based on predefined criteria.

How supervisory control can be implemented through Stateflow/Statemachine to minimize reliance on backup sources in a microgrid is discussed as follows:

Define states and transitions: Use Stateflow/Statemachine to define states representing different operating modes or conditions of the microgrid, such as grid-connected mode, islanded mode, or backup power mode. Define transitions between these states based on specific criteria, such as power availability, demand, or system stability.

Establish decision-making logic: Within each state or transition, define the decision-making logic that determines the appropriate actions to be taken. This logic can consider various factors, including the availability of renewable energy sources (such as solar or wind), battery storage capacity, grid power availability, and load demand.

Prioritize power sources: Based on the defined decision-making logic, establish rules for prioritizing power sources. For example, the control system may prioritize using renewable energy sources and battery storage first before resorting to backup sources like a diesel generator or the main utility grid.

Load shedding and power redistribution: In situations where power demand exceeds the available supply, the control system can implement load shedding algorithms to prioritize critical loads while shedding non-critical loads. This ensures that essential services continue to receive power while minimizing reliance on backup sources.

Real-time monitoring and adaptation: Continuously monitor the microgrid's energy generation and demand, as well as the state of each power source. Update the control logic in real-time based on the current operating conditions to optimize the use of available energy sources and minimize backup source reliance.

Simulation and testing: Simulate the designed supervisory control system in Stateflow/Statemachine to evaluate its performance and make necessary adjustments. Use representative scenarios and data to validate the effectiveness of the control system in minimizing reliance on backup sources.

It's important to note that the specific implementation details of supervisory control using Stateflow/Statemachine may vary depending on the microgrid's configuration, available power sources, and desired performance objectives. Customization and fine-tuning of the control system will be necessary to ensure optimal operation and minimize reliance on backup sources.

The choice between Stateflow and statemachine techniques for an energy management system depends on various factors and requirements of the specific application. Both Stateflow and

statemachine techniques have their own advantages and considerations:
To determine which technique is better for an energy management system, you should consider factors such as the complexity of the system, the available development tools, the programming language preferences, the need for real-time behavior, and the specific requirements of the application. It is recommended to evaluate the strengths and weaknesses of each technique and choose the one that aligns best with the system's requirements and the development team's expertise.

3.1 State-Flow Based EMS

Stateflow is a graphical programming environment provided by Labview/Simulink. It offers advanced modeling capabilities, visualization, and simulation tools. Stateflow allows for the design of complex state-based systems with hierarchical states, parallel states, and event-driven behaviors. It provides a more flexible and expressive modeling approach, making it suitable for complex control and decision-making systems. Stateflow is particularly useful when the energy management system involves intricate logic and complex state transitions.

To minimize reliance on backup sources, the supervisory control system using Stateflow can follow a set of rules and algorithms to prioritize power generation sources. The control system continuously monitors the energy generation and demand within the microgrid and makes decisions based on predefined criteria.

It's important to note that the specific implementation details of supervisory control using Stateflow may vary depending on the microgrid's configuration, available power sources, and desired performance objectives. Customization and fine-tuning of the control system will be necessary to ensure optimal operation and minimize reliance on backup sources.

The supervisory control block is realized using Stateflow. To satisfy the Energy management of the overall system, algorithm is developed to ensure the well functionality of different components of the system, before going to more developed algorithms. It is comprised of PV system, energy storage unit and the ac loads [14, 15].This system is connected to utility power supply or diesel generator and battery storage acts as backup. The flowchart of figure 6 shows the different paths and conditions of the energy management controller that has been developed and tested. The controller compares and analyzes different values and parameters: P_PV 'PV power', SOC 'State of Charge' of the battery and P_Load 'Load power'..

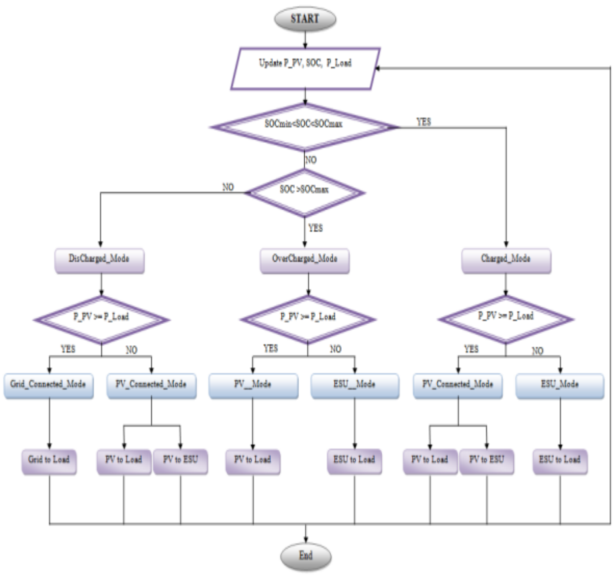

Figure .6: Flowchart of State-Flow Algorithm.

First condition to be verified is SOC of the battery, and it yields to three different modes:

- ✓ Over-charged mode: the SOC is greater than or equal SOC max .
- ✓ Discharged mode: the SOC is less than or equal SOC min .
- ✓ Charged mode: the SOC is between SOC min and SOC max .

Table I inputs and outputs of stateflow.

Input	Description	Output	Description
P_PV	The power delivered from the PV array	PV_Load	Control signal governing the connection between the PV and the load
P_Load	The power demanded by the load	PV_ESU	Control signal governing the connection between the PV and the ESU
		ESU_Load	Control signal governing the connection between the ESU and the load
SOC	State of charge of the battery	Grid_Load	Control signal governing the connection between the grid and the load

Second condition to be verified is P_PV compared to P_Load, and it yields depending on the battery mode to other different modes:

- ✓ Over-charged mode: if P_PV is greater or equal to P_Load, it recognizes PV mode. Otherwise, ESU mode is enabled.
- ✓ Charged mode: if P_PV is greater or equal to P_Load, it recognizes PV_connected mode. Otherwise, ESU mode is enabled.
- ✓ Discharged mode: if P_PV is greater or equal to P_Load, it recognizes PV_connected mode. Otherwise, Grid_connected mode is enabled.

To clarify more, each sub-mode can be described as follows:

- ✓ PV mode: The PV system is only connected to the load. Hence no battery is charging.
- ✓ ESU mode: The battery is connected and discharged through the load.

- ✓ PV_connected mode: The PV system is connected to both battery and load. Hence the load demand is supplied by the PV system and the excess power is used to charge the battery.
- ✓ Grid_connected mode: Because of their non-availability, neither PV system nor the battery are connected to the load. Hence, the grid is used to satisfy the load demand.

To apply this protocol in SIMULINK, a series of measurements and comparison operations are performed. These operations result in Boolean control signals that are used to control ideal switches; each switch connects a power source to the load (PV_Load, ESU_Load, Grid_Load) or a power source to another (PV_ESU). Table I defines the different controller inputs and outputs.

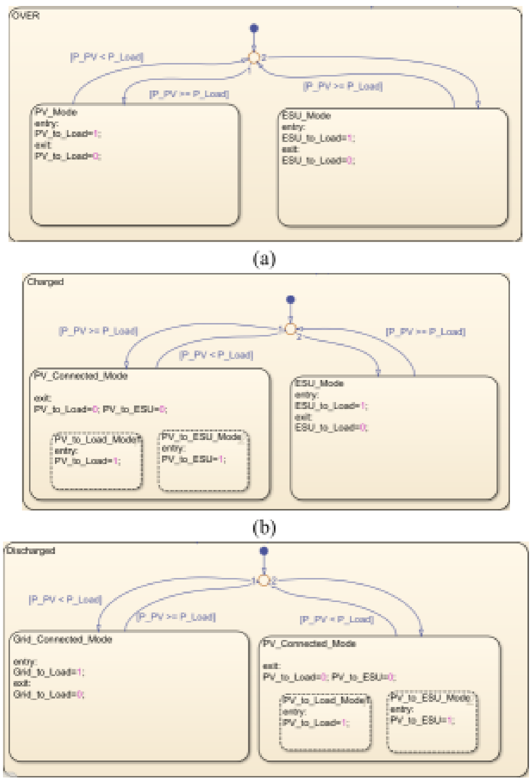

Figure. 7: the stateflow of the different modes: (a) the over charged mode (b) the charged mode (c) the discharged mode.

The Stateflow chart model illustrated in figure 7 shows the different modes of the supervisory control that can be used to satisfy the requirements.

The overall system that can be implemented using Simulink model is shown in figure 8.

3.2 State-Machine Based EMS

State machine technique is a general concept used to model systems that can exist in different states and transition between those states based on events or conditions.

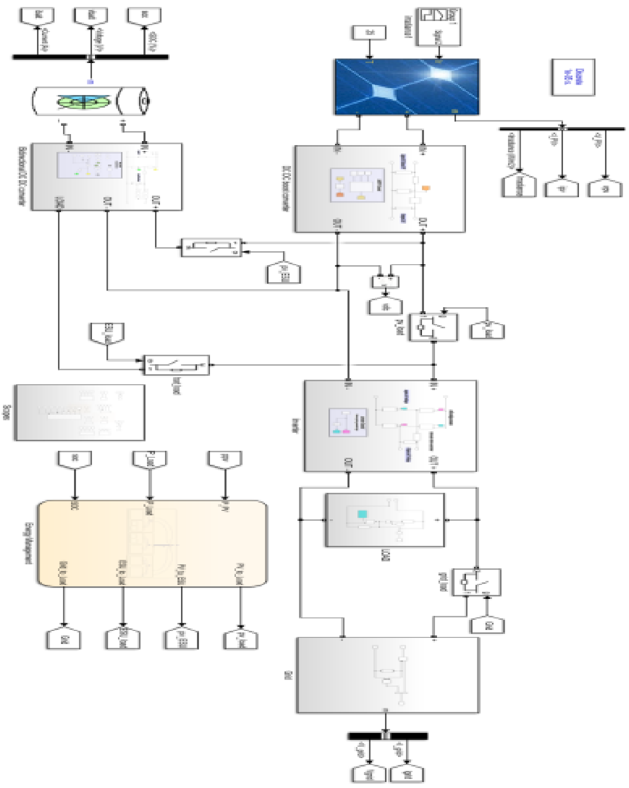

Figure.8: Overall system architecture.

It can be implemented using various programming languages or tools. State machine implementations are typically simpler and more lightweight compared to Stateflow [16]. They are often used in smaller-scale systems or applications where the state transitions and logic are relatively straightforward. State machines are suitable when the energy management system requires basic state-based control without the need for advanced modeling or simulation capabilities.

After acquiring the essential data (PV power, SOC, battery power, battery temperature, power of critical and non-critical loads and state of the grid), the algorithm will decide which mode will be enabled [18, 17]. There are three main modes: (1) Islanded Mode, (2) Grid Mode, and (3) Backup Generator Mode.

Islanded Mode: In this mode, only the power of the PV panel, battery, or a combination of both will be utilized. This mode is activated when: PV power is sufficient for critical loads. PV and Battery are sufficient for critical loads. The state of charge of the battery is greater or equal than SOCmin (20%) and it is operating in its normal condition which indicates that the temperature and current levels are within the defined range described by the manufacture.

There are five sub-modes within this mode:

PV MODE 1: PV power for critical and non-critical loads.

PV MODE 2: PV power for critical and non-critical loads and charging the battery.

SOC MODE 1: PV and Battery (discharging) to power critical and non-critical loads.

SOC MODE 2: PV for critical loads.

SOC MODE 3: PV and Battery (discharging) for critical loads.

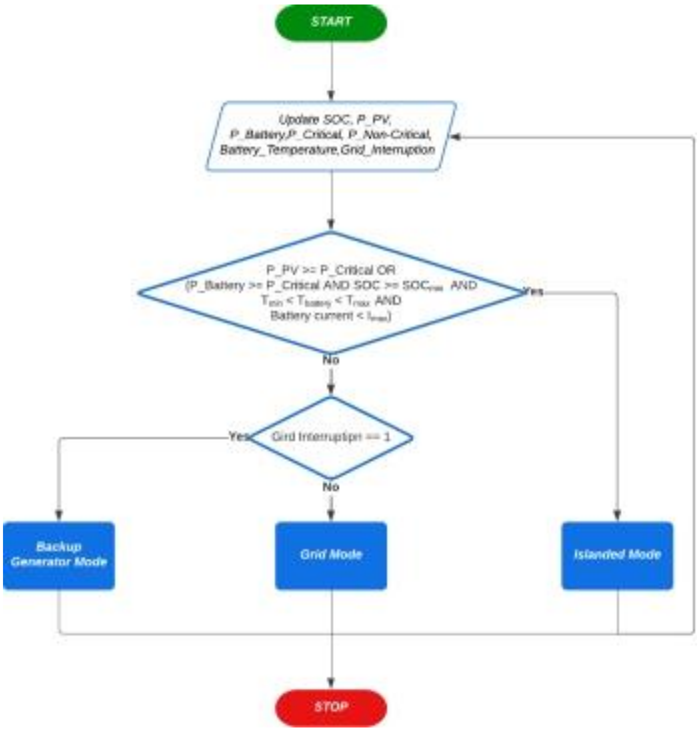

Figure.9: Flowchart of the statemachine algorithm

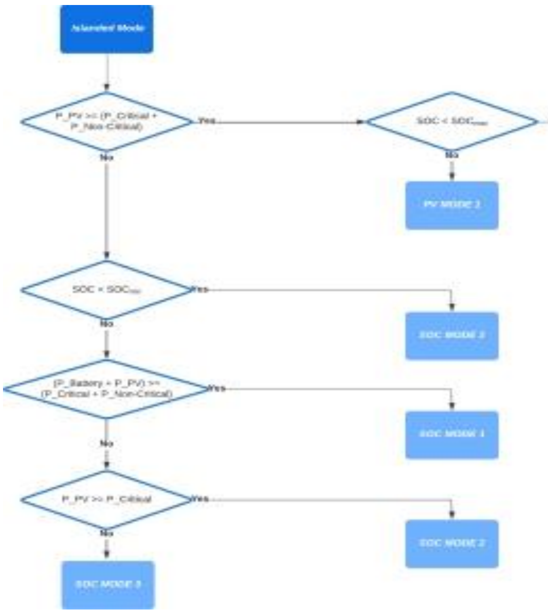

Figure.10: Flowchart of the Islanded Mode subroutine.

Grid Connected Mode: In this mode, the main grid is utilized to supply power to both critical and non-critical loads. Additionally, a rectifier is employed to charge the battery. This mode will be activated when the conditions of islanded mode are not fulfilled.

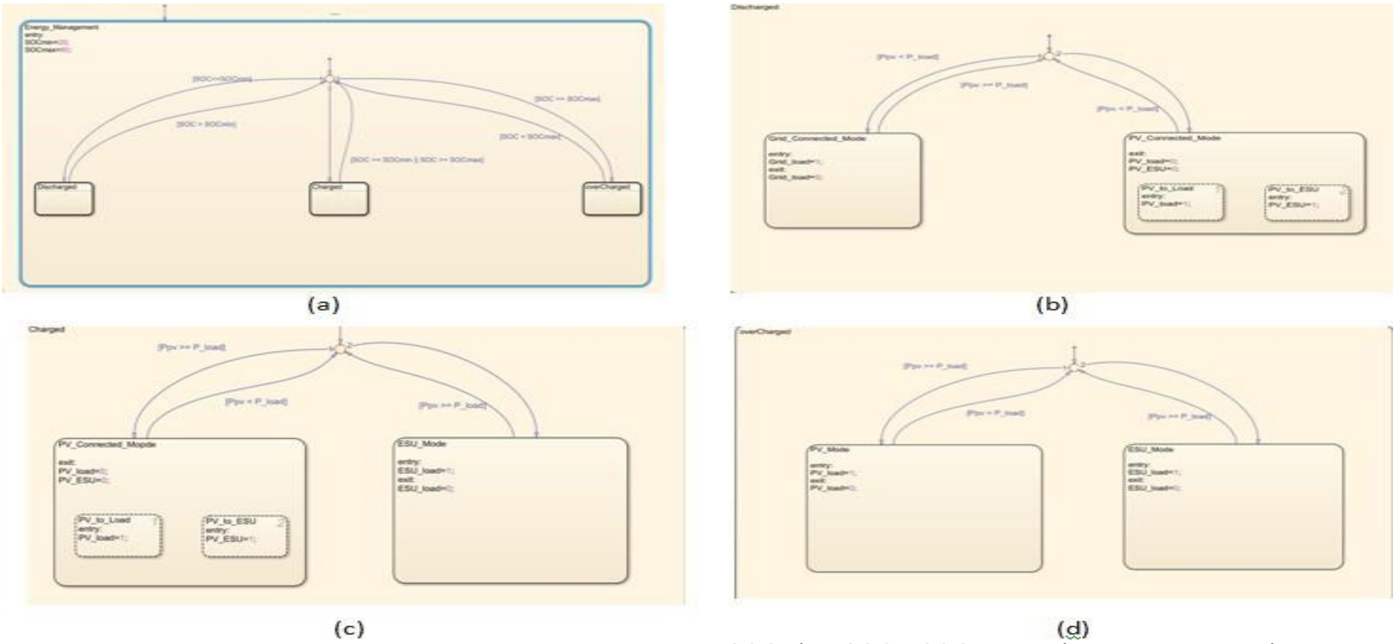

Figure.11: (a) State Chart for the EMS (b) State Chart for the Discharged Mode (c) State Chart for Charged Mode (d) State chart for Overcharged Mode .

Note: To prevent multiple switches between modes, it has been determined that transitioning to islanded mode will occur when the state of charge of the battery exceed 50% while charging in this mode, instead of the previous threshold of 20%. However, SOCmin=20% and SOCmax=80% in the other modes. Its implementation is shown in figure 11.

Backup Generator Mode: This mode activates the backup generator when the system operates in grid mode and experiences a grid interruption. The user can opt for charging the battery or not depending on the requirement of use when building the system.

After gathering the necessary data such as state of charge (SOC), photovoltaic (PV) power and load power, the algorithm will determine the appropriate mode to activate. The system consists of four modes:

Grid_Connceted_Mode: grid is connected to the load.

PV_Connected_Mode: PV panel is connected to the load and it is charging the battery.

PV_Mode: PV panel is connected to the load only.

ESU_Mode: Battery is discharging to the load.

The first mode “Grid_Conncted_Mode” will be activated when SOC < SOCmin and PV power < Load power

The second mode “PV_Connected_Mode” will be activated when: SOC < SOCmin and PV power > Load power

SOCmin<SOC <SOCmax and PV power > Load power The third mode “PV_Mode” will be activated when:

SOC > SOCmax and PV power > Load power. The last Mode “ESU_Mode” will be activated when:

SOC >SOCmax and PV power < Load power.

SOCmin< SOC <SOCmax and PV power < Load power.

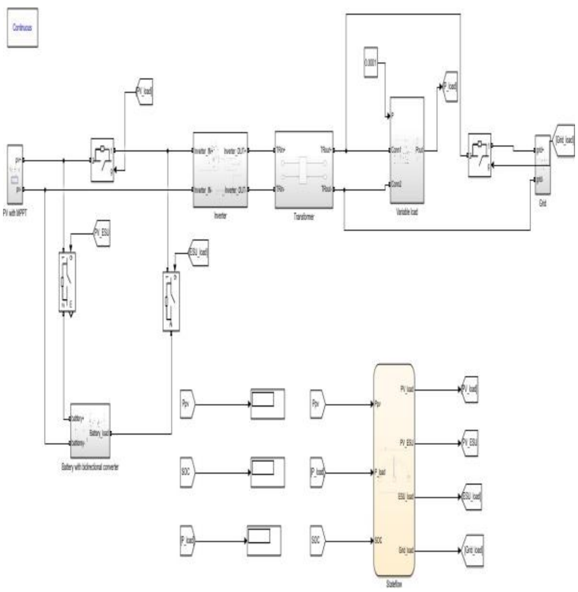

Figure. 12: Overall system Simulink Model

The Statemachine flow chart model illustrated in figure 11 shows the different modes of the supervisory control that can be used to satisfy the requirements.

The overall system that can be implemented using Simulink model is shown in figure 12.

5. OPC-UA Based EMS

OPC-UA (OPC Unified Architecture) can be used in an Energy Management System (EMS) to facilitate communication and data exchange between different components of the microgrid. Some ways of OPC-UA that can be utilized in an EMS are described below.

- ✓ Data Acquisition: OPC-UA can be used to collect data from various devices and sensors within the energy management system. It allows for standardized and secure data acquisition from different sources, such as power meters, sensors, SCADA systems, and other devices. OPC-UA provides a unified interface to access real-time and historical data.
- ✓ Interoperability: OPC-UA enables interoperability between different systems and components in an EMS. It provides a standardized communication protocol that allows seamless integration of devices and software applications from different vendors. OPC-UA ensures that data can be exchanged and understood by different components within the EMS.
- ✓ Remote Monitoring and Control: OPC-UA supports remote monitoring and control capabilities in an EMS. It allows authorized users to access and control the EMS components from remote locations, enabling efficient monitoring of energy consumption, equipment status, and system performance. Real-time data can be accessed securely, enabling remote troubleshooting and decision-making.
- ✓ Integration with SCADA and DCS: OPC-UA can be used to integrate an EMS with Supervisory Control and Data Acquisition (SCADA) systems and Distributed Control Systems (DCS). It provides a standardized interface for exchanging data between the EMS and these control systems, enabling centralized monitoring and control of energy-related processes.
- ✓ Historical Data Analysis: OPC-UA supports the collection and storage of historical data in an EMS. It enables the retrieval of historical data for analysis and reporting purposes. By leveraging OPC-UA's standardized format, historical data from different sources can be easily accessed and analyzed to identify trends, patterns, and anomalies in energy consumption and system performance.

OPC-UA plays a vital role in enabling seamless and standardized communication, data exchange, and interoperability in an Energy Management System. It enhances the efficiency, reliability, and scalability of the system by facilitating the integration of various components and enabling remote monitoring and control capabilities

OPC-UA can be used to collect data from different sources, including power meters and sensors, in an Energy Management System (EMS). How OPC-UA that facilitates data collection from the different sources is discussed as follows.

- ✓ OPC-UA Server: Power meters and sensors that support OPC-UA functionality can act as OPC-UA Servers. They expose their data as OPC-UA Variables or Data Points that can be accessed by OPC-UA Clients.
- ✓ OPC-UA Client: The EMS incorporates an OPC-UA Client component that can connect to the OPC-UA Servers of the power meters and sensors. The OPC-UA Client establishes a secure and standardized communication channel with the OPC-UA Servers to retrieve data.
- ✓ Address Space: The OPC-UA Server organizes the data from power meters and sensors into an address space. The address space represents the structure and hierarchy of the available data points. Each data point is assigned a unique OPC-UA NodeID.
- ✓ Browsing and Discovery: The OPC-UA Client can browse the address space of the OPC-UA Server to discover available data points. It can navigate the hierarchy, identify the desired variables or data points related to power meters and sensors, and retrieve their NodeIDs.
- ✓ Read and Subscribe: The OPC-UA Client uses the NodeIDs to read data values from the power meters and sensors. It can periodically poll or subscribe to data changes in real-time. The OPC-UA Client sends read or subscribe requests to the OPC-UA Server, which responds with the requested data.
- ✓ Data Access: The OPC-UA Client receives the data values from the power meters and sensors. The data can include energy consumption, voltage readings, current measurements, temperature values, and other relevant parameters. The OPC-UA Client can process and store this data for further analysis and visualization within the EMS.

Thus, through the use of OPC-UA's standardized communication protocol and address space structure, an EMS can collect data from power meters and sensors in a unified and efficient manner. OPC-UA enables seamless integration of diverse data sources, simplifies the data retrieval process, and ensures the compatibility and interoperability of different devices and systems within the EMS.

4. CONCLUSION

The paper discusses an Energy Management System (EMS) designed for a DG-PV-ESU hybrid microgrid using State-Machine and State-Flow methods. It delves into the concept of a microgrid, where diverse power generation sources and power electronic devices are integrated to fulfill specific requirements.

The supervisory control, implemented through state-flow and state-machine, aims to minimize reliance on backup sources such as the utility grid. The utilization of SM and SF not only expanded the researchers' knowledge but also provided a user-friendly tool for designing and modifying state flow charts and transitions.

In determining the most suitable techniques such as SM or SF for an energy management system, factors like the system's complexity, available development tools, programming language preferences, the need for real-time behavior, and specific application requirements should be considered. It is recommended to evaluate the strengths and weaknesses of each technique and select the one that aligns best with the system's needs and the expertise of the development team.

The improved EMS has the potential to conserve fossil fuels, mitigate global warming, and maintain a clean and green environment. Simultaneously, it reduces reliance on the grid by prioritizing the utilization of photovoltaic (PV) and Energy Storage Unit (ESU) energy.

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