An energy management system enhancement for micro-grid using state-flow

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ABSTRACT

This research focuses on the use of state-flow (SF) technique to enhance the energy management system (EMS) of a smart micro-grid that integrates multiple renewable energy sources. An EMS is responsible for efficiently balancing energy generation and electricity demand by controlling various energy sources, integrating photovoltaic (PV) system as the primary electrical source, batteries, and the utility grid or engine-generator sets as backups. A supervisory control algorithm is implemented within the EMS to optimize power flow among the micro-grid components. In this study, a control system based on the SF technique is designed, implemented, and evaluated under various operational scenarios. The proposed approach is simulated using MATLAB/Simulink and tested under different environmental and load conditions to assess its performance and validate its effectiveness. During testing, the PV system operates as the primary energy source, while the other electrical power sources function as backups. The EMS prioritizes the use of PV panels associated with the battery storage unit for satisfying the load demand. The simulation obtained results demonstrate that the proposed SF-based control approach improves the EMS performance, and hence the overall efficiency, reliability and the stability of smart micro-grid.

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1. INTRODUCTION

The rapid proliferation of renewable energies such as photovoltaic (PV) generation, wind energies, and battery energy storage systems (BESS) has positioned micro-grids as an important solution to the challenges of energy sustainability and resilience. Micro-grids can operate either in islanded mode, independently supplying local loads, or in grid-connected mode, supporting the main utility network during disturbances [1], [2]. Despite their potential, conventional micro-grids often rely on static operational strategies with limited communication and supervisory control, leading to inefficiencies in balancing power generation and demand and low reliability [3], [4].

To address these shortcomings, smart micro-grids have integrated real-time monitoring and automated control functions based on information that are acquired using advanced communication technologies. By including dynamic optimization of generation, storage, and consumption, they improve system reliability, cost-effectiveness, and renewable energy integration [4]–[7]. A central element in this architecture is the energy management system (EMS), which supervises power flow, coordinates different energy sources and ensures optimal utilization of renewable resources. Numerous EMS strategies have been investigated in the literature.

Guerrero *et al.* [8] proposed hierarchical control architectures for intelligent micro-grids, while Olivares *et al.* [9] reviewed trends in micro-grid control strategies, highlighting centralized, decentralized, and distributed methods. Rule-based EMS approaches and fuzzy logic controllers (FLC) have been proposed as EMS strategies in the literature [10], [11]. Additionally, heuristic optimization algorithms, including genetic algorithms (GA) and particle swarm optimization (PSO), have been applied in EMS frameworks to minimize cost and improve system stability [12], [13]. More recently, artificial intelligence (AI) techniques—such as machine learning (ML), reinforcement learning and deep learning-based forecasting—have been leveraged to enhance predictive capability and real-time decision-making [14]–[17]. Regardless of these improvements, numerous challenges remain unresolved.

Many existing EMS approaches are computationally intensive, limiting their real-time applicability. Others do not adequately address the intermittency of renewable sources, resulting in unnecessary reliance on backup generators or the utility grid [18]. Furthermore, while supervisory algorithms effectively optimize system performance, they often lack flexibility in managing diverse system states and transitions, especially under highly variable operating conditions such as irradiance and load. Cybersecurity vulnerabilities and high deployment costs also hinder large-scale implementation [19], [20].

This research introduces an EMS enhancement based on the state-flow (SF) technique. Unlike conventional rule-based or optimization methods that require high computational capacity, the Stateflow-based approach provides an event-driven, state-transition control mechanism that dynamically adapts to operational scenarios, including PV availability, state of charge (SOC) of battery, and load variations. This approach reduces computational overhead while offering flexible and adaptive supervisory control.The originality of this work lies in the incorporation of the Stateflow paradigm into EMS design in smart microgrids, enabling dynamic switching between operational modes with minimal reliance on external backup sources.

This control methodology of a Simulink-based Stateflow controller is used for complex EMS application, which offers significant advantages, primarily the ability to implement sophisticated parallel control logic using intuitive state machine diagrams that mimic industrial sequential function charts (SFC), a graphical programming language defined in IEC61113-3 standard. A key feature of this model-based design approach is the seamless transition from simulation to hardware implementation via automatic code generation. The optimized controller code can be efficiently deployed to diverse physical targets, including industrial programmable logic controllers (PLCs) for seamless integration into existing infrastructure, or high-performance real-time embedded ARM controllers for compact, specialized applications. This versatility ensures a scalable and efficient solution for prototyping, validating, and deploying advanced EMS control strategies. According to our knowledge, no prior study has demonstrated the systematic application of Stateflow for supervisory control of PV–battery hybrid microgrids with comprehensive scenario-based validation.

The remaining sections of this paper is structured as follows: section 2 reviews the architecture and components of the studied micro-grid. Section 3 details the design of the SF-based EMS and supervisory control model. Section 4 presents simulation scenarios, results, and discussions under varying load and irradiance conditions. Finally, section 5 concludes with key findings, emphasizing the effectiveness of the proposed approach and outlining directions for future research.

2. MICRO-GRID

A non conventional hybrid micro-grid system with more than one source of electric power including renewable energy resources is considered. The most usefull configuration of micro-grid integrates gas or diesel engine generator with a PV/wind plant as well as energy storage units (ESU) [21], [22].

Figure 1 shows micro-grid integrating PV system powering AC loads. This micro-grid can function in either islanded mode or connected to utility power supply or diesel generator with batteries as ESU for backups. Then, a smart micro-grid consists mainly of PV panels, storage energy system unit and DC-DC converters and an inverter.

2.1. Photovoltaic panels

The Simulink PV array block shown in Figure 2, include parameters such as the number of cells, open circuit voltage (Voc), and short circuit current (I_{sc}), voltage and current at the maximum power point (MPP), and the maximum power output at the MPP under standard test conditions (STC). These parameters are used to calculate five key parameters : light-generated current (I_L), diode-saturation current (I_s), diode ideality factor (n), series resistance (R_s), and shunt resistance (R_{sh}) that can be derived from single diode model (SDM) given as (1) [23]:

$$I = I_L - I_s \left[e^{\left(\frac{V+I*R_s}{n*V_t}\right)} - 1 \right] - \frac{V+I*R_s}{R_{sh}} \quad (1)$$

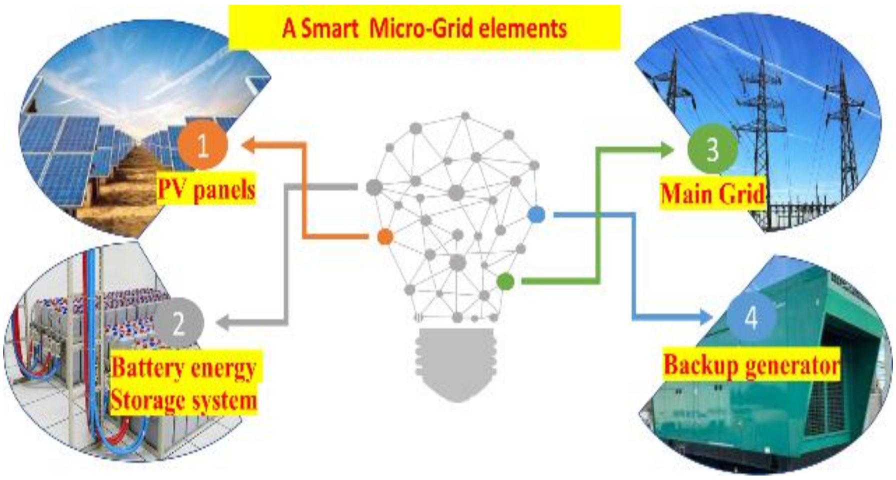


Figure 1. Micro-grid components

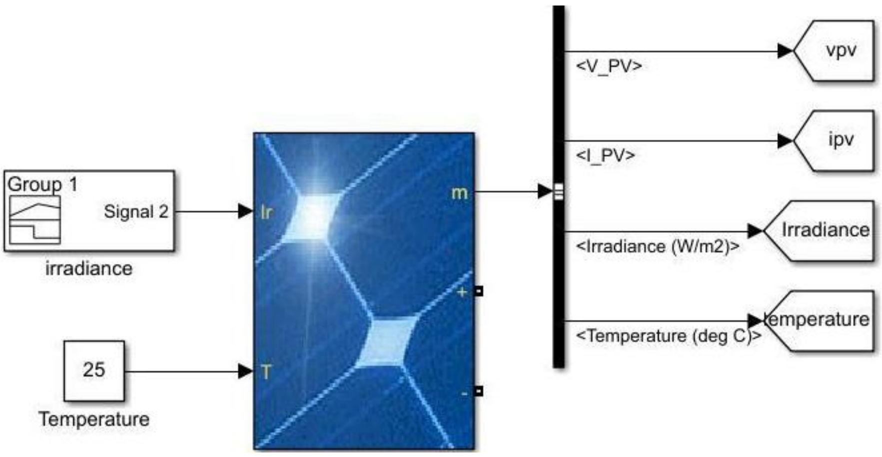
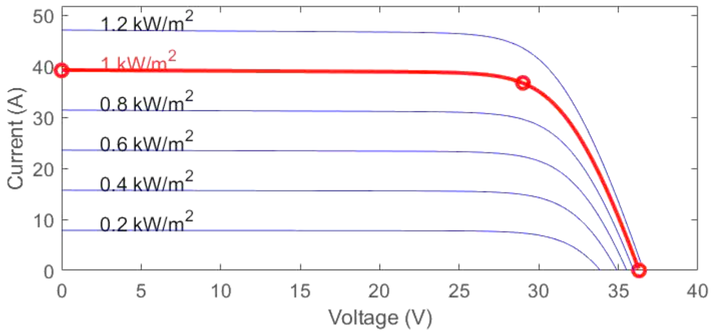


Figure 2. Simulink PV panel model

Table 1 summarizes the characteristics of the selected 1Soltech PV panel, obtained from the Simscape library in MATLAB/Simulink (2020 version). Simulation results of the PV system, illustrated in Figure 3, such as the current as function of voltage (I–V) curve as shown in Figure 3(a) and power versus voltage (P–V) characteristic (see Figure 3(b)) can be obtained under different irradiance intensities ranging from 200 W/m² to 1200 W/m² at a constant temperature of 25 °C. It is observed that variations in solar irradiance significantly influence the output current, while voltage variation is comparatively less sensitive. As irradiance decreases, the generated current reduces proportionally, leading to a corresponding decrease in output power. The open-circuit condition corresponds to zero current at Voc.

Table 1. PV module 1soltech (1STH-215-P)

Designation	Values
Maximum power (W)	213.15
Open-circuit voltage V_{oc} (V)	36.3
Voltage at MPP V_{mp} (V)	29
Temperature coefficient of Voc (%/deg/C)	-0.36099
Cells per module (N_{cells})	60
Current at MPP Imp (A)	7.35
Temperature coefficient of I_{sc} (%/dec.C)	0.102



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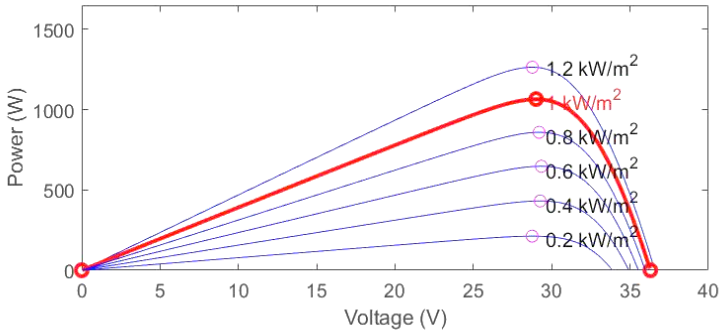


(b)

Figure 3. PV array; (a) I as function of V characteristic and (b) P versus V curve

2.2. Energy storage unit

Batteries are generally used for storing excess electrical energy generated by PV panels in ESU, which store surplus PV energy and release it when generation is insufficient, such as during nighttime or cloudy conditions. Common technologies include lead-acid and lithium-ion batteries, with lithium-ion cells being preferred due to their higher energy density, improved efficiency, and longer operational lifetime, despite their higher cost.

An important parameter of batteries for an EMS is the SOC, which measures the available energy in a battery at a particular time, stated as a percentage [24]. In this study, the battery model is implemented using Simulink/Simscape tools, as illustrated in Figure 4. The model provides terminal voltage (V_{batt}) using a measured current (I_{batt}) at dc bus and the battery's nominal capacity (C_{rated}). SOC is estimated using the Coulomb counting technique, expressed as:

$$SOC(t) = SOC(t_0) + \frac{1}{C_{rated}} \int_{t_0}^{t} I_{batt}(t)\, dt \quad (2)$$

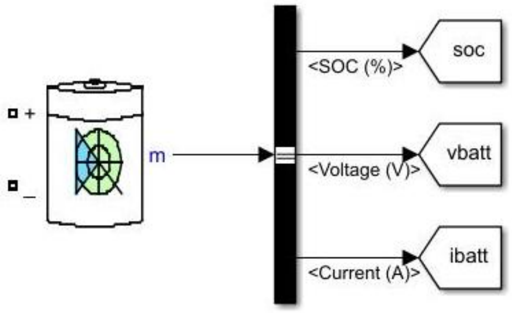


Figure 4. Simulink battery model

2.3. Bidirectional DC-DC converter

The battery is connected to the DC bus through a bidirectional DC-to-DC converter, as shown in Figure 5. This converter regulates charging and discharging process of the battery while maintaining stable DC bus voltage. Its topology includes two controlled IGBT switches with anti-parallel diodes besides an inductor and a DC-link capacitor on the battery side. These power semiconductor devices regulate the direction of power flow and protect the battery from abnormal operating conditions such as overcharging and deep discharge.

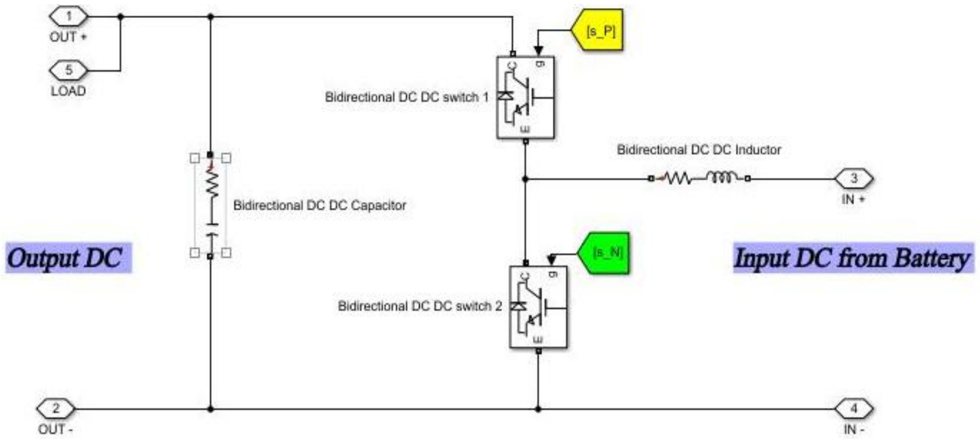


Figure 5. Simulink DC-DC bidirectional battery controller circuit

During charging operation, electrical energy is transferred from the DC bus to the battery, and the converter operates in a buck mode. However, during discharge mode, energy flows from the battery to the DC bus, and the converter behaves as boost stage. A PI-based voltage regulator is employed to maintain DC bus stability, using PWM signals to control the switching devices.

2.4. Solar charge controller (DC-to-DC converter with maximum power point tracking)

The PV panel is connected to the DC bus via a solar charge controller acting as a boost converter, as illustrated in Figure 6. This stage that includes an inductor, diode, power switch, and output capacitor, regulates voltage levels between the PV panels and the DC bus. A DC-link capacitor is also incorporated to reduce voltage fluctuations between generation and load, while simultaneously reducing current ripples caused by switching actions.

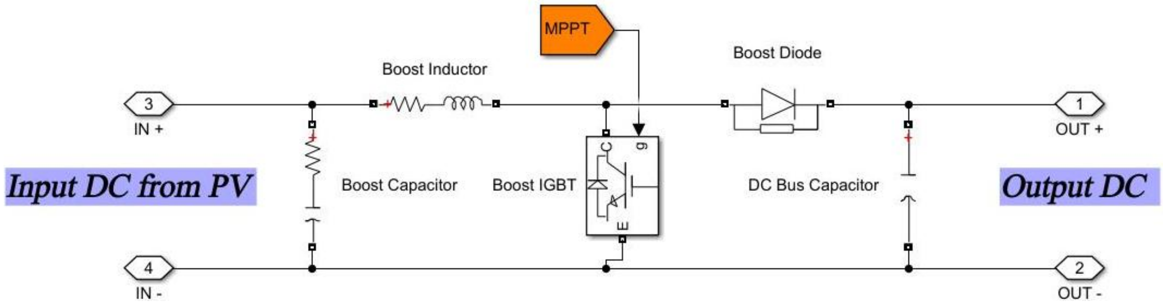


Figure 6. DC-DC converter circuit

2.4.1. Maximum power point tracking

To enhance the performance of the PV panel, track its maximum power, the maximum power point tracking (MPPT) algorithm using the perturb and observe (P&O) illustrated in Figure 7 is implemented [25]. This technique, which widely used, adjusts the duty cycle of the DC-to-DC converter to continuously search for the operating point where PV output power is maximized [26]. Its operation is based on slightly perturbing the system voltage Vpv and noting the resulting change in output power. Then, the operating point is adjusted accordingly using PWM. One disadvantage of this method is the oscillations around the MPP under rapidly changing environmental conditions. The control logic is implemented in MATLAB using a function block, where measured PV voltage and current are processed to generate the appropriate PWM duty cycle for the switching device.

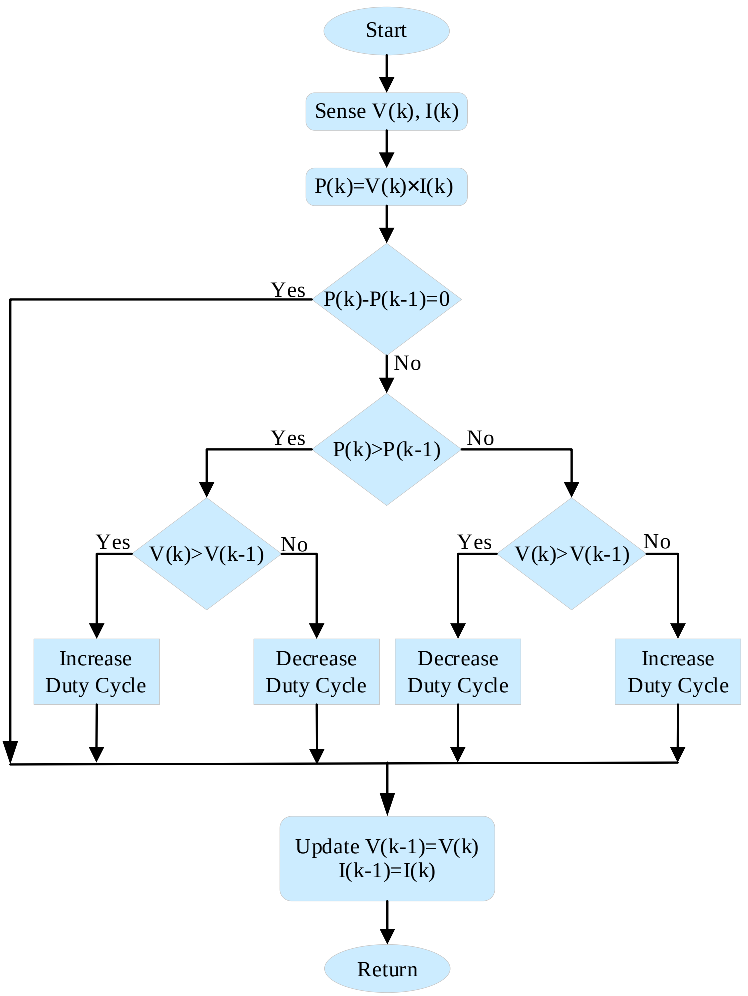


Figure 7. Flowchart of the P&O technique [25]

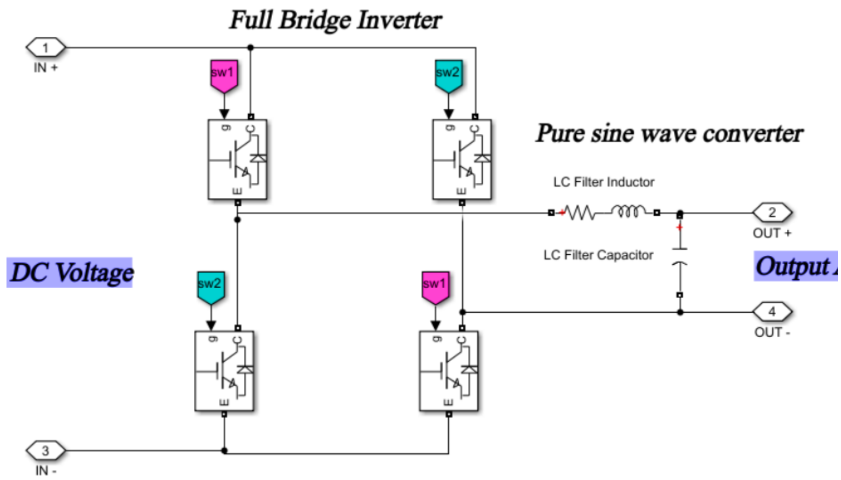
2.5. Inverter

The inverter is used to transform the DC voltage of the DC bus (supplying from either the PV array or the battery) into a single-phase AC voltage suitable for feeding the AC load. The inverter topology consists of a full-bridge including four controlled IGBT switches, each equipped with anti-parallel diodes. The direct switching operation of the full-bridge inverter produces a square-wave AC output voltage. However, to ensure compatibility with the utility grid and standard AC loads, the output voltage must meet two essential requirements: i) an appropriate RMS magnitude corresponding to 230 V and ii) a low-distortion sinusoidal waveform.

These requirements can be achieved by introducing an LC filter at its output, which attenuates high-frequency switching harmonics and shapes the square-wave voltage into a near-sinusoidal waveform with reduced total harmonic distortion (THD). The inverter circuit, including the LC filter and associated with its control (PWM signal generator), is presented in Figure 8.

By properly selecting the carrier frequency and modulation index, the PWM technique allows precise control of both the output frequency (fixed at 50 Hz) and the RMS magnitude of the inverter voltage. Furthermore, high-frequency switching shifts harmonic components to higher frequencies, facilitating their attenuation through the LC output filter shown in Figure 8(a) and ensuring a low-distortion sinusoidal voltage at the load terminals [26].

In this approach, the inverter switching signals are generated using a PWM pulse generator block available in the MATLAB/Simulink library as illustrated in Figure 8(b). The control scheme compares a high-frequency carrier signal with a 50 Hz sinusoidal reference signal. The resulting modulated pulses are used to drive the IGBT switches in the full-bridge inverter, turning them ON and OFF in a controlled manner.



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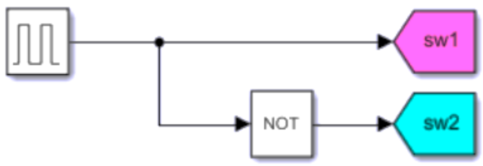


(b)

Figure 8. Simulink model of inverter and its control circuit; (a) inverter power circuit and (b) inverter control circuit (pulse generator logic)

3. STATE-FLOW BASED 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 EMS refers to a suite of power network applications that includes generation control, scheduling, and monitoring functions. It is often implemented through a microprocessor based system designed for the automated control and monitoring of energy-intensive equipment installed in power systems, smart micro-grids and smart homes and buildings. EMS can be deployed in various settings, from single structures to complex networks. These systems typically include metering capabilities, enabling self-diagnosis, optimization, trend analysis, and annual consumption estimates [27], [28].

There are several reasons why EMSs are needed:

– They are effective in influencing daily operations and behavioural patterns.
– 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 such as in smart grid.

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.
– Potential equipment failures or poor equipment performance.

3.1. State-flow

SF is a graphical programming environment provided by MATLAB/Simulink. It offers advanced modelling capabilities, visualization, and simulation tools. SF technique allows for the design of complex state-based systems with hierarchical states, parallel states, and event-driven behaviours. SF provides a more flexible and expressive modelling approach, making it suitable for complex control and decision-making systems. It is particularly useful when the EMS involves complicated logic and complex state transitions.

To minimize reliance on backup sources, the supervisory control system using SF 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 micro-grid and makes decisions based on predefined criteria.

It is important to notice that the implementation specification details of supervisory control using SF may vary depending on the micro-grid's configuration, availability of 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.

3.2. Supervisory control modelling

Supervisory control is implemented using SF. To fulfil the EM requirements of the entire system, an algorithm is developed to ensure the proper functioning of different micro-grid components. It consists of PV panels, ESU, the main power grid or engine-generator set and the load.

First condition to be verified is SOC of the battery (ESU), and it yields to three different modes:
- Charged mode: the SOC is between SoCmin and SoCmax.
- Discharged mode: the SOC is less than or equal SoCmin.
- Over-Charged mode: the SOC is greater than or equal SoCmax.

Second condition to be verified is P_PV compared to P_Load, and it yields depending on the battery mode to other different modes or sub-modes:
- PV mode: the PV system is only connected to the load. Hence no battery is charging.
- ESU mode: the battery supplies the load enabling discharging proces.
- PV_connected mode: the PV system provides power to both ESU (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: due to non-availability of power from all the renewable sources, neither PV system nor the battery is connected to the load. In this mode, only the main grid satisfies the load demand.

To clarify more, the previous battery-modes can be more described as follows:
- Over-Charged mode: if P_PV is greater or equal to P_Load, it recognizes PV_connected 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.

A single consistent flow diagram to summarize SoC - based transitions is illustrated in Figure 9. The flowchart shown in Figure 10 illustrates the various paths and conditions of the EM controller that has been developed and tested. The controller compares and analyses different measured values and parameters, including P_PV (PV power), SOC of the ESU (battery), and P_Load (Load power).

To validate this approach using Simulink/MATLAB, measurements and comparative studies are performed. These operations result in Boolean control signals that are used to control relays; each relay connects a power source to the load (PV_Load, ESU_Load, and Grid_Load) or a power source to another one (PV_ESU). Table 2 outlines the different controller outputs and inputs.

Figure 11 shows the SF Simulink models with the different modes in Figure 11(a) and the supervisory control developed to satisfy the requirements in Figure 11(b). Following the modelling process in MATLAB/Simulink, the complete system has been implemented, as depicted in Figure 12. The use of SF reduces the computational complexity of the problem solving and effectively demonstrates the behaviour of the EMS.

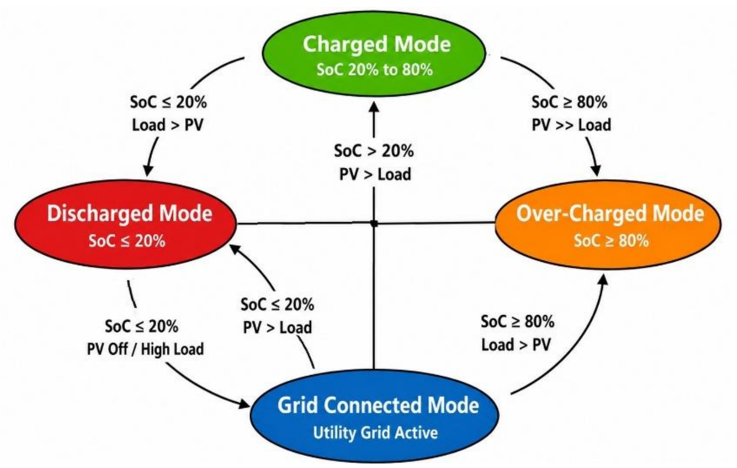


Figure 9. SOC based transition diagram

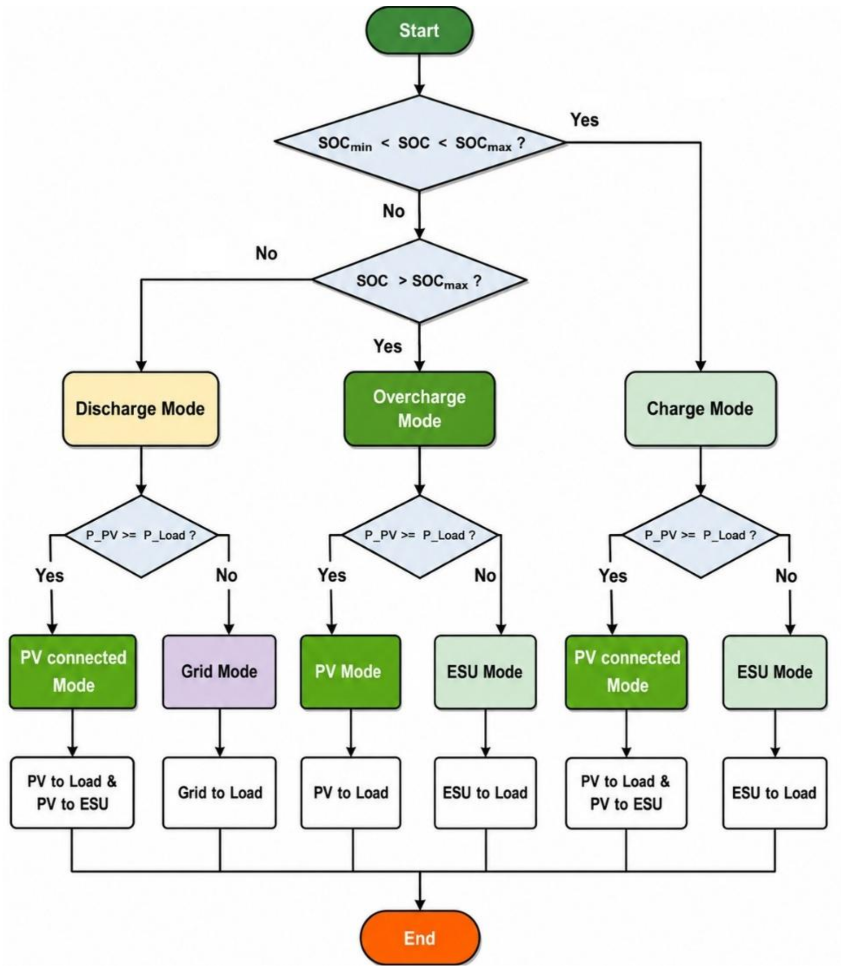
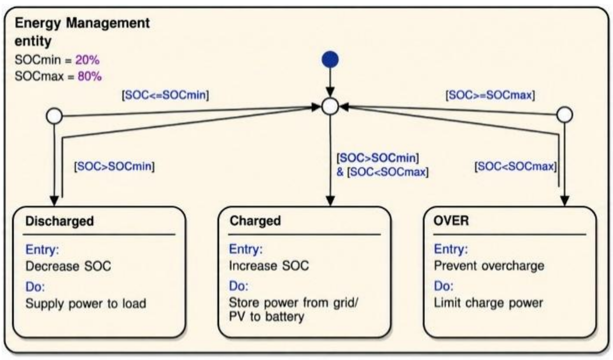


Figure 10. Flowchart of proposed algorithm

Table 2. Inputs and outputs of SF

Input/output	Description
P_PV	The power provided by PV array
P_Load	The power needed by the load
SoC	SoC of the battery
PV_Load	Control signal for connecting the PV to the load
PV_ESU	Command signal for connecting the PV to the ESU
ESU_Load	Control signal governing the connection between the ESU and the load
Grid_Load	Control signal governing the connection between the grid and the load



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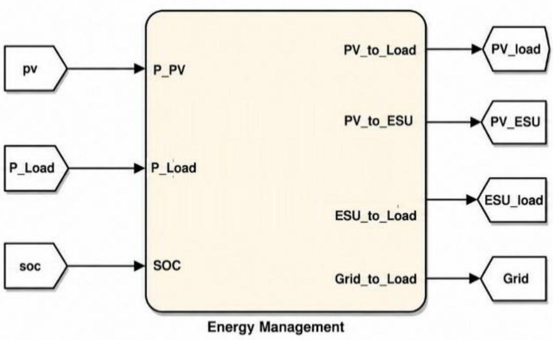

(b)

Figure 11. SF based EMS Simulink model; (a) SF of the three modes Simulink model and (b) EMS with components in Simulink

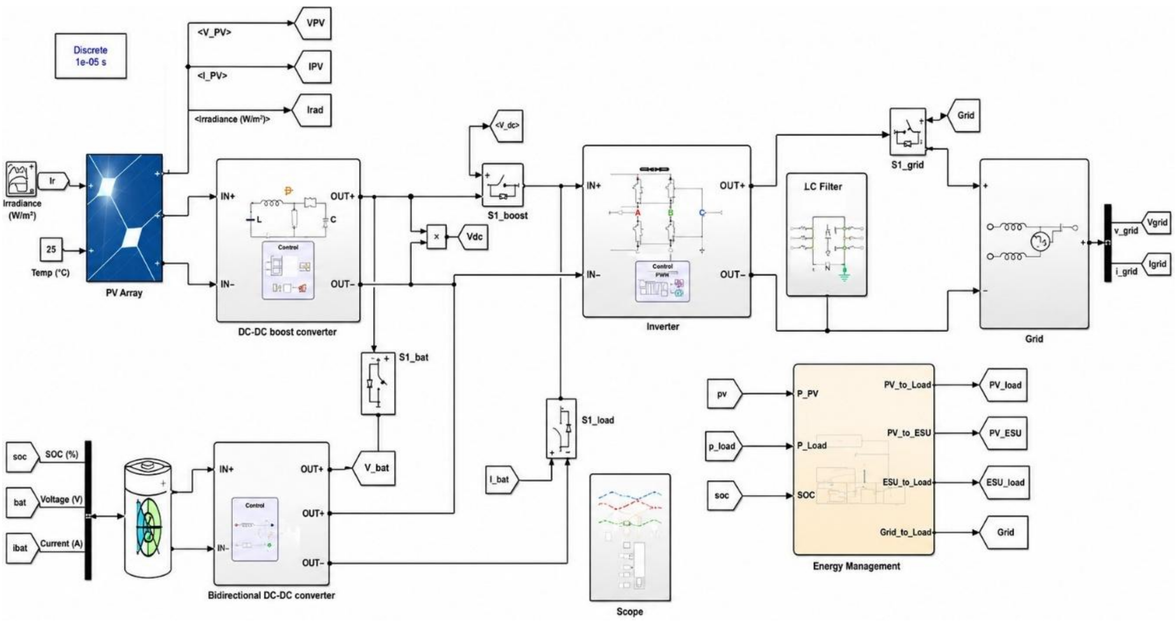

Figure 12. Microgrid Simulink model associated with SF based EMS

4. SYSTEM SIMULATION RESULTS AND DISCUSSION

In order to test all possible cases and evaluate the performance of SF based EMS implemented in microgrid Simulink model illustrated in Figure 12, different scenarios have been performed. The irradiance and the load demand are adjusted to satisfy the proposed scenarios. Different simulated scenarios (shown in Figure 13) that include all the possible situations and modes are given as follows.

4.1. Scenario 1: [0–240 simulation time in seconds] (battery discharge)

The battery is initially set at a SOC of approximately 23%, which is above the minimum SOC threshold (SOCmin=10%), leading to the selection of the Charged mode initially. The load's power demand varies between 150 W and 400 W, which cannot be supplied by the PV panels due to the absence of irradiance (e.g., during night hours), as shown in Figure 13(a). As a result, the system switches to ESU mode, utilizing the ESU and transferring a power from the battery to the load (discharging process), as illustrated in Figure 14.

4.2. Scenario 2: [240–300 simulation time] (grid connection)

The continuous discharg of the battery eventually brings the SOC down to the SoCmin (10%), triggering a switch to Discharged mode. This operation limit is used to avoid deeper discharge of the battery which is considered as battery stress. At this point, the power demand has increased to around 400 W, but the PV panels still cannot meet the load demand, as shown in Figure 13(b). In such scenarios, the system prioritizes supplying the load from the grid instead of the battery to avoid deep discharge. This activates the Grid-connected mode, as illustrated in Figures 13(c) and 14.

4.3. Scenario 3: [300–940 simulation time] (photovoltaic availability, sufficiency, and excess)

The PV panels are now exposed to sunlight with an irradiance of 1220 W/m² shown in Figure 13(a), generating a MPP of approximately 1320 W shown in Figure 13(b). This allows the system to easily meet the 1285 W load demand by selecting PV-connected mode, as shown in Figure 13(c). The excess power is directed to the battery, rising the SOC above the SoCmin, allowing the system to return to Charged mode.

During this period in Charged mode, the PV panel supplies more power than the demand, fully supplying the load. If the SOC is below the SOCmax (80%), the supervisory control enables the charging process until the SOC reaches the upper limit of SOCmax. This is achieved by maintaining the PV-connected mode, as illustrated in Figure 14.

4.4. Scenario 4: [940 s-1040 s] (photovoltaic availability and sufficiency, battery fully charged)

As the ongoing charging process brings the battery to a full charge, reaching SOCmax (80%), the supervisory controller halts the charging process and switches to Over-Charged mode to prevent the battery from overcharging. In this mode, further charging of the battery is prohibited for maximizing battery ifetiem the protect it from damage. Meanwhile, due to the continued sufficiency of the PV system, the load remains supplied by the PV panel, meeting the load demand shown in Figure 13(d), with PV mode enabled, as illustrated in Figure 14.

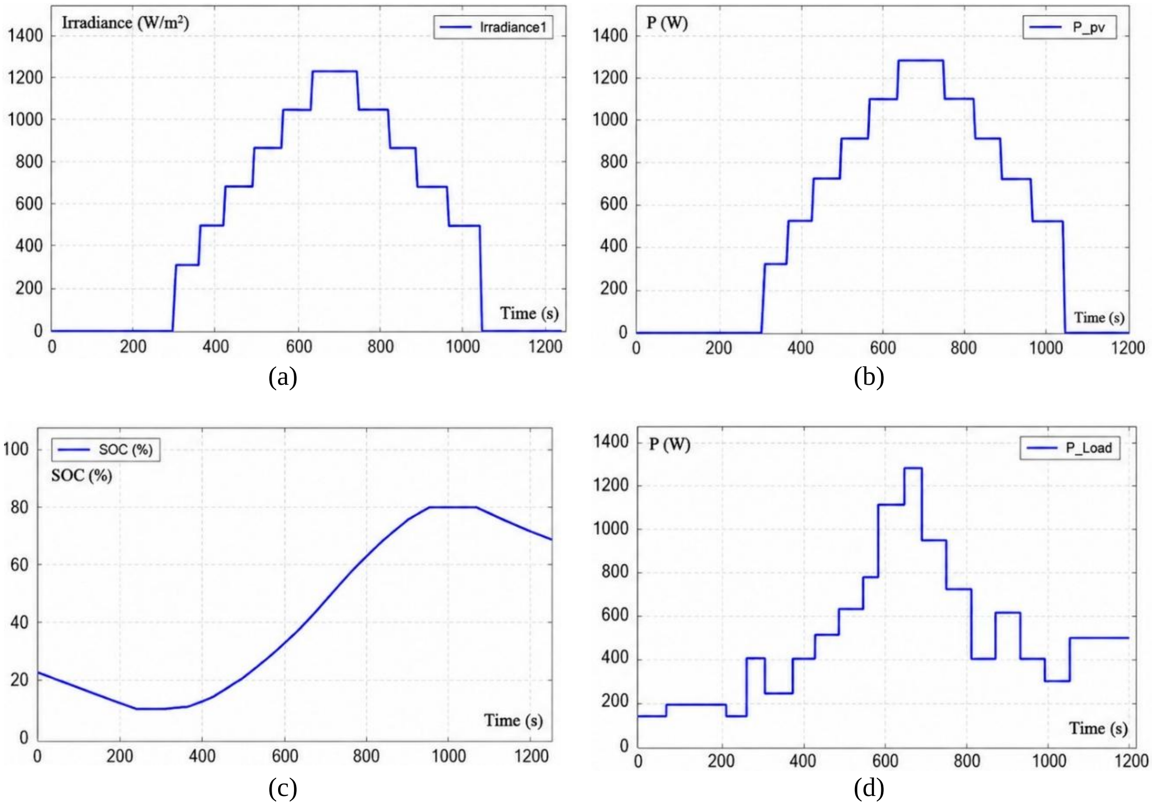

Figure 13. Power flow scenarios; (a) irradiance variation, (b) PV power, (c) SOC of the battery, and (d) load power demand

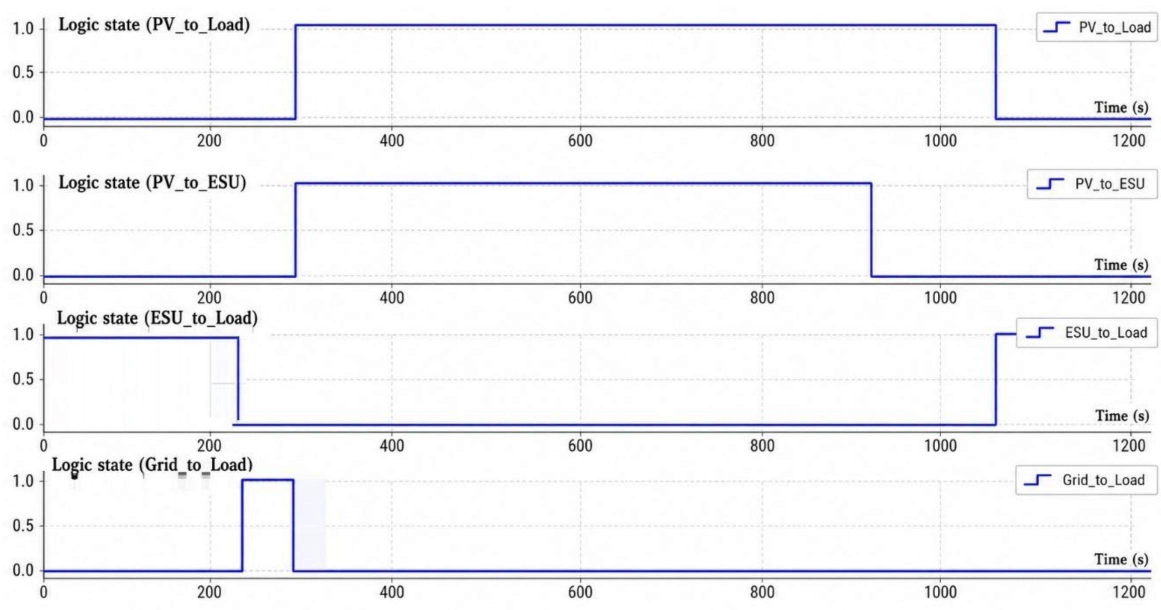

Figure 14. The order of the modes passed by the supervisory control

4.5. Scenario 5: [1040 s-1200 s] (battery discharge)

The last scenario ensures a seamless transition between all supervisory modes, making it preferable to revert the system to its initial mode, Charged mode. To achieve this, the energy collected during daylight hours should be utilized at night to minimize reliance on the power grid. Without irradiance input, the PV system cannot supply the load, leading to the battery discharging to satisfy the load as illustrated in Figure 13.

The supervisory controller sequentially transitions through all primary and secondary modes, as shown in Figure 14. The SF-based EMS outputs (switch states) are depicted in Figure 15. Table 3 summarizes the supervisory logic. This formalization eliminates ambiguous overlapping rules common in heuristic EMS.

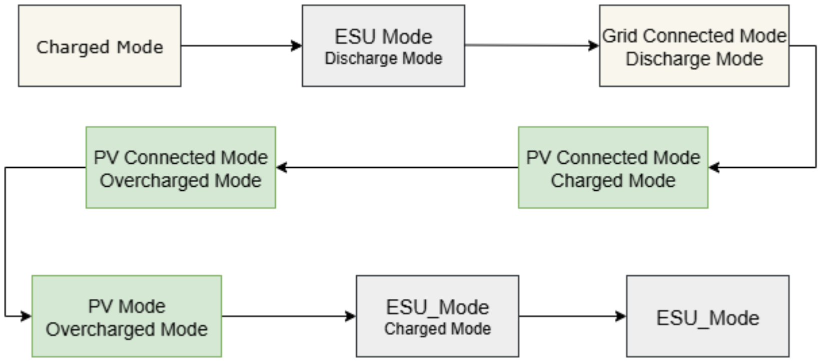

Figure 15. SF outputs (switches state)

Table 3. State transition logic

Current state	Condition	Next state	Action
Grid-connected	Grid fault detected	Islanded	Disconnect grid
Islanded	Grid restored	Grid-connected	Synchronize
Charging	SoC≥SoCmax	Idle	Stop charging
Discharging	SoC≤SoCmin	Load shedding	Disconnect non-critical load
Islanded	ΔP>0 and SoC<SoCmax	Charging	Store surplus
Islanded	ΔP<0 and SoC>SoCmin	Discharging	Supply deficit

The proposed configuration effectively meets the power demand, charges the battery with excess energy, reduces the use of conventional power generation during daylight hours, and transitions to the backup system (ESU) during night-time.

The proposed SF-based EMS was validated in MATLAB/Simulink under five operating scenarios designed to activate all supervisory states under varying irradiance and load conditions. The evaluation addressed four objectives: (H1) minimizing grid dependency, (H2) ensuring battery protection, (H3) guaranteeing reliable load supply, and (H4) maintaining low computational complexity.

The controller successfully transitioned between Charged, Discharged, and Over-Charged modes without oscillation or logical conflict. Table 4 summarizes the operational scenarios. The supervisory controller prioritized PV generation whenever available, redirected excess energy to battery charging, and activated the grid only when both PV generation was unavailable and the SOC reached its minimum threshold (10%).

Table 4 summarizes the operational scenarios

Scenario	Irradiance	Load	SoC behavior	Mode	Main source
S1	0 W/m²	150–400 W	23%→10%	ESU	Battery
S2	0 W/m²	≈400 W	≤10%	Grid	Utility
S3	1200 W/m²	≈1285 W	10%→80%	PV-connected	PV+charging
S4	1200 W/m²	≈1285 W	≥80%	PV	PV
S5	0 W/m²	Variable	80%→~30%	ESU	Battery

Key performance indicators (KPIs) confirm the effectiveness of the proposed approach:
Grid utilization: ≈5% of total simulation time, validating reduced dependency (H1).
Renewable utilization: ≈100% during irradiance periods.
SOC compliance: strictly maintained within 10–80%, ensuring battery protection (H2).

Load continuity: no interruption observed (H3).
Computational demand: event-driven state-machine logic without iterative optimization (H4).

During irradiance availability (S3–S4), PV power fully supplied the load and charged the battery until SOCmax (80%), after which charging was automatically disabled to prevent overcharging. In deficit conditions (S1, S5), the battery supplied the load until SOCmin (10%) was reached, at which point grid support was activated. This deterministic logic ensures renewable prioritization, battery health preservation, and uninterrupted supply.

Compared to optimization-based (GA, PSO, and MPC) and EMS strategies (rule-based, AI, and fuzzy), the proposed SF-based controller offers lower computational complexity and deterministic transitions. While optimization methods may enhance economic dispatch, they often require significant processing resources, limiting real-time embedded implementation. The SF paradigm provides a practical trade-off between flexibility, simplicity, and industrial deployability, particularly for PLC and embedded ARM controllers with automatic code generation capability.

The results demonstrate improved micro-grid autonomy, enhanced renewable penetration, and extended battery lifespan. The structured state-machine approach eliminates ambiguous supervisory rules common in heuristic systems and ensures stable mode transitions.

However, limitations must be acknowledged. Validation was conducted solely in simulation; real-time hardware implementation and experimental verification were not performed. Scalability to multi-DER or multi-load micro-grids remains to be investigated, and no economic optimization layer was integrated. Future work should therefore include hardware-in-the-loop (HIL) testing, real-time embedded deployment, scalability analysis, and integration of forecasting or cost-based scheduling strategies.

In conclusion, the proposed SF-based EMS provides a robust, computationally efficient, and industry-compatible enhancement for smart micro-grid operation. By maximizing renewable utilization, protecting storage systems, and minimizing grid dependency, it represents a scalable solution for next-generation decentralized energy systems.

5. CONCLUSION

Smart micro-grids represent the future of decentralized energy systems, offering substantial advantages in energy efficiency, sustainability, and resilience. By integrating advanced EMS, renewable energy generation, and communication technologies, smart micro-grids play an significant role in the development toward a more sustainable and reliable smart grid. The techniques applied to EMS in smart micro-grids are diverse, encompassing heuristic methods, AI-based approaches and hybrid techniques. Each of these methods addresses specific challenges such as real-time optimization, energy forecasting, and system adaptability.

The incorporation of SF adds an additional layer of event-driven control, allowing for dynamic switching between operational states. This capability is particularly useful for adapting to fluctuating renewable energy availability and load demands. The supervisory control implemented through SF aims to minimize reliance on backup sources, such as the utility grid, by optimizing the use of local renewable energy sources and energy storage systems. The simulation results of employing this control strategy demonstrate its effectiveness in reducing dependence on external backup sources.

Future work should emphasize comprehensive experimental validation under real operating conditions, including HIL testing to assess controller robustness and dynamic performance. In addition, the proposed approach should be extended to larger-scale microgrids to evaluate its scalability, interoperability, and computational efficiency. The integration of advanced economic optimization strategies and accurate forecasting techniques for load and renewable generation is also recommended to improve overall system performance. Finally, real-time embedded implementation on dedicated control platforms should be investigated to demonstrate practical feasibility and industrial applicability.

Finally, the proposed smart micro-grid system associated with SF based EMS contributes to conserving fossil fuels, mitigating global warming, maintaining a clean and green environment, and reducing grid dependence by prioritizing the use of PV systems associated with batteries. This demonstrates the potential of SF based EMS in smart micro-grids to significantly advance energy sustainability and resilience.Thus, the SF-based EMS provides a scalable, industry-compatible solution for next-generation decentralized energy systems.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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