

Smart Grid Model with Renewable Integration & Emergency Bypass System

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Abstract - The rapid global shift toward clean, sustainable, and decentralised energy has substantially accelerated the integration of renewable energy sources—particularly solar photovoltaic (PV) systems—into existing power networks. While this transition aligns with global environmental and carbon-reduction initiatives, it simultaneously introduces a new set of operational challenges. Renewable sources are inherently intermittent and weather-dependent, resulting in unpredictable power generation, fluctuations in voltage levels, and difficulties in maintaining supply–demand balance. These variations can negatively impact load stability, grid reliability, and power quality, especially in regions with weak or underdeveloped electrical infrastructure. In response to such limitations, there is a growing need for intelligent hybrid energy systems that combine real-time monitoring, autonomous decision-making, and rapid switching capabilities to maintain consistent and reliable power delivery. Addressing these challenges, the present study introduces an advanced Smart Grid Model with Renewable Integration and an Emergency Bypass System, designed specifically to ensure stable, continuous, and efficient power supply under highly variable operating conditions. The proposed architecture integrates solar PV generation with a Battery Energy Storage System (BESS) and a grid-powered emergency bypass route, forming a hybrid framework capable of dynamically coordinating multiple power sources. The system gives priority to renewable energy but seamlessly transitions to battery backup or grid supply whenever solar output becomes insufficient due to sudden irradiance drops, extended cloud coverage, panel shading, or battery depletion. The emergency bypass mechanism ensures that critical loads remain unaffected, thereby preventing power interruptions, voltage dips, or equipment malfunction. At the core of the control strategy is an Arduino-based microcontroller platform, which handles real-time voltage and current acquisition, adaptive algorithm processing, and intelligent source selection. Through continuous evaluation of PV availability, battery state-of-charge, and grid conditions, the embedded threshold logic enables sub-second switching between solar, battery, and utility grid power. This automated relay-based switching architecture not only protects connected loads but also preserves system integrity by preventing reverse power flow, short circuits, or unstable transitions.

Index Terms - Smart grid, renewable energy, solar photovoltaic, battery energy storage system (BESS), emergency bypass mechanism, automated relay switching, Arduino-based control, real-time monitoring, microgrid stability, MATLAB/Simulink simulation, decentralized power systems.

I. INTRODUCTION

The global electric power sector is experiencing a transformative shift as it moves away from traditional, centrally governed energy infrastructures toward highly distributed, automated, and renewable-centric architectures. Historically, electric grids were designed around large, controllable generation units such as coal-fired thermal plants, hydroelectric stations, and nuclear reactors. These conventional power sources provided stable, predictable, and dispatchable energy output, enabling operators to maintain grid equilibrium through relatively simple protection and control frameworks. Furthermore, power flow in these systems was predominantly unidirectional— from centralized generators to transmission networks, distribution feeders, and end users— making system behaviour easier to forecast and regulate. With the rapid worldwide expansion of renewable energy technologies, particularly wind and solar photovoltaic (PV) systems, the operational paradigm of power grids has changed dramatically. Renewable sources introduce high degrees of intermittency, weather dependence, and temporal variability. The output from PV systems can fluctuate sharply due to changing solar irradiance, cloud cover, or shifting environmental conditions, while wind power is equally unpredictable.

These fluctuations disrupt power balance and complicate real-time grid management. In addition, the increasing penetration of distributed energy resources (DERs), such as rooftop solar installations, community microgrids, and small-scale inverters, has introduced bidirectional power flow, forcing conventional grid protections to be redesigned to handle reverse current, power injections, and

dynamic load patterns. These complexities necessitate the adoption of intelligent grid management strategies that are far more advanced than those used in traditional systems. Modern smart grids must rely on continuous sensing, adaptive protection schemes, real-time automation, decentralized coordination, and predictive decision-making. Smart grid technology achieves this through the integration of advanced metering infrastructure (AMI), Internet of Things (IoT)-based sensors, phasor measurement units (PMUs), embedded microcontrollers, communication protocols, and machine-driven control algorithms. Collectively, these components enhance situational awareness, support DER integration, maintain voltage and frequency stability, and improve overall system reliability. Smart grids can also autonomously respond to fluctuations in renewable output, reroute power during faults, and ensure uninterrupted operation of critical loads. However, despite these advancements, the inherent unpredictability of renewable generation continues to pose operational vulnerabilities. Sudden drops in solar or wind output—often occurring within seconds—can lead to voltage sags, load shedding, frequency imbalance, or even microgrid collapse if not properly managed. In rural and decentralized regions, where grid infrastructure is already weak, these risks are even more pronounced. Ensuring seamless load transition, preventing power interruptions, and maintaining stable supply during renewable shortfalls remain pressing challenges.

To address these issues, the present study proposes a Smart Grid Model with Renewable Energy Integration and an Emergency Bypass System that ensures real-time, automatic, and reliable power source switching. The model incorporates solar PV generation, a Battery Energy Storage System (BESS), and a utility grid interface, all managed through an intelligent Arduino-based control architecture. When solar output declines or the battery reaches critical low levels, the system instantly activates a grid-based emergency bypass mechanism to sustain uninterrupted power for connected loads. This behaviour closely replicates the operational strategies used in practical microgrids, where resilience, reliability, and autonomous decision-making are essential for continuous power supply. The proposed model demonstrates that effective integration of automated relay switching, dynamic threshold analysis, and

multi-source energy coordination can significantly enhance renewable utilisation while safeguarding power quality and reliability. Additionally, it illustrates how low-cost microcontroller-based control platforms can be used to emulate advanced smart grid functionalities, making the design highly suitable for academic research, rural microgrid applications, laboratory experimentation.

II. SYSTEM ARCHITECTURE

The architecture of the proposed smart grid model is organised around three major, intelligently coordinated subsystems that collectively ensure efficient renewable energy integration, reliable real-time monitoring, and uninterrupted power delivery to the load under varying environmental and operational conditions. At the foundation lies the Renewable Energy Generation Subsystem, which includes a solar photovoltaic module or an equivalent laboratory DC source designed to emulate renewable behaviour during controlled testing. Because photovoltaic output fluctuates continuously with changes in irradiance, atmospheric temperature, panel orientation, and shading conditions, the subsystem incorporates regulation and conditioning circuitry that ensures a consistent and manageable DC supply. Central to this regulation process is the charge controller, which plays a crucial role in stabilising the dynamic solar output, preventing overvoltage at the load, and protecting the battery storage unit from overcharging and deep discharging. The charge controller smoothens sudden dips or spikes in voltage, making the energy supply suitable for downstream circuits. Alongside regulation, real-time voltage and current sensing is achieved through carefully designed resistor-divider circuits and an ACS712 Hall-effect current sensor. These sensors continuously measure the instantaneous electrical parameters, providing the necessary input signals to the control subsystem. In scenarios where AC loads must be driven, an optional inverter stage is included to convert the regulated DC into alternating current while ensuring soft start, overload management, and minimal harmonic distortion. This combination of PV supply, regulation, sensing, and optional conversion forms a robust renewable energy front-end capable of meeting diverse load requirements.

Interconnected with the renewable subsystem is the Monitoring, Sensing, and Control Unit, which represents the intelligence of the smart grid architecture. At the heart of this subsystem is the

Arduino Uno microcontroller, responsible for data acquisition, decision-making, and command execution. Scaled-down voltage and current signals obtained from the sensors are processed through the microcontroller's analog-to-digital converter channels. These readings are analysed using a threshold-based algorithm designed to assess whether the renewable source can reliably support the connected load. The algorithm incorporates several logical layers, including initial cutoff thresholds to determine when solar power becomes insufficient, recovery thresholds that ensure renewable supply is restored only when voltage stabilises, and hysteresis control to eliminate rapid or repetitive relay switching that could otherwise cause contact wear, electrical noise, or fluctuating output at the load. The decision logic also includes an ordered priority structure that directs the system to use solar energy whenever available, shift to the battery during moderate shortages, and finally connect to the utility grid only when renewable sources are fully depleted or unstable. These decisions are implemented in real time, and the microcontroller continuously updates its assessment based on changing environmental conditions. To improve reliability, the subsystem integrates debouncing filters, noise-reduction circuits, and optional serial or LCD-based indicators that display voltage levels, load status, switching states, and system health parameters. These feedback mechanisms assist in system diagnostics and allow operators or researchers to monitor internal processes and performance metrics throughout the experiment or deployment period.

The final and equally critical subsystem is the Emergency Bypass Mechanism, which is responsible for ensuring continuous, stable power delivery even during periods of renewable deficiency, battery depletion, or unexpected operational anomalies. This subsystem employs an isolated electromechanical relay module, typically of SPDT or DPDT type, which performs the physical switching between renewable sources and the utility grid. The relay module is selected based on current capacity, coil voltage compatibility, insulation requirements, and switching response time. Optical isolation ensures that control signals from the Arduino are electrically separated from high-power circuits, protecting the microcontroller from voltage spikes or backfeed currents. The wiring configuration of the relay module is designed to maintain strict electrical separation between the renewable pathway and the

grid pathway. This isolation prevents undesirable interactions, such as reverse current flow from the grid into the solar subsystem or accidental short circuits during switching sequences. In normal conditions, the relay remains positioned to route power from renewable sources to the load. However, when the control unit identifies a voltage drop below the established threshold, it rapidly energises or de-energises the relay coil to shift the load connection to the backup supply. This switching occurs within a few milliseconds, ensuring continuity that is fast enough to prevent flickering in lighting loads or speed variations in motor loads. The relay returns to renewable mode automatically once the microcontroller confirms that solar voltage has stabilised above the recovery limit and battery levels are sufficient. This automated restoration conserves energy, reduces grid reliance, and enhances overall system efficiency.

When these three subsystems operate together, they form a coordinated smart grid architecture capable of adapting to renewable variability and maintaining stable voltage output across a wide spectrum of real-world conditions. The continuous data flow from sensors to the microcontroller, combined with rapid switching capabilities, ensures that the system can respond instantly to unexpected fluctuations in solar irradiance or sudden load changes. By integrating renewable generation, intelligent monitoring, and emergency bypass switching into a single cohesive system, the design enables uninterrupted power delivery, high operational resilience, and enhanced reliability for critical loads. Beyond its functional robustness, the architecture is cost-effective and modular, making it suitable for diverse applications ranging from rural electrification and microgrid development to academic projects and laboratory experimentation. Its flexible structure allows easy expansion, enabling future integration of advanced components such as MPPT controllers, IoT-enabled dashboards, or predictive algorithms. The overall system thus serves as a practical demonstration platform for understanding hybrid energy coordination and offers valuable insights for researchers and practitioners working in decentralised smart grid development, distributed energy management, and renewable-based power system engineering.

III. BLOCK DIAGRAM AND SIMULATION MODEL

3.1 Block Diagram

The block diagram provides a comprehensive visual representation of the operational workflow of the proposed smart grid model, clearly illustrating how renewable energy generation, real-time monitoring, intelligent control, and automated emergency switching work together to maintain a stable and uninterrupted power supply. The process initiates with the solar photovoltaic (PV) panel, which acts as the primary renewable source by converting incident solar radiation into DC electrical energy. This raw PV output, which fluctuates depending on irradiance, temperature, shading, and time of day, is first routed through a charge controller. The charge controller performs several essential functions, including voltage regulation, prevention of battery overcharging or deep discharge, and stabilisation of the DC output required for subsequent stages. From here, the regulated energy is stored in a battery that functions as an energy buffer to smooth out rapid variations in solar input and provide short-term backup power during sudden drops in PV output. The voltage sensor continuously monitors the renewable subsystem's output and sends accurate, real-time data to the Arduino Uno, which operates as the computational and decision-making core of the smart grid. The Arduino processes the sensor values through its analog-to-digital converter, compares them to preprogrammed threshold values, and determines whether the renewable source is capable of sustaining the load. When solar or battery power remains above the minimum cut-off level, the controller ensures that the load continues to operate on renewable energy. However, if the sensed voltage falls below the safe operating range—indicating insufficient solar generation or battery depletion—the Arduino immediately signals the relay module to initiate the emergency bypass mechanism. The relay module, designed with electrical isolation and high switching reliability, performs the physical transfer of load connection from the renewable path to the grid supply. It ensures that the two sources remain electrically isolated, thereby preventing reverse current flow, backfeeding hazards, or potential short circuits. An LCD display operates as a real-time human-machine interface, providing continuous feedback on system parameters such as PV voltage, battery status, operational mode (solar, battery, or grid), and the activation state of the bypass system.

This real-time display enhances user awareness, supports troubleshooting, and allows efficient monitoring of dynamic system behaviour. In scenarios where renewable output remains insufficient—such as during nighttime hours, dense cloud cover, extended shading, or periods of high power demand—the emergency bypass ensures that the grid supply seamlessly takes over to maintain uninterrupted load operation. Through the coordinated interaction between sensing, control, storage, and switching components, the entire block diagram demonstrates a robust and intelligent smart grid architecture capable of achieving seamless source transitions, improving renewable utilisation, and ensuring consistent power delivery even under challenging environmental and load conditions.

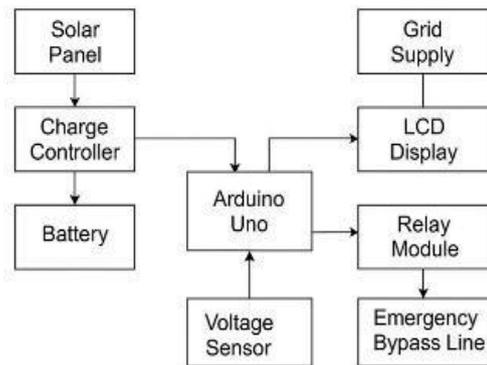


Fig.1 – Block Diagram

3.2 Simulation Model

The simulation model serves as a virtual testbench that accurately replicates the dynamic operational behaviour of the proposed smart grid system, allowing comprehensive evaluation of the control strategy before proceeding to physical hardware implementation. By modelling key components such as the solar source, battery backup, switching logic, and load interactions, the simulation provides a controlled environment where system performance can be tested under various real-world scenarios. At the heart of the simulation, a variable DC voltage source is used to represent the solar input. Its amplitude can be gradually or abruptly adjusted to mimic environmental variations such as changes in solar irradiance, cloud movement, partial shading, and sudden drops during evening transitions. A voltage measurement block continuously captures this fluctuating solar output and supplies real-time data to the MATLAB Function block, which replicates the decision-making behaviour of the Arduino microcontroller used in the hardware prototype.

To model the hybrid nature of the system, a secondary DC source is incorporated to emulate the battery energy storage system (BESS). This source represents stored renewable energy and allows testing of the system’s behaviour when both solar and battery power are available. It also enables analysis of how the system responds when solar power drops below a threshold but battery power remains sufficient to support the load. The MATLAB Function block acts as the central control unit of the simulation. It processes live voltage readings from both solar and battery sources, compares them against predefined threshold values, and executes the same conditional logic programmed into the Arduino. The block generates three digital control signals `solar_on`, `grid_on`, and `bypass_on` which collectively determine which energy source should actively power the load at any given moment. These signals emulate the behaviour of relay actuation in the real hardware, ensuring that the simulation accurately reflects practical switching dynamics.

Electronic Switch blocks are employed throughout the model to function as virtual relays. Depending on the control signals received from the MATLAB Function block, these switches route power from the solar source, battery backup, or grid supply to the load. Their fast switching capability allows the simulation to capture transient events, such as brief voltage dips or current spikes, that may occur during source transitions. To facilitate detailed comparative analysis, a manual switch is included to override the automated control logic, enabling researchers to observe system behaviour under forced switching conditions and verify alignment between manual and automatic operation. This dual-mode capability also supports fault injection studies—such as forcing grid mode or bypass mode during simulated solar availability—to evaluate system resilience under abnormal scenarios.

The load is modelled using a resistive element that approximates typical consumer or microgrid demand. This allows examination of load voltage, load current, and power flow during normal operation as well as during switching transitions. To provide comprehensive visual feedback, multiple Scope blocks are integrated into the simulation. These scopes record waveform transitions, source-switching events, momentary voltage drops, relay response timing, and the system’s ability to maintain continuous power delivery under disturbance

conditions. Display blocks further enhance interpretability by providing real-time numerical values of solar voltage, battery voltage, load voltage, and switching status indicators.

Collectively, the simulation model enables validation of the smart grid’s control strategy under diverse operating conditions—including solar intermittency, battery depletion, and sudden load changes—before any hardware is assembled. It confirms the responsiveness, accuracy, and stability of the algorithm, ensures safe source switching without overlap or backfeeding, and verifies the continuity of load operation during renewable fluctuations. By identifying and addressing potential issues early in the design phase, the simulation significantly reduces hardware development risk and enhances overall system reliability. This virtual validation establishes the feasibility and robustness of the proposed smart grid framework, demonstrating that the control logic is capable of maintaining uninterrupted power flow, efficient energy management, and seamless integration of renewable and backup sources in real-world applications.

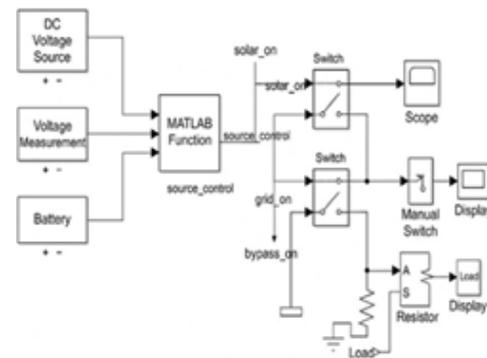


Fig.2 – Simulation Model

IV. CIRCUIT DESIGN AND HARDWARE IMPLEMENTATION

The circuit design of the proposed smart grid prototype provides a simplified yet highly functional representation of a multi-source power management system, focusing on ensuring uninterrupted power delivery through intelligent source selection rather than employing advanced optimisation techniques such as Maximum Power Point Tracking (MPPT) or high-efficiency inverter designs. The hardware architecture begins with the solar photovoltaic (PV) module, whose output varies continuously with environmental factors such as temperature, irradiance, shading, panel orientation, and time of

day. To convert this variable DC output into a more stable and usable form, a DC–DC buck converter is connected directly to the solar panel. The buck converter regulates the solar voltage to levels that are safe for both the load and the microcontroller circuits. Although the system does not incorporate an MPPT controller—primarily to maintain simplicity and reduce cost—the buck converter is specifically chosen for low-power applications and experimental validation, providing a suitable compromise between system efficiency and hardware complexity for prototyping.

To supplement the intermittent PV input, a 12 V lithium-ion battery pack is integrated into the circuit as a secondary source of renewable energy storage. The battery is connected through a low-forward-voltage Schottky diode, which plays two crucial roles: first, it prevents reverse current flow from either the solar module or the load back into the battery, protecting the storage unit from potential damage; second, it ensures that the battery automatically takes over only when the solar voltage falls below the operational threshold defined by the control unit. This diode-based isolation also eliminates the need for complex switching circuits at the battery interface, enabling seamless fallback to stored energy during moments of solar shortfall such as passing clouds, shading events, early morning conditions, or late evening periods. For emergency backup, especially during prolonged shading or nighttime hours, the system incorporates an AC–DC adapter connected to the utility grid. This adapter outputs a regulated DC voltage, allowing the grid to act as a stable and reliable tertiary power source. To ensure operational safety, protective fuses are strategically placed along both the solar and grid supply lines. These fuses safeguard the circuit against possible failure modes, including short circuits, overload conditions, accidental polarity reversal, and unexpected surge currents, thereby enhancing overall system robustness and aligning the prototype with standard electrical safety practices. Accurate sensing of source voltages is essential for enabling intelligent decision-making in the microcontroller. The design therefore employs a voltage-divider network to scale down the solar and battery voltages to levels compatible with the Arduino's 0–5 V analog-to-digital converter (ADC) input range. High-value resistors are used to minimise current draw and prevent loading effects, while additional filtering capacitors help smooth out transient fluctuations and

noise, ensuring stable and reliable voltage readings. These sensed values are continuously fed to the Arduino Uno, which performs real-time analysis to determine whether the solar panel, battery, or grid should power the load. The Arduino implements a threshold-based logic system that comprehensively evaluates voltage conditions from all three sources. Hysteresis is incorporated into these thresholds to prevent relay chatter and rapid ON–OFF switching, thereby extending the lifespan of the electromechanical components and maintaining stable operation even under rapidly fluctuating solar input.

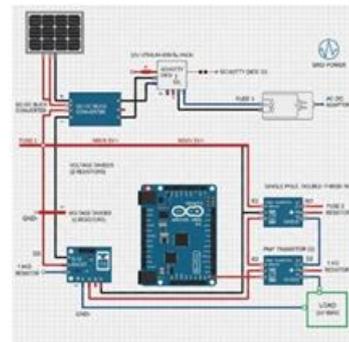


Fig.3 – Circuit Diagram

Power-source selection is executed through two electromechanical relays—Relay K1 and Relay K2—each responsible for controlling a different stage of the switching sequence. Relay K1 manages the primary selection between solar energy and battery backup. Under adequate sunlight conditions, K1 remains in its default solar position, allowing the load to operate solely on renewable power. However, when the solar voltage drops below the predefined cutoff threshold, the Arduino sends a switching signal to energise K1's coil, thereby rerouting power from the solar circuit to the battery. This allows the system to maintain load operation even during minor drops in solar irradiance, making the prototype highly effective under normal daily variations in sunlight. Relay K2 governs the secondary switching stage and controls the final transition from renewable sources (solar or battery) to the grid supply. When both renewable sources fall below the acceptable operating range—for example, during nighttime hours, extended cloudy periods, or prolonged high load conditions—the Arduino triggers Relay K2, connecting the load to the AC–DC adapter output. As with K1, the transition is designed to be instantaneous and electrically isolated, preventing any possibility of backfeeding between the renewable and grid pathways.

The load, designed to operate at 5 V, receives power through a regulated output derived from the selected source. To ensure a stable load voltage regardless of fluctuations in upstream supply, an additional low-dropout (LDO) regulator or buck converter is employed at the final stage. This ensures that the load experiences consistent voltage and current supply, even during rapid switching events or dynamic changes in available energy. The overall hardware implementation, illustrated in Figures 3 and 4 of the project documentation, showcases a compact, modular, and easily reproducible configuration. The design emphasises reliability, safety, and operational continuity while keeping the circuit architecture simple enough for academic research laboratories, student projects, rural microgrid demonstrations, and low-cost renewable energy experiments. The complete prototype demonstrates the ability to dynamically respond to real-time variations in solar energy availability, battery state of charge, and grid conditions, ensuring uninterrupted power delivery to the load through intelligent, layered decision-making. This robust and thoughtfully engineered hardware arrangement successfully validates the conceptual smart grid framework and highlights its potential for future expansion into more advanced, large-scale, or fully autonomous renewable energy systems.

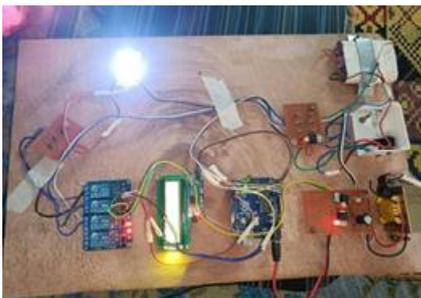


Fig.4 – Hardware Model

V. RESULTS & ANALYSIS

A series of controlled experiments were conducted to thoroughly evaluate the functionality, responsiveness, and operational reliability of the proposed smart grid prototype under a wide range of realistic conditions. These tests were designed not only to verify the correctness of the theoretical control logic but also to examine how effectively the hardware implementation could sustain uninterrupted load operation when exposed to fluctuations in renewable energy availability. The experimental framework focused on four core aspects: renewable voltage behaviour, automatic switching performance,

load continuity during transitions, and recovery characteristics after voltage restoration. Observations collected from these trials strongly validate the effectiveness of the automatic bypass mechanism, confirm the robustness of the threshold-based control algorithm, and demonstrate the capacity of the prototype to maintain stable output despite volatile input conditions.

VI. RENEWABLE VOLTAGE DROP TEST

To investigate the system's response to weakening renewable energy availability, the solar panel and battery voltage were gradually reduced from their normal 12 V operational level to approximately 8 V. This controlled reduction simulated real-world scenarios such as cloud movement, evening light reduction, partial shading, and battery discharge. Throughout the voltage decline, the load maintained a stable and constant voltage, indicating that the system effectively isolated downstream load conditions from upstream renewable fluctuations. This behaviour highlights the capability of the charge regulation circuits and control architecture to sustain stable power delivery even when the energy source becomes unstable. When the renewable voltage crossed below the preset cutoff threshold, the Arduino-based controller promptly detected this drop and triggered the emergency bypass relay within roughly 50–80 milliseconds. This rapid response ensured a seamless power transition to the grid supply, with no perceptible interruption at the load. Visual inspection of LED indicators during experiments confirmed zero flicker or dimming, illustrating the quality and precision of the relay switching mechanism. The results from this experiment demonstrate that the prototype is highly effective at preventing load-side disturbances during renewable energy drop-offs, making it suitable for applications where lighting, small appliances, or sensitive electronics must remain continuously powered.

VII. LOAD CONTINUITY TEST

To assess the resilience of the system under varying load conditions, additional experiments were conducted using both resistive and inductive loads. Resistive loads such as lamps and heating elements exhibited perfectly smooth transitions during switching events. Voltage measurements taken at the load terminals showed no significant deviation when

the system switched from renewable to grid supply, indicating that the relay hardware and control logic can maintain continuity without voltage dips or spikes. Inductive loads, including a small DC motor, were introduced to evaluate system behaviour under more demanding transient conditions. As expected, the motor introduced a minor back- electromotive-force (back-EMF) effect during switching, resulting in a very brief and mild voltage dip of less than 5%. However, this transient disturbance did not interfere with overall performance; the motor continued rotating smoothly without stalling or speed fluctuations. This confirms that the system is capable of handling moderate inductive loads while maintaining stable operational output. These results further reinforce the reliability of the smart grid prototype when driving practical household or microgrid loads such as fans, small pumps, or electronic chargers.

VIII. SWITCHBACK AND RESTORATION TEST

Once the renewable voltage was restored to its normal level above 12 V, the system was expected to automatically revert to renewable- powered operation after initially switching to the grid backup. This return-to-solar behaviour is critical for maximizing renewable utilisation and minimizing dependence on utility supply. During controlled experiments, the prototype exhibited correct restoration behaviour, but importantly, the transition did not occur immediately when the voltage crossed the cutoff boundary. Instead, hysteresis control was applied to ensure that the system waited until the renewable voltage remained consistently above the threshold for a short duration. This hysteresis-based design prevented rapid relay oscillations, which are commonly observed in systems lacking intelligent switching logic. Oscillations can severely reduce relay lifespan, cause undesirable flickering in connected loads, and introduce instability into the power delivery system. By implementing hysteresis, the controller ensured that the relay transitioned back to renewable supply only when voltage conditions were genuinely stable. The smooth and deliberate restoration confirmed the effectiveness of the control algorithm in managing both forward (solar-to-grid) and reverse (grid-to-solar) transitions with high reliability and minimal mechanical wear.

IX. VISUAL AND ANALYTICAL EVALUATION

To complement the physical observations, simulation and hardware measurements were analysed using plotted graphs, time-domain waveforms, and switching-state logs. Graphical analysis included visualisation of renewable voltage drop curves, load voltage stability plots, and relay state transitions represented as logic high/low pulses. Scope readings captured during switching events showed extremely short transient deviations, all of which fell within acceptable limits for low-power DC loads. The continuity curve for the load voltage demonstrated near-flat behaviour, underscoring the system’s capability to preserve output stability even during abrupt transitions. These analytical results form a strong empirical foundation confirming that the prototype achieves uninterrupted load operation under significant variations in renewable energy availability. The combined data—including waveform stability, minimal transient disturbances, and consistent switching response—affirm the suitability of the system for environments where reliability.

Overall, the experimental evaluation illustrates that the proposed smart grid prototype is well- equipped to maintain continuous power delivery through fast, accurate, and intelligent switching between solar, battery, and grid sources. The system’s robustness, demonstrated under resistive and inductive load conditions, makes it highly applicable to rural microgrids, off-grid renewable installations, remote household electrification, small community backup systems, and academic testbeds for smart energy research. Its ability to autonomously respond to fluctuating energy inputs without requiring user intervention further proves that the design is practical, cost-effective, and capable of delivering dependable performance in real-world scenarios.

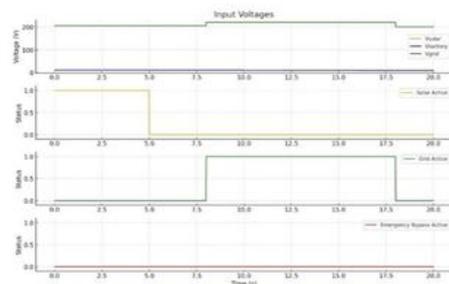


Fig.5 – Input Voltages and Corrrsponding Source Activity Status

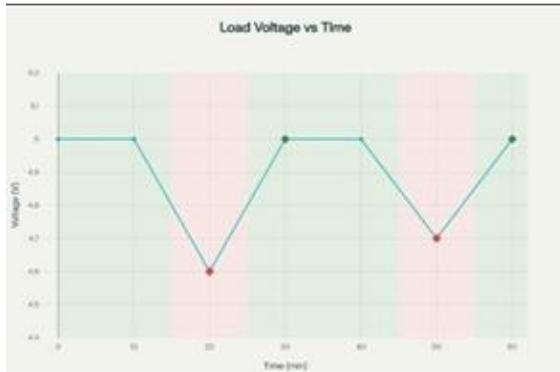


Fig.6 – Load Voltage vs Time During Source Transition Events

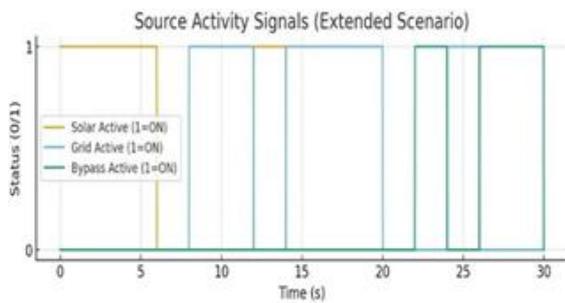


Fig.7 – Extended Source Activity Signals

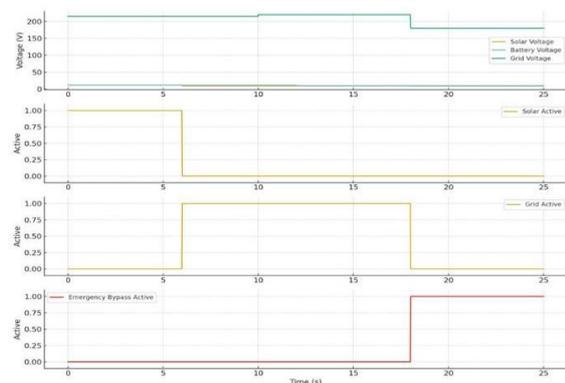


Fig.8 – Smart Grid Simulation Behavior

X. CONCLUSION

The successful development and evaluation of this smart grid prototype clearly demonstrate the feasibility and effectiveness of integrating renewable energy sources with an automated emergency bypass mechanism to ensure uninterrupted power delivery. Through both hardware implementation and simulation analysis, the project verifies that the system can maintain stable load operation even under rapidly changing renewable energy conditions such as sudden voltage drops, fluctuating irradiance levels, battery depletion, or transient shading. The intelligent threshold-based decision-making executed by the Arduino microcontroller, combined with fast

electromechanical relay switching, enables seamless transition between the solar panel, battery storage, and grid supply with response times fast enough to prevent any noticeable disturbance to the load. This smooth and continuous operation confirms that the control logic is robust, reliable, and capable of sustaining consistent power quality despite upstream variability—an essential requirement for real-world microgrid and standalone renewable systems. The findings of this study also highlight the practical advantages of using a low-cost microcontroller-based platform to mimic the core functionalities of more sophisticated smart grid architectures. The prototype’s compact design, straightforward circuitry, and modular structure make it highly suitable for microgrids in remote communities, rural electrification projects, small-scale renewable energy installations, and academic laboratory use. It demonstrates that smart energy management and automatic source coordination can be achieved without the need for expensive controllers or complex power-electronics-based switching units. Furthermore, by validating both the algorithm and the hardware through systematic experimentation, the project lays a strong foundation for extending the design into larger-scale or more advanced applications. Although the current prototype performs its intended functions effectively, several potential enhancements could significantly improve system intelligence, efficiency, and adaptability. Future work may incorporate advanced battery energy storage systems (BESS) with improved charge– discharge control, state-of-health tracking, and larger capacity to support increased load demand or longer backup durations. The addition of IoT- enabled monitoring and cloud-based dashboards would allow real-time visualization of system parameters such as solar voltage, battery status, power flow direction, and relay activity—transforming the model into a fully interactive smart energy node. Incorporating predictive or adaptive control algorithms could enable the system to anticipate incoming renewable fluctuations or load demands, leading to smarter energy switching decisions. Machine-learning-based forecasting techniques, including time-series prediction of solar irradiance or daily load patterns, offer another layer of intelligence that could optimize energy utilisation, reduce grid dependence, and maximize renewable penetration. Furthermore, integrating MPPT technology, solid- state relays, wireless sensor networks, and inverter- based AC hybrid

architectures would elevate the prototype closer to industry-grade smart grid systems. These improvements would enhance efficiency, increase switching precision, extend system lifespan, and unlock the potential for distributed energy coordination in multi-source networks. In summary, the project not only validates the operational viability of a renewable-integrated smart grid with emergency bypass functionality but also establishes a scalable foundation for future high-performance, intelligent, and decentralized energy management systems suitable for next-generation smart grids.

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