

ESP32-Based Control Logic for Safe Automatic Transfer Switching in Smart Power Changeover Systems

Olawale J. B¹, Akinola A. O², Adedeji O. O³, Idowu A. K⁴, Olawoye T. O⁵, Stephen-Lemo O. K⁶

^{1,2,3,4}Department of Computer Engineering, Rufus Giwa Polytechnic, Owo, Ondo State.

^{5,6}Department of Electrical and Electronics Engineering, Rufus Giwa Polytechnic, Owo, Ondo State.

Abstract— Reliable automatic transfer switching depends not only on power-contact hardware but also on embedded decision logic that can distinguish transient disturbances from sustained source failure while guaranteeing break-before-make source isolation. This study presents an ESP32-based control architecture for a smart single-phase power changeover system that continuously monitors grid and generator or inverter voltages, evaluates source validity, coordinates automatic and authorized manual/remote commands, and supervises isolated switching outputs. The firmware is structured as a finite-state control process comprising measurement, decision, switching, communication, protection, and user-interface functions. Source voltages are conditioned and evaluated using RMS estimates against prototype limits of 170–250 V. Transfer to the backup source occurs only after grid failure is established and backup-source stability is verified; restoration of the grid initiates a confirmation state rather than an immediate retransfer. Active-source under-voltage or over-voltage produces rapid isolation, warning indication, and remote notification. Experimental functional tests under simulated source-failure and restoration conditions showed grid-to-backup transfer in approximately 1 s and active-source fault isolation in less than 500 ms. The architecture therefore combines deterministic source-priority logic, electrical interlocking, voltage-quality protection, and communication-independent local safety. The design is suitable as a low-cost foundation for IoT-enabled changeover systems and can be extended with watchdog supervision, authenticated commands, event logging, redundant sensing, and three-phase operation.

Keywords— Automatic Transfer Switch; ESP32; Embedded Control; Finite-State Machine; IoT; Source Interlocking; Voltage Monitoring.

I. INTRODUCTION

Continuity of electrical supply is important in residential, commercial, institutional, and light-industrial installations where utility outages and voltage excursions can interrupt essential loads (Gönen et al., 2024). However, the reliability of an automatic transfer switch (ATS) is determined by more than the rating of its relays, contactors, or circuit breakers (Dwomoh et al., 2025).

The embedded controller must correctly identify source conditions, reject unstable voltage, enforce source isolation, and execute switching in a predictable sequence (Trabelsi et al., 2022).

Earlier microcontroller-based changeover systems demonstrated the feasibility of automatic source selection and programmable transfer logic (Dwomoh et al., 2025; Ehiabhili et al., 2018; Obasi et al., 2015). Low-cost ATS designs have also incorporated over-voltage protection and source-quality supervision (Olatomiwa & Olufadi, 2014), while practical changeover implementations emphasize reliable backup operation (Effraim et al., 2022; Kibet, 2021). These developments establish the value of programmable control, but a smart changeover controller must additionally coordinate state retention, communication, user confirmation, and fail-safe behavior without allowing remote communication to become a prerequisite for protection (Rubio et al., 2025).

The ESP32 provides a suitable platform for this purpose because it combines processing capability, analog and digital interfaces, hardware serial communication, and integrated wireless functionality. In the present work, the controller is used as the supervisory element of an IoT-capable changeover system. Its principal task is to transform conditioned voltage measurements and user commands into mutually exclusive switching decisions while preserving a defined operating state.

The main contribution of this paper is the formulation and implementation of a state-aware ESP32 control strategy that integrates: (i) continuous monitoring of grid and backup voltages; (ii) preferred-source prioritization; (iii) break-before-make switching with an interlock delay; (iv) active-source under-voltage and over-voltage isolation; (v) a confirmation state for controlled return to the grid; and (vi) local protection that remains operational when GSM communication is unavailable. The study focuses specifically on embedded control logic and its functional validation rather than on the mechanical design of the transfer contactors.

II. SYSTEM REQUIREMENTS AND CONTROL ARCHITECTURE

The controller was specified to satisfy six primary engineering requirements: continuous source monitoring, priority selection of the grid when permitted, automatic transfer to a valid backup source after grid failure, prevention of simultaneous source connection, detection and isolation of abnormal active-source voltage, and acceptance of authorized local or remote commands. These requirements were translated into a modular firmware architecture in which sensing, decision, switching, communication, and interface functions are separated.

The finite-state approach stores the current supply state, a pending grid-return confirmation condition, fault status, and override status. This structure reduces ambiguous transitions because each event is processed relative to a known operating state. It also supports systematic functional testing: a source failure, source restoration, invalid-voltage event, confirmation command, or override request must produce a defined next state and output action.

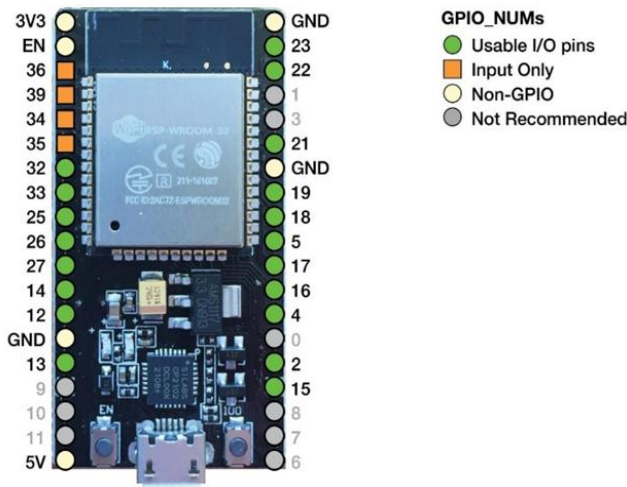


Figure 1. ESP32 development board pin-out used for planning control, sensing, and communication interfaces

A. Functional Modules

The measurement module acquires scaled grid and backup-source voltage signals and converts them into usable voltage estimates. The decision module compares the resulting values with the configured validity band and evaluates source priority. The switching module issues relay or contactor commands while enforcing mutual exclusion between the two sources. The communication module initializes the GSM interface, transmits alerts, polls incoming commands, parses valid messages, and clears processed commands.

The user-interface module updates the LCD, LEDs, and buzzer so that the local operating condition remains visible even when remote communication is unavailable.

Modularization is important for reliability because a communication delay or display update should not prevent execution of the protection path. The design therefore treats communication as supervisory feedback rather than as the mechanism that guarantees source isolation.

III. VOLTAGE MONITORING AND DECISION LOGIC

Grid and generator or inverter voltage signals are sampled through conditioned controller inputs. RMS estimation is applied before a source is classified. For a sampled waveform with N conditioned samples V_k , the RMS estimate can be represented as:

$$V_{RMS} = \sqrt{\left\{ \left(\frac{1}{N} \right) \sum (k = 1 \dots N) V_k^2 \right\}} \quad (Eqn.... 1)$$

The estimated voltage is then compared with the prototype operating limits. A source is treated as acceptable when $170 \text{ V} \leq V_{RMS} \leq 250 \text{ V}$. If the active source falls below 170 V or rises above 250 V, the controller de-energizes the corresponding switching output, activates the warning indication, and initiates an alert. These limits reflect the prototype test environment and are configurable rather than universal; deployment values should be selected according to applicable supply standards, equipment tolerances, and the characteristics of the connected load.

To reduce false transfer decisions caused by short disturbances, the logic uses confirmation and timing rather than acting on an isolated sample. Likewise, a deliberate interlock interval separates source disconnection from connection of the alternative source. This break-before-make behavior is central to the prevention of source overlap and unsafe back-feeding.

A. Source-Selection Logic

Let G and B denote the validity of the grid and backup sources respectively, where a valid source satisfies the configured voltage band. Under automatic operation, the preferred sequence is: maintain the grid when $G = 1$; when $G = 0$, disconnect the grid and evaluate B ; connect the backup only when $B = 1$ and the interlock requirement has been satisfied; and isolate the load from an invalid active source. When grid voltage returns while the load is supplied from backup, the system enters a confirmation state and retains the backup connection until a valid local or SMS confirmation is received. This deliberate return policy avoids immediate retransfer during a short-lived restoration event.

IV. FIRMWARE STATE-MACHINE OPERATION

The main firmware loop repeatedly performs five operations: acquire source voltages, poll local and SMS commands, evaluate automatic changeover conditions, supervise the active source for faults, and refresh the local interface. The operating states can be expressed as GRID_ACTIVE, BACKUP_ACTIVE, WAIT_BACKUP, GRID_RETURN_PENDING, FAULT_ISOLATION, and OVERRIDE. The exact implementation may encode these states numerically, but their behavioral separation is the important design feature.

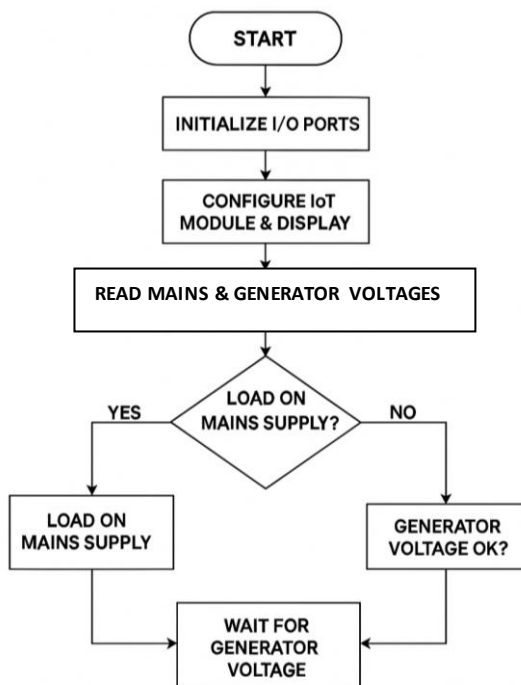


Figure 2. Firmware flowchart for source reading, source decision, and waiting states.

TABLE 1. Controller States, Entry Conditions, Actions, and Exit Conditions.

Operating state	Entry condition	Controller action	Exit condition
GRID_ACTIVE	Grid valid and selected	Grid output ON; backup output OFF; monitor grid	Grid fails/invalid or authorized override
WAIT_BACKUP	Grid unavailable; backup not yet confirmed	Both sources isolated; verify backup and timing	Backup valid and interlock satisfied
BACKUP_ACTIVE	Backup valid after grid loss	Backup output ON; grid output OFF; monitor backup and grid return	Grid restored, backup fault, or override
GRID_RETURN_PENDING	Grid restored while backup active	Keep backup active; issue prompt; await confirmation	Valid local/SMS confirmation or grid lost again
FAULT_ISOLATION	Active source outside 170–250 V	Disconnect active source; warn and alert	A valid source/state is re-established
OVERRIDE	Authorized local or remote request	Execute permitted command subject to source isolation	Command completion or return to automatic mode

V. PROTECTION, INTERLOCKING, AND COMMUNICATION RELIABILITY

Protection is implemented as an embedded function of the local controller. The switching logic does not permit both source outputs to be asserted simultaneously. Before energizing an alternative source, the previously active source is removed and an interlock delay is observed. This sequencing complements the electrical isolation provided by the switching hardware and addresses a critical failure mode in transfer systems.

The active-source voltage is supervised continuously. When the measured value violates the configured band, the controller prioritizes disconnection over notification. Consequently, GSM availability does not determine whether the protection action occurs. The alert path reports the event after, or in parallel with, local protective action. This hierarchy is important because communication networks may be delayed or unavailable during a power disturbance.

The prototype accepts manual or remote override commands, but such commands remain subordinate to source-isolation rules. For a production implementation, the remote-command path should additionally include sender or session authentication, command integrity checks, rate limiting, and auditable event logging. Watchdog supervision, nonvolatile fault records, and redundant sensing would further strengthen fault tolerance.

VI. IMPLEMENTATION AND EXPERIMENTAL EVALUATION

The firmware was developed in the Arduino IDE environment. Wire and LiquidCrystal_I2C were used for display interfacing, a voltage-sensor library supported RMS estimation, and Hardware Serial provided communication with the GSM module. Functional testing was performed by simulating source availability, source restoration, and voltage-fault conditions and observing switching outputs, warning indications, user prompts, and transfer timing.

The evaluation was intended to verify deterministic control behavior rather than to characterize contactor lifetime or long-term grid statistics. The principal acceptance criterion was that each simulated event should lead to the state and output action defined by the control logic while preserving mutual source isolation.

Testing confirmed that the state logic executed the expected actions under simulated source failure and restoration. Grid failure caused automatic transfer to backup within approximately one second. Grid restoration caused an SMS prompt rather than immediate transfer.

TABLE 2. Functional Validation Matrix Derived from the Prototype Tests.

Test condition	Expected control response	Observed outcome	Performance indicator
Stable grid supply	Maintain grid; isolate backup	Expected state executed	Normal-source retention
Grid failure with valid backup	Disconnect grid; verify backup; transfer after interlock	Expected state executed	Transfer ≈ 1 s
Grid restoration while on backup	Issue prompt; remain on backup pending confirmation	Expected state executed	No immediate retransfer
Active-source under/over-voltage	Disconnect active source; warn; send alert	Expected protection executed	Isolation < 500 ms
Authorized local/SMS command	Execute permitted action without source overlap	Expected state executed	Interlock maintained
GSM unavailable	Continue local automatic protection	Safety logic independent of GSM	Fail-safe local control

A. Discussion

The tests show that the controller can distinguish the preferred operating source from a valid alternative source and can execute a controlled transfer without deliberate source overlap. The approximately 1 s grid-to-backup transfer reflects the combined effect of failure recognition, backup validation, interlock timing, and switching response. The sub-500 ms active-source isolation result indicates that the fault-protection path is faster than the complete transfer sequence, which is appropriate because removing an unacceptable source is a different control objective from establishing a replacement supply.

The confirmation state on grid restoration differentiates the design from a simple threshold-triggered changeover. Instead of assuming that a newly restored grid is immediately suitable for retransfer, the controller notifies the user and preserves the existing backup state until confirmation. This feature is particularly useful where utility restoration may be intermittent, although the trade-off is that restoration to the preferred source can depend on user response.

Compared with conventional relay-only arrangements, the programmable state-machine structure offers clearer sequencing and easier modification (Hosseinzadeh et al., 2021; Idoko et al., 2018). Compared with communication-dependent smart systems, the present architecture keeps the safety-critical path local (Akpan et al., 2019; Maniktala, 2012). These features are consistent with the broader progression from basic microcontroller changeover systems toward protected and monitored automatic transfer systems.

VII. CONCLUSION

This paper presented an ESP32-based embedded control strategy for safe automatic transfer switching in a smart power changeover system. The design integrates conditioned voltage monitoring, finite-state decision logic, preferred-source selection, break-before-make interlocking, abnormal-voltage isolation, local and remote command handling, user notification, and confirmation-controlled return to the grid. Prototype testing demonstrated grid-to-backup transfer in approximately one second and active-source fault isolation in less than 500 ms while maintaining source isolation. The design principle is that communication enhances supervision but is not required for local protection. The resulting architecture provides a practical basis for low-cost IoT-capable changeover systems and supports future extension to stronger cybersecurity, event logging, redundant sensing, and three-phase applications.

REFERENCES

- [1] Akpan, E. P., Orike, S., Odeyemi, F. M., & Nkpolu-Oroworukwo, P.-H. (2019). An Improved Microcontroller-Based Automatic Three-Phase Analyzer and Selector. *Journal of Newviews in Engineering and Technology (JNET)*, 1(1), 53–61.
- [2] Dwomoh, L., Addo, P., Osei-Kwame, E., Arkorful, I., & Ampem, I. (2025). Design and Implementation of a Power Dispatch Controller for Optimal Energy Management in a Grid-Connected System. *Journal of Power, Energy, and Control*, 2(1), 55–66.
- [3] Effraim, P., Addison, M. N., & Bayor, M. A. A. (2022). Design and Analysis of an Automatic Power Changeover with Backup. *International Journal of Research and Innovation in Applied Science*, 7(08), 42–49.
- [4] Ehiabhili, J., Ezech, C., Orji, O., & others. (2018). Single Phase Microcontroller-Based Automatic Changeover Switch. *International Journal of Electronics, Communication & Instrumentation Engineering Research and Development (IJECIERD)*, 8(1), 7–16.
- [5] Gönen, T., Ten, C.-W., & Mehrizi-Sani, A. (2024). *Electric power distribution engineering*. CRC press.
- [6] Hosseinzadeh, N., Aziz, A., Mahmud, A., Gargoom, A., & Rabbani, M. (2021). *Voltage Stability of Power Systems with Renewable-Energy Inverter-Based Generators: A Review*. *Electronics* 2021, 10, 115. s Note: MDPI stays neutral with regard to jurisdictional claims in
- [7] Idoko, E., Udenze, P., & Ikule, F. (2018). Design and implementation of three phases automatic change over switch. *International Journal of Advanced Engineering Research and Technology (IJAERT)*, 6(7), 435–439.
- [8] Kibet, F. J. (2021). *Design and Implementation of a Microcontroller-Based Automatic Changeover System for Transformers in Power Stations* [PhD Thesis]. JKUAT-COPAS.
- [9] Maniktala, S. (2012). *Switching Power Supplies A-Z*. Elsevier.
- [10] Obasi, C. C., Olufemi, B., John, J., Ibiam, V., & Ubadike, C. (2015). Design and Implementation of Microcontroller Based Programmable Power Changeover. *Computer Engineering and Intelligent System*, 6(12), 51–56.
- [11] Olatomiwa, L., & Olufadi, R. (2014). *Design and development of a low cost automatic transfer switch (ATS) with an over-voltage protection*.
- [12] Rubio, S., Bogarra, S., Nunes, M., & Gomez, X. (2025). Smart grid protection, automation and control: Challenges and opportunities. *Applied Sciences*, 15(6), 3186.
- [13] Trabelsi, M., Alquennah, A. N., & Vahedi, H. (2022). Review on single-DC-source multilevel inverters: Voltage balancing and control techniques. *IEEE Open Journal of the Industrial Electronics Society*, 3, 711–732.