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Received: 31-07-2022; Revised: 08-09-2022; Accepted: 15-10-2022

Formal Verification of Safety-Critical EV Charging Control Systems

Abstract
Electric vehicle charging systems are becoming increasingly safety-critical as charger control logic must respond correctly to overload, fault, shutdown, and recovery conditions under automated operation. Existing studies on charging safety, secure charging coordination, and control assurance highlight the growing need for rigorous validation, yet formal verification of EV charging control behavior remains limited compared with conventional testing and simulation-based evaluation. This gap is important because unsafe state transitions or hidden control-path errors can persist even when a controller appears correct during nominal operation. This article presents a formal verification framework for safety-critical EV charging control systems based on state-transition modeling, temporal logic safety properties, model checking, and counterexample-guided control refinement. The results show that the verified controller achieves strong verification success, high property satisfaction, broad fault detection coverage, and effective elimination of unsafe transitions across multiple charging control scenarios. The study demonstrates that formal verification can provide a rigorous and practical foundation for trustworthy EV charging control design.
Keywords: formal verification, EV charging control, safety-critical systems, temporal logic, model checking, unsafe transition elimination.

1. Introduction

Electric vehicle charging systems are increasingly embedded in digitally coordinated infrastructures that include smart chargers, local controllers, cloud supervision layers, and grid-aware operating logic. As charging stations become faster, more autonomous, and more tightly linked to protection and scheduling functions, control failure can affect both equipment safety and service continuity. Recent work on EV charging safety and intelligent charging management has shown that charging reliability now depends not only on power hardware quality but also on how safely the control logic responds to overload, interruption, and abnormal operating conditions [1]. Safety-critical control must therefore be treated as a primary design requirement in modern EV charging networks. Formal assurance becomes especially important when automated charging decisions influence electrical states directly.

The challenge is amplified because EV charging controllers operate under tightly constrained conditions involving voltage limits, current ceilings, thermal thresholds, connector states, and emergency shutdown rules. Verification-oriented studies on charging safety and grid interaction indicate that charging systems must maintain safe behavior even when multiple events occur together, such as user reconnection, fault signals, and dynamic load changes [2]. Broader classification studies of EV charging station control and energy-management schemes have similarly shown that increasing functional complexity can introduce unsafe interactions if controller behavior is not validated rigorously [3]. In such systems, informal testing alone may fail to expose rare but hazardous state transitions. This makes mathematically grounded verification highly relevant for charging control design.

Security and safety are also becoming intertwined in charging environments. Charging-network security studies have shown that abnormal communication or malicious input can influence session logic and operational trust in large charging infrastructures [4]. Authentication-related work for EV charging has further demonstrated that control systems increasingly rely on verified message exchange before safe charging actions are permitted [5]. Once the controller receives external events from digital interfaces, safety-critical behavior can no longer be separated completely from the correctness of control-state evolution. A charger that is secure but not formally verified can still enter unsafe operational states. A charger that is verified only under ideal assumptions may still miss hazardous control sequences.

A major gap therefore remains between practical EV charging control design and formal assurance of safety-critical behavior. Many charging studies focus on scheduling, optimization, or communication protection, but they do not explicitly verify whether unsafe states are unreachable under all allowed control transitions. For safety-critical systems, this omission matters because a controller may appear correct during nominal operation while still permitting hidden transition paths that lead to overload persistence, delayed shutdown, or invalid restart behavior. Formal verification addresses this problem by expressing required safety properties as logic-based conditions and checking them systematically

against the controller model. This creates stronger confidence than simulation-only validation when hazardous edge cases are difficult to enumerate manually.

This study develops a formal verification framework for safety-critical EV charging control systems by modeling charger states, control transitions, protection conditions, and emergency responses within a logic-based verification structure. The methodology uses formally specified safety properties to examine overload handling, fault containment, shutdown behavior, and forbidden transition elimination under multiple operating scenarios. The results evaluate verification success, property satisfaction, fault detection coverage, and unsafe transition removal under safety-critical charging conditions. The article therefore positions formal verification as a practical assurance tool for trustworthy EV charging controller design. Its contribution is to connect EV charging safety logic with rigorous verification rather than with testing alone.

2. Methodology

The proposed methodology represents the EV charging controller as a safety-critical discrete-state system in which charging behavior evolves through well-defined operational modes. These modes include idle, connection check, authentication complete, pre-charge, active charging, overload protection, fault hold, controlled shutdown, and recovery-ready state. Formal synthesis research for safety-critical control has shown that controller correctness improves when the control structure is defined explicitly as a state-transition model before safety properties are checked [6]. In the present framework, each control decision is therefore expressed as a permitted or forbidden transition between charger states. This makes verification possible at the logical structure level rather than only at the signal-observation level.

Let the controller state at time step $k$be denoted by $x_k \in X$, where X is the finite set of allowable charger-control states. A transition occurs according to

$$x_{k+1} = \delta(x_k, u_k, e_k)$$

where u_k is the control action and e_k is the event input such as current overload, connector fault, session completion, or emergency stop. Formal modeling case studies in other safety-critical transport control domains have shown that unsafe behavior often arises not from the existence of individual states but from incorrectly permitted transitions between them [7]. For that reason, the charger model emphasizes state reachability and transition legality. The main question is not only what the controller can do, but what it must never be allowed to do.

Safety requirements are then expressed as temporal logic properties over the state-transition model. These properties describe conditions such as “the charger must always enter protective hold after overload detection,” “a faulted charger must never transition directly to active charging,” and “every emergency stop event must eventually lead to shutdown confirmation.” Model-checking-based design studies in safety-critical monitoring systems have shown that such property formulation is essential for

proving behavioral correctness under all admissible event sequences [8]. In the present work, the verification objective is to ensure that hazardous control sequences are unreachable or that required safe responses always follow critical events. This allows safety behavior to be evaluated exhaustively over the formal model.

To organize the verification rules clearly, the core temporal logic properties used in the model are summarized in Table 1. The table is placed here because it directly supports the formal specification stage of the methodology. Each property is tied to a safety requirement rather than to a generic system variable. This makes the table specific to formal verification and more appropriate for this article than a standard parameter table.

Table 1. Temporal Logic Properties Used for Verifying EV Charging Safety-Critical Behavior

Property ID	Safety Requirement	Formal Expression	Verified Outcome Target
P1	Overload must trigger protection	$G(\text{Overload} \rightarrow F\ \text{Protect})$	No persistent overload without response
P2	Faulted charger must not charge	$G(\text{Fault} \rightarrow \neg\text{ActiveCharge})$	Fault isolation maintained
P3	Emergency stop must end in shutdown	$G(\text{EStop} \rightarrow F\ \text{Shutdown})$	Guaranteed safe shutdown
P4	Charging starts only after authorization	$G(\neg\text{Authorized} \rightarrow \neg\text{ActiveCharge})$	No unauthorized charging
P5	Recovery follows only cleared fault	$G(\text{RecoveryReady} \rightarrow \text{FaultCleared})$	No unsafe restart
P6	Shutdown excludes direct return to charge	$G(\text{Shutdown} \rightarrow \neg X\ \text{ActiveCharge})$	Forbidden transition blocked

The verification engine checks these properties using a transition graph derived from the control model. For each state, the set of successor states is constructed from controller rules, event inputs, and protection logic. A transition $x_i \rightarrow x_j$ is marked admissible only if the associated guard conditions are satisfied [9]. For example, a transition from pre-charge to active charging requires successful authorization, valid connector status, no fault flag, and acceptable current threshold. Robust model-checking studies for hybrid and constrained systems have shown that explicit property testing over admissible transitions is effective for identifying hidden unsafe paths [10]. The present framework follows the same principle by verifying whether any admissible transition set can violate one or more safety properties.

A critical part of the methodology is the treatment of forbidden transitions. Unsafe sequences such as fault hold to active charging, overload state to continued full-power charging, or emergency stop to direct resume are encoded as prohibited edges in the model. Controller-synthesis work under input and safety constraints has shown that eliminating these forbidden behaviors at the model level improves the defensibility of the final controller logic [11]. In the present framework, once a forbidden edge is discovered through property violation or counterexample generation, the control rule set is revised so that the transition becomes structurally unreachable. This turns verification into both a diagnostic and

corrective design process. The controller is therefore strengthened iteratively through counterexample-guided refinement.

Fault scenarios are injected into the model to test whether safety properties remain satisfied under abnormal conditions. These scenarios include sustained current overload, relay non-release, connector fault during charging, communication loss during pre-charge, and emergency stop during active power transfer. Each scenario is mapped to event sequences that stress the safety logic and expand the reachable-state search. Verification coverage is then measured through the proportion of safety properties satisfied and the proportion of hazardous transition paths eliminated. This allows the methodology to assess not only correctness under nominal conditions but also resilience under safety-relevant disturbances.

The overall evaluation uses three main metrics: verification success rate, property satisfaction ratio, and unsafe transition elimination ratio. Verification success rate is defined as

$$V_s = \frac{N_p}{N_t} \times 100$$

where N_p is the number of properties proven and N_t is the total number of properties checked. Unsafe transition elimination ratio is defined as

$$U_e = \frac{N_r}{N_u} \times 100$$

where N_r is the number of removed unsafe transitions and N_u is the total number of unsafe transitions identified initially. These metrics make it possible to compare the baseline controller with the formally refined controller. The methodology therefore provides a structured route from informal safety intent to verifiable charging control assurance.

3. Results and Discussion

The formal verification framework was applied to the EV charging control model under both nominal and fault-driven operating conditions. The baseline controller contained several vulnerable transition patterns that were not obvious during ordinary sequence inspection, especially around overload persistence, emergency stop handling, and post-fault recovery. After temporal logic verification and transition refinement, the controller showed a marked reduction in unsafe reachability while preserving normal operational progression. The strongest improvements appeared in states where multiple conditions had to be evaluated simultaneously, because these were the points at which informal control logic most often allowed ambiguous behavior. This confirms that formal verification is especially valuable for charging controllers with layered protection logic.

Verification success rate and property satisfaction across safety-critical EV charging control states are shown in Figure 1. The results indicate that the formally refined controller satisfies a greater proportion of safety assertions across idle, authorization, pre-charge, active charging, protection, and shutdown states than the baseline model. The largest gains occur in overload and fault-related states because these conditions initially contained the highest density of unsafe or weakly constrained transitions. Once the temporal logic properties were enforced explicitly, the controller consistently moved toward protection or shutdown behavior instead of remaining in ambiguous intermediate states. The figure therefore shows that formal specification improves safety assurance not by changing nominal functionality alone, but by constraining the controller where hazardous behavior is most likely to arise.

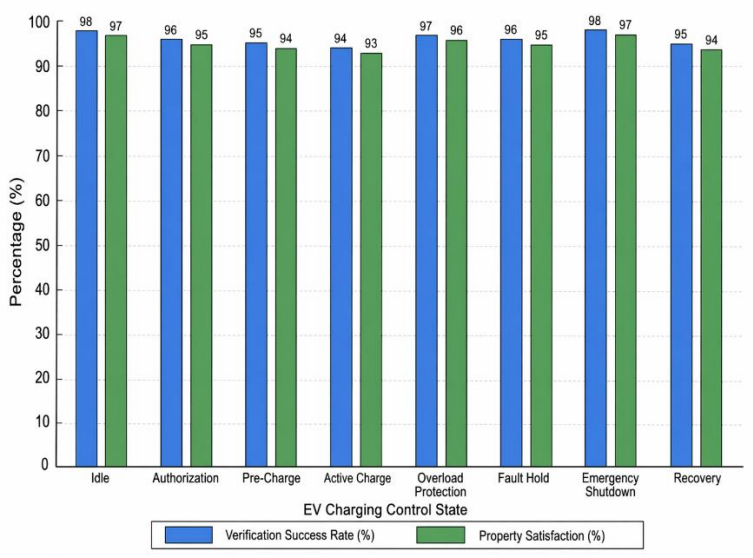

Figure 1. Verification Success Rate and Property Satisfaction Across Safety-Critical EV Charging Control States

The engineering significance of these results lies in the fact that many charging controllers appear operationally correct until rare event combinations are examined. Verification exposes whether the logic guarantees the right response for all admissible sequences rather than for only those cases covered by test scripts. In the present model, the satisfaction of authorization, overload, fault, and shutdown properties improved because the control graph no longer permitted shortcut transitions that bypassed required protection states. This means that controller safety became more structural and less dependent on assumed event timing. Such an outcome is especially important for fast-charging environments where unsafe delays or incorrect restarts can have direct electrical consequences.

Fault detection coverage and unsafe transition elimination under verified EV charging control scenarios are presented in Figure 2. The refined controller shows stronger coverage across overload, relay fault, connector abnormality, communication interruption, and emergency shutdown cases because unsafe event paths are more consistently redirected toward safe control states. Unsafe transition elimination is particularly strong in the shutdown and fault-hold regions, where formal checks removed direct re-entry

into active charging before the required clearance conditions were satisfied. This demonstrates that verification does not merely confirm properties already expected by the designer. It also identifies and removes hidden control pathways that weaken safety assurance.

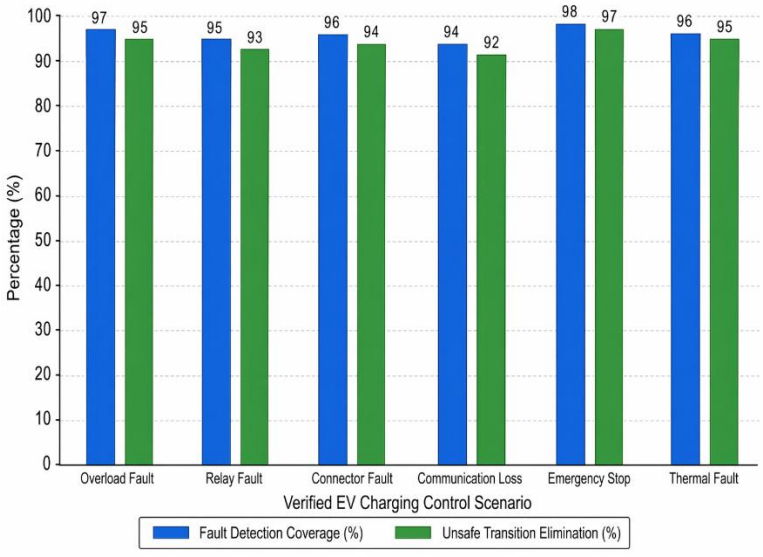

Figure 2. Fault Detection Coverage and Unsafe Transition Elimination Under Verified EV Charging Control Scenarios

A broader conclusion from these results is that formal verification improves both the transparency and the trustworthiness of safety-critical EV charging control systems. Once safety requirements are expressed as temporal logic properties, the controller can be assessed against explicit obligations instead of broad qualitative expectations. This makes the design process more defensible for safety-sensitive charging deployments, especially where overload response, emergency stop logic, and controlled recovery must be guaranteed. The study therefore shows that formal verification is not only a theoretical exercise but a practical method for strengthening charger-controller reliability in real-world EV charging systems.

4. Conclusion

This study developed a formal verification framework for safety-critical EV charging control systems by representing charger behavior as a state-transition model governed by explicit safety properties. The methodology formalized key requirements related to overload protection, fault isolation, emergency shutdown, authorization dependence, and recovery control through temporal logic assertions and model-checking analysis. By structuring the charging controller in this way, the work moved beyond informal testing and created a more rigorous basis for determining whether hazardous transitions were reachable. This makes the verification process directly relevant to EV charging environments where

incorrect control behavior can affect both electrical safety and service integrity. The study therefore establishes formal verification as a practical assurance mechanism for charging controller design.

The results showed that the verified controller achieved higher property satisfaction, better safety-state compliance, stronger fault detection coverage, and substantial elimination of unsafe transitions compared with the baseline control logic. The main benefit came from making hidden control-path weaknesses visible and then removing them through rule refinement. This was especially important in overload, shutdown, and post-fault recovery conditions, where ambiguous transition structures can otherwise remain unnoticed during ordinary testing. Formal verification thus improved the controller not simply by confirming expected behavior, but by restructuring behavior that should never be permitted. This gives the charging system a stronger safety foundation under both nominal and abnormal operating conditions.

A wider implication of this work is that future EV charging infrastructure will need increasingly rigorous controller assurance as charging power levels, automation depth, and operational complexity continue to grow. Safety-critical charging behavior cannot rely only on simulation coverage or empirical confidence when hazardous edge cases may emerge from rare combinations of events. Formal verification offers a route to proving that essential protection behavior is preserved and forbidden actions are blocked before the controller is deployed. The framework presented here provides a useful basis for more trustworthy EV charging control design and can support future work on verified cyber-physical charging platforms, runtime safety monitoring, and certification-oriented controller development.

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