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Research Article

Unit Commitment under Security Constraints in Smart Grids via Robust Optimization Based on Advanced Genetic Algorithm

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Extended Abstract:

The Unit Commitment (UC) problem stands as a cornerstone of power system operation, tasked with determining the optimal on/off status and generation schedule of thermal and other dispatchable units over a planning horizon to meet forecasted load demand at minimum cost while respecting a multitude of technical and security constraints. In the era of smart grids, this classical problem has been profoundly transformed by the large-scale integration of Renewable Energy Sources (RES) such as wind and solar, whose inherent intermittency and uncertainty introduce significant operational risks. Simultaneously, the emergence of Energy Storage Systems (ESS) and the proliferation of Electric Vehicles (EVs)—which can act as distributed, mobile storage assets via Vehicle-to-Grid (V2G) technology—present new opportunities for enhancing system flexibility and resilience. However, harnessing these opportunities within a UC framework that is robust to forecasting errors, secure against network contingencies, and computationally tractable for large-scale systems remains a formidable challenge.

This paper addresses this critical gap by proposing a comprehensive robust optimization model for the Security-Constrained Unit Commitment (SCUC) problem in smart grids. The core innovation of the work lies not only in its holistic modeling framework but, more significantly, in its solution methodology: the development and application of an Advanced Genetic Algorithm (AGA) that dramatically improves convergence speed, solution quality, and scalability compared to conventional optimization techniques.

The proposed robust SCUC model is meticulously formulated to capture the full complexity of modern power systems. Its multi-component objective function minimizes the total operational cost, which includes:

- Fuel and variable generation costs for conventional units,
- Start-up and shut-down costs to account for the thermal inertia of generators,
- No-load costs for committed units,
- Costs associated with involuntary load curtailment (a critical security measure),
- Environmental costs related to greenhouse gas emissions,
- Operational costs of charging and discharging for both stationary ESS and aggregated EV fleets.

This economic objective is subject to a comprehensive set of security and operational constraints, ensuring physical feasibility and N-1 security:

- Power balance at every node in every time period, incorporating power injections/withdrawals from RES, ESS, and EVs.
- Generator limits on minimum/maximum output, along with ramping rate constraints to model realistic dynamic behavior.

- Minimum up/down time rules to prevent excessive cycling of thermal units.
- AC power flow-based line flow limits to enforce network security and prevent thermal overloads.
- Dynamic energy balance equations for both ESS and EVs, with constraints on state-of-charge (SoC), charge/discharge power limits, and round-trip efficiencies.
- Demand flexibility, allowing for a controlled percentage of load to be shifted or curtailed as part of the operational strategy.
- Robustness against uncertainty is explicitly modeled through uncertainty sets that bound the potential forecast errors for both load demand (±α%) and RES generation (±γ%), ensuring that the UC schedule remains feasible under a wide range of plausible realization scenarios.

To solve this highly complex, non-convex, and mixed-integer problem, the paper introduces an Advanced Genetic Algorithm (AGA) that significantly enhances the standard GA framework through several key modifications:

1. Hybrid Selection Mechanism: It combines *Roulette Wheel Selection* (which favors high-fitness individuals) with *Tournament Selection* (which preserves population diversity) to strike an optimal balance between exploitation and exploration.
2. Uniform Crossover: This operator facilitates a more thorough mixing of parental genetic material, promoting the discovery of novel and high-performing solution regions.
3. Variable Mutation Rate: The mutation probability is high in the early generations to maintain diversity and avoid premature convergence, and it gradually decreases in later generations to fine-tune the best solutions and accelerate convergence to a high-quality optimum.

This AGA is specifically tailored to handle the mixed discrete-continuous nature of the SCUC problem. Each chromosome in the algorithm's population encodes the complete UC schedule, including the on/off status of all units, the dispatch levels, and the charge/discharge schedules for ESS and EVs. A robust feasibility-checking and repair mechanism is integrated to ensure that all candidate solutions respect the problem's hard constraints before evaluation.

The performance of the proposed model and AGA is rigorously validated through extensive simulations on four standard IEEE test systems of increasing complexity: the 6-bus, 24-bus, 118-bus, and 300-bus networks. The evaluation is structured around three key scenarios:

- Scenario 1 (Baseline): A conventional system with only thermal generation and no RES or storage.
- Scenario 2 (RES Integration): The baseline system augmented with uncertain wind and solar generation.
- Scenario 3 (Full Smart Grid): The system integrates RES, stationary ESS, and a fleet of controllable EVs.

The results are compelling and demonstrate the superiority of the proposed approach:

- On the 24-bus system, the total operational cost in the full smart grid scenario (Scenario 3) is $1,084.9k, a 26.8% reduction compared to the baseline ($1,482.7k). This is achieved while simultaneously reducing the costly load curtailment from 38.1 to 7.9 units.
- The integration of ESS and EVs increases the penetration of RES from 23.5% to 26.1%, showcasing their role in enabling greater renewable utilization by mitigating their variability.
- The computational efficiency of the AGA is remarkable. It achieves convergence in 21.3 seconds for the 24-bus, 89.7 seconds for the 118-bus, and 157.4 seconds for the 300-bus system—all within a practical timeframe for day-ahead or even intraday operational planning, especially when compared to the often prohibitive runtimes of traditional Mixed-Integer Linear Programming (MILP) solvers for such large-scale, non-convex problems.

In conclusion, this paper presents a powerful and practical framework for modern SCUC. By synergistically combining a robust, security-constrained, and multi-resource integrated model with an advanced, purpose-built genetic algorithm, it successfully tackles the key challenges of cost, security,

and uncertainty in smart grids. The results confirm that the proposed strategy can significantly lower operational costs, enhance system resilience, and promote the integration of clean energy technologies, all while being computationally scalable to real-world, large-scale power systems. This work paves the way for more intelligent, flexible, and economically efficient power system operations in the face of an increasingly complex and uncertain energy landscape.

Keywords: Unit Commitment, Smart Grid, Genetic Algorithm, Renewable Energy Sources.

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