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Compensation Optimization for Automatic Generation Control Services of Coal-Fired Units Using an Improved Genetic Algorithm

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SUMMARY: *Traditional static compensation methods fail to account for the different development paths of performance and operating costs in coal-fired power plants under AGC operations; therefore, there are significant deviations between economic reward and true grid-aid capability. To solve the problem of asymmetric structure and realise a completely equal ancillary Ancillary Service Market Architecture, this paper establishes a new theoretical concept based on high-performing enhanced genetic algorithm to optimise the AGC compensation strategy theoretically. Proposed in this paper is a new multi-dimensional historical operation trajectory synthesis mechanism that constructs an all-around evaluation of the AGC regulation effect through regulation rates, accuracy indexes and latency indicators. Simultaneously, the method builds a strict AGC feasible operation range constraint matrix and integrates it with a continuous dynamic topology correction mechanism to determine the definite quantified latent units' dispatch capacity deterministically. On this basis, a sophisticated multi-objective optimisation topology model is built to establish that the absolute minimum of aggregate system-level regulation cost should be the sole mathematical target function. In order to solve the non-convex and high-dimensional problem space in mathematics, an improved genetic algorithm has been deployed; Strictly combined with adaptive probabilistic crossover-mutation operators integrated into a deterministic elite-preservation selection scheme to synthesise optimally for each individual's remuneration distribution topology. Empirical validations systematically show that the introduction of this proposed dynamic optimisation approach leads to a statistical significance in achieving conformity among fiscal compensation allocation with the internal mechanical regulation accuracy; At the same time, it significantly reduces system-operational expenses by eliminating macroscopic deviations and establishes an absolute-parity institutional framework for competition-based electricity auxiliary-service market.*

KEYWORDS: *Automatic Generation Control; Ancillary Service Compensation; Dynamic Feasible Region Constraints; Advanced Genetic Algorithm; Multi-Objective Mathematical Topology; Coal-Fired Power Plants.*

1 Introduction

Synchronous grid topological consistency must be ensured by maintaining a state of constant dynamic balance among short-term aggregate load demands and long-term aggregated generation outputs spanning multiple nodes of an interlinked Power Grid [1]. Given the current

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tendency toward widespread application of high penetration stochastic renewable energy sources that significantly increases the amplitude of short-term variations in active power and weakens grid rotation inertia by a greater degree; thus enhancing system sensitivity to such transient perturbations [2]. In this deeply transitional Energy Architecture where coal-fired generating units are still indispensable within a broad context of global decarbonisation as they remain essential infrastructure with considerable thermodynamic reserve capacity and mechanical inertia that provides substantial, continuous, and highly responsive auxiliary service capabilities [3]. Structural Asymmetry continuously disrupts the operation laws of current electricity auxiliary service market; In particular, the financial compensation mechanism for AGC deployment is an issue [4]. Orthodox compensation models generally rely on fixed, static capacity-division matrices or uniform post-event distance-payment ratios; They ignore deep thermodynamic and mechanical heterogeneity at an individual coal-fired power plant level [5]. The deep-rooted static system operates on an incorrect mathematical premise of equal-unit-responsibility response; it completely ignores the actual circumstances that different mechanical ageing profiles, complex boilers-turbines coupling delay, and various steam valve non-linearity cause very different control accuracy, time-response lagging behind, as well as physical damage loss in diverse generations of power generation equipment [6]. Therefore, the generators that implement superior tracking fidelity often bear unilaterally asymmetric thermal-operational costs without corresponding compensation mechanisms; under such an inequitable market mechanism, it subsidises low-performing grid support and rewards high-performance one.

There have also been extensive studies by scholars on the serious problems in the auxiliary-service market, including their correction efforts to avoid a collapse of grid-frequency-stabilisation mechanisms. Most of the early theoretical forms in the literature focused on the macroscopic structural Design of uniform clearing-price buildings, aiming to balance their system-scale grid-stabilisation cost through rudimentary post-event capacity settlement and simple proportional-integral tracking evaluation. Subsequently, some mathematical and economic improvements added pay-as-bid and marginal price-topological-hybridisation mechanisms to stimulate market participation; however, they mainly optimise for the ex ante financial bid-competitive mechanism's operational efficiency rather than evaluate the precise ex post mechanical-execution correctness of the prime mover [7]. Stochastic financial clearing algorithms and deterministic cyber-physical system performance metrics remain disconnected; therefore, a new paradigm of highly granular, outcome-oriented reward systems is needed [8]. However, most existing performance-based compensation theoretical models mainly use static, time-averaged historical evaluation coefficients and cannot reflect in real-time that generation's dispatchability declines sharply due to severe grid-frequency stress events or temporary thermal constraints [9]. Parallel computational research has mapped out the exact spatial limits of operating units to refine parameters for compensation matrices more precisely; usually, it combines multiple dimensions' assessment indicators such as gross regulation distance, steady-state tracking accuracy, and delay-time vector [10]. Although there has been a certain degree of innovation in theory at present, classic optimisation methods applied to these problems still suffer from serious deficiencies, including premature convergence and dimensionality explosion under highly non-convex and discontinuous environments resembling complex boiler-turbine thermodynamic system boundaries [11].

To systematically decompose this kind of market difference and set up a mathematically precise compensation Topology, it must be necessary first that the core governing equations relating to area control directly translate into specific unit-unit physical thermodynamic limitations. The instantaneous active power frequency deviation mitigation in a multi-area interconnected power system must respond to the continuously improving state of the Area

Control Error metric. The highest-level managing parameter of the cyber-physical system, expressed mathematically in calculations.

$$ACE_i(t) = \Delta P_{tie,i}(t) + B_i \Delta f_i(t) \tag{1}$$

where the instant topological generated-load imbalanced vector $ACE_i(t)$ for a particular control area i at an exact time t can be expressed as the precise algebraic sum of the aggregate tie-line active power flow difference $\Delta P_{tie,i}(t)$ and the localized system frequency deviation $\Delta f_i(t)$, rigorously scaled by the inherent area frequency response characteristic constant B_i. The entire correction of this kind of stochastic error vector must depend absolutely on the continuous and physical-mechanical modulations of the involved AGC generating units [12]. The actual active power output trajectory of the j-th participating coal-fired unit, which operates under strict condition for Dynamic AGC dispatch setting points, cannot be regarded as unconstrained mathematical variables; Rather than continuous circumscription in transient dynamic feasible region constraints, they are formally presented as follows:

$$P_j^{min}(t) \leq P_j(t - \Delta t) + \int_{t-\Delta t}^{t} \upsilon_j\,(\xi) d\xi \leq P_j^{max}(t) \tag{2}$$

where $P_j(t - \Delta t)$ refers to the previous stable thermal power base; $\upsilon_j(\xi)$ is an instantaneous continuous step change rate vector restricted within the absolute mechanical operating range of $[-R_j^{down}, R_j^{up}]$. Essentially, the dynamic change of $P_j^{min}(t)$ and $P_j^{max}(t)$ indicates that it is in a state of fluctuation due to various reasons such as boiler thermal stress at any time, changes in steam temperature gradient during operation, and non-linear main control valve position saturation constraints. Because the traditional algorithm for markets cannot be used to constantly track and integrate this whole-dimensional continuous bound, it will continue to misjudge real-unit capabilities; therefore, it will destroy the fair distribution of remuneration.

The central hypothesis of this article is that the rigorous, unified synthesis of these nonlinear feasible boundaries for cyber-physical systems combined with a high-end, multiconstrained multi-objective genetic algorithm system architecture can form a dynamic equilibrium solution of AGC compensation optimization under mathematics. Deeply integrate the high-resolution historical operational telemetry system with instant regulation speed, tracking error vector and mechanical action delay, etc., to form a high-fidelity dynamic feasible area topology correction mechanism [13]. Operate strictly within this highly-accurate quantitative operating boundary, establish a rigorous multi-objective topological model to reduce the overall system's regulatory cost while maximising the mathematical consistency of unit financial compensation with actual physical-mechanical effort [14]. Through a high-complexity, nonlinear resolution in the objective function space based on an enhanced Genetic Algorithm Solver that includes adaptive probability-based crossover and mutation operations as well as deterministic elite-preserving mathematical vectors, it eliminates the inherent local minimum trapping issue of conventional optimisation heuristic methods. The following subsequent chapters are systematic dissection of the strict combination formation of continuous-performance-evaluation index systems, the deduction results from dynamical-boundary-constraint matrix constructions, the full-topological-architecture construction procedures of the algorithmic-solver system, as well as the detailed empirical verification schemes deployed on actual-grid-telemetry data sets.

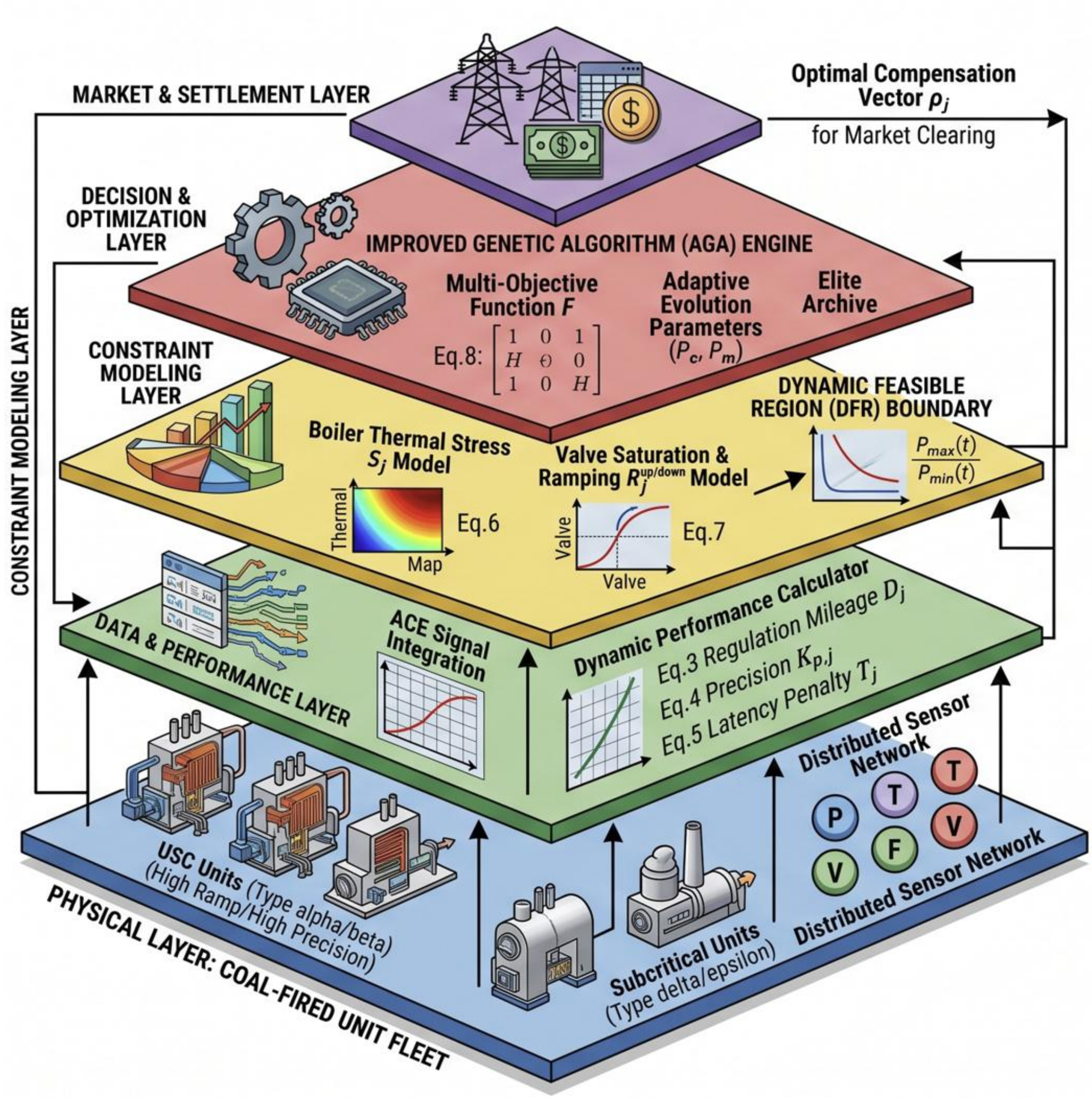

Figure 1: Overall Structure Design of the Advanced AGC compensation optimisation system.

2 Comprehensive Formulation of the AGC Regulation Performance Evaluation Index

2.1 Mathematical Quantification of Thermodynamic Regulation Mileage and Ramp Trajectories

Fundamentally, the evaluation of any coal-fired generating plant that takes part in a highly dynamic automatic generation control ancillary-service ecosystem inevitably needs to be rigorously mathematically quantified; this quantity is typically referred to in power-system dispatching protocols as regulation margin. It is not simply a sum of the operational setting points; it is a non-linear mechanical change from the prime mover's internal kinetic energy with respect to instantaneous grid-Frequency deviation [15]. The continuous temporal tracking of the mechanical active power output requires computing the total effective mechanical mileage by integrating the absolute instantaneous operating acceleration slope over a precisely specified time period; all types of transient load oscillations and extremely complicated thermodynamic hysteresis in heavy-duty subcritical and supercritical pulverised coal combustion systems need to be fully considered here. Specifically, the instantaneous mechanical regulation mileage D_j for the j-th participating generating unit is rigorously defined by the following continuous differential integration topology:

$$D_j = \int_{T_{start}}^{T_{end}} \left| \frac{dP_j(t)}{dt} \right| dt \quad (3)$$

where the continuous-time domain variable $P_j(t)$ represents the instantaneously actual active power generated strictly under measurement conditions at the level of the step-up transformer terminal; and $[T_{start}, T_{end}]$ is represented as an unbroken rigid interval in time with respect to the strict implementation range of the regional independent system operator's automated generation control command [16].

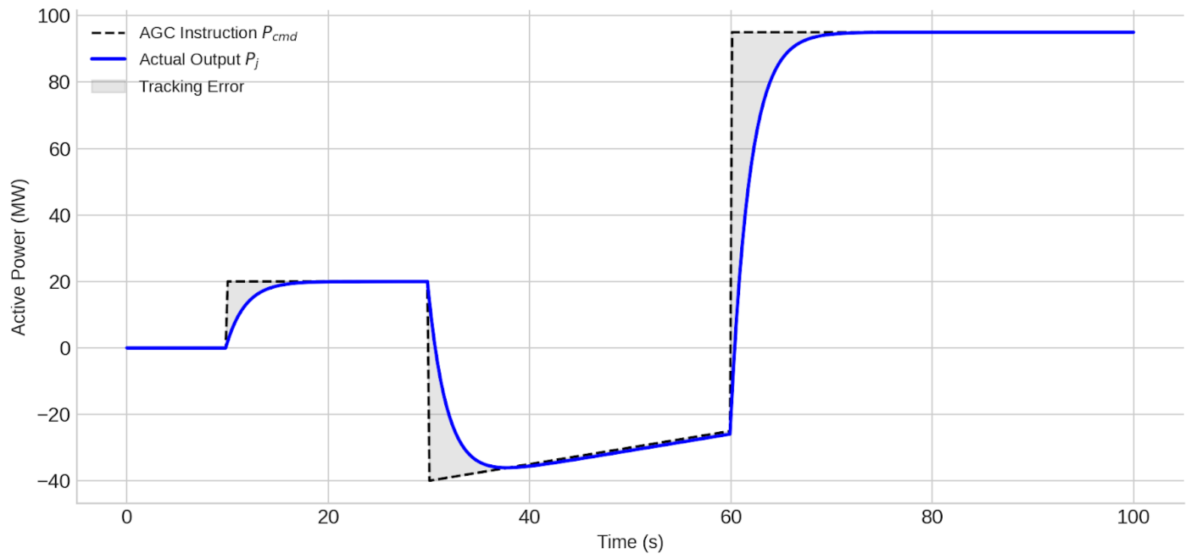

Figure 2: High-precision Line Chart of AGC instruction tracking and regulation mileage.

Continuous integration formulation can separately calculate that a constant thermal power is actually outputted to drive the high-pressure-turbine-cylinder, while an infinite physical throttling action takes place inside the turbine through its main control valve (MCV) system. Through structural capture of the entire range of directions to obtain an extremely specific reference point for measuring serious physical-mechanical ageing, low-cycle material fatigue caused by rapid temperature rise in the rotor during operation, and overall damage to high-temperature stress environment across the primary boiler headers. Therefore, the integral is absolutely mapped in the unit's kinetic response accuracy and serves as the foundation of quantitatively measuring multi-dimensional financial compensation algorithms to define the volume mechanical action independently from arbitrary steady-state capacity references.

2.2 Deterministic Assessment of Control Precision and Cyber-Physical Latency Penetration

Though rough integrated volumetric mileages draw lines on the large scale, the actual temporary stabilizer strength that a complex thermal generator can produce really comes down to mostly how well it can keep its long term steady state for a very long time and also continuously minimize those weird electronic fluid delay times: A basic physical truth when it comes to coal-fired thermodynamic water - steam cycle is there exists an inherent and unavoidable, extremely non linear time lag between sending out a digital continuous active power order and seeing some altered electric output coming out of the synchronous generator's stator: To take into consideration the needed lag time from when we begin to adhere to us terminating our track, we represent this with showing the normalized tracking precision index over infinity on top of an rms spatial error on a space domain [17]. For the very precise and targeted precision coefficient $K_{p,j}$ regarding the generating unit undergoing clear assessment it is structurally calculated according to the determined continuous formula:

$$K_{p,j} = 1 - \sqrt{\frac{1}{\Delta T}\int_{T_{start}}^{T_{end}} \left(\frac{P_{cmd,j}(t) - P_j(t)}{P_{N,j}}\right)^2 dt} \tag{4}$$

within which dynamic reference variable $P_{cmd,j}(t)$ represents the continuous set-point trajectory being sent through Supervisory Control And Data Acquisition Network, $P_{N,j}$ is the manufactered nominal maximum active Power which acts like an absolute non-dimensionalising scalar Denominator and ΔT stands for the total time duration of a particular window in which Cyber Physical Instructions are given [18]. Topologically formulated which can be free from being excused by maths imposes severe penalties on large and sudden deviants of the generated active power due to primary control valves saturated, coal powder transportation tardiness etc., if equipment's response is very quick here in such cases the loss in generation is multipliers [19] And then there’s also another important Temporal Lag parameter which is subsequently integrated into into this constant flow of math. Significant response latency in actually performing any real physical action, even that will add more uncompensated Transient Spatial Errors immediately right from the get go while we first start dynamically increasing things and it just makes sense all within our grand unified Mathematical Precision Scalar without necessitating the deployment of disparate, highly subjective algorithmic deadband evaluation modules [20].

2.3 Synthesis of the Multi-Dimensional Composite Performance Multiplier

Finally, in a fundamentally fair manner, mechanically representing such an equitable remuneration matrix requires the high-level synthesis of these four previously isolated volumes: thermodynamic volume; Steady-State precision measurement vector; And the highly granular composite evaluation multipliers. [21] Mathematical convergence mechanisms thus prevent substantial localised market distortions, where a generating unit can strategically manipulate the generation speed and gross error in active power injection to artificially increase its isolated mileage compensation indicators at the cost of actual grid-frequency stability deterioration [22]. The unified automatic-generation-control composite performance index $K_{AGC,j}$ that directly regulates the following financial-clearing architecture is constructed using a continuous-balancing multi-dimensional-weighted-linear-topological-transformation, and its mathematical expression is given by:

$$K_{AGC,j} = \omega_v K_{v,j} + \omega_p K_{p,j} + \omega_t K_{t,j} \tag{5}$$

where the discrete operational scalar $K_{v,j}$ mathematically represents the unit’s normalized absolute regulation rate capability, $K_{p,j}$ embodies the previously derived transient tracking precision integrated vector, and $K_{t,j}$ quantifies the precisely measured cyber-physical temporal response latency penalty. The structural integrity and economic viability of this mathematical synthesis are strictly governed by the application of dynamic algorithmic weighting coefficients ω_v, ω_p, and ω_t, which are inherently subjected to the absolute constraint equation $\omega_v + \omega_p + \omega_t = 1$. Extremely different from conventional static models of market compensation, these weight assignment parameters will be constantly updated and re-calculated automatically in real time according to the immediate macroscopic grid-frequency-stress conditions by the regional energy-management-system computation centre. In case of a severe low-frequency disturbance causing an increase in the rate of frequency change, the region optimisation controller can dynamically boost the impact of the delay time-weighted function on rewards by increasing ω_t at this moment. On the other hand, for steady-state localised micro-fluctuations accompanied by minor load changes, precision weight ω_p obtains mathematical precedence to ensure absolute correctness of the dispatch setpoint unconditionally. A dynamically generated and corrected self-multiplying mathematician that is seamless in its transition from the raw physical cyber-mechanical continuous assessment to the next-generation multiple-objective economic compensation genetic algorithm solver.

3 Dynamic Feasible Region Modelling and Multi-Objective Optimization Construction

3.1 Mathematical Formulation of the Thermodynamic Dynamic Feasible Region Constraints

Fundamentally, the lack of adequacy in modern electric energy auxiliary service-clearing algorithm is due to its continuous dependence on a static, unchanging capacity boundary; it cannot capture the sudden thermal degradation and intricate boiler-turbine-hysteresis phenomenon that directly impact the instantaneity of high inertia coal-fired power generation units [23]. In order to eliminate the inherent system topology defect in full extent, it needs to construct a dynamic feasible region constraint matrix as an unbreakable mathematical bound of all multi-objective financial compensation algorithms' working area. The real-time active power path for any thermal generator included in a continuous Automatic Generation Control loop will always be constrained within the boundaries formed by the instantanous thermodynamic states, such as primary-secondary-pressure changes and throttling valve non-linearity characteristics. Therefore, the dynamic absolute upper and lower operating constraints for the j-th generating unit at any precise continuous time point t should not be scalars; instead, they need to be expressed as temporal-integrated continuous functions of the previous active power state and the instantaneous thermodynamic ramp capability.

$$P_j^{max}(t) = \min\left(P_{N,j}, P_j(t-\Delta t) + \int_{t-\Delta t}^{t} R_j^{up}(\tau, T_{steam}, P_{ms})d\tau\right) \quad (6)$$

$$P_j^{min}(t) = \max\left(P_{min,j}, P_j(t-\Delta t) - \int_{t-\Delta t}^{t} R_j^{down}(\tau, T_{steam}, P_{ms})d\tau\right) \quad (7)$$

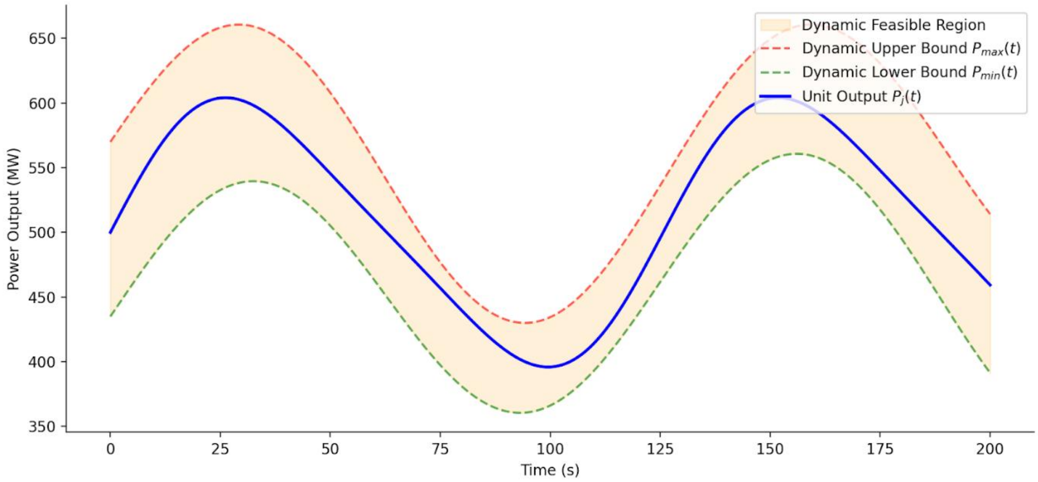

Figure 3: Envelope plot of the dynamic feasible region (DFR) evolution under thermal stress.

Under a very limited continuous mathematical topology environment, variables $P_{N,j}$ and $P_{min,j}$ denote the strict structural Design limitations on the mechanical prime mover's structure to define the border region of optimisation Space outside. Continuously time-integrated terms determine the real-time access to mechanics in a sense; The dynamic directionality ramp rate function R_j^{up} and R_j^{down} is a strict parameterised multi-dimensional nonlinear continuous dependence of its input variables directly mapping onto instantaneous main-steam temperature T_{steam} and transient main-steam pressure P_{ms} located at the high-pressure turbine inlet. Rigorous boundary integration in computation ensures that no financial remuneration vector is assigned to any mathematical capacity region that the physical thermodynamic boiler cannot immediately reach without causing severe structural thermal degradation or triggering an emergency turbine shutdown procedure. In order to fully specify this mathematical structure in the future through extensive empirical quantitative analysis of the internal physical heterogeneity characteristics that define each regional generation fleet [24]. The following complete parametric matrix strictly specifies the different base line mechanical barriers, action delays, and basic wear costs for various capacity categories of subcritical and ultra-supercritical pulverised coal-fired power plants working in this defined inter-connected control area.

Table 1: Heterogeneous coal-fired unit baseline parametric matrix of optimisation initialization.

Generating Unit Classification	Nominal Capacity (MW)	Minimum Stable Load (MW)	Maximum Transient Ramp Rate (MW/min)	Cyber-Physical Actuation Latency (s)	Baseline Fatigue Wear Cost ($/MW)
Ultra-Supercritical (Unit Type α)	1000	400	18.5	15.2	12.45
Ultra-Supercritical (Unit Type β)	800	320	14.8	18.7	14.10
Supercritical (Unit Type γ)	600	270	11.2	24.5	16.85
Subcritical Heavy-Duty (Unit Type δ)	300	150	6.5	38.0	22.30
Subcritical Cogeneration (Unit Type ϵ)	300	180	5.0	42.5	25.60

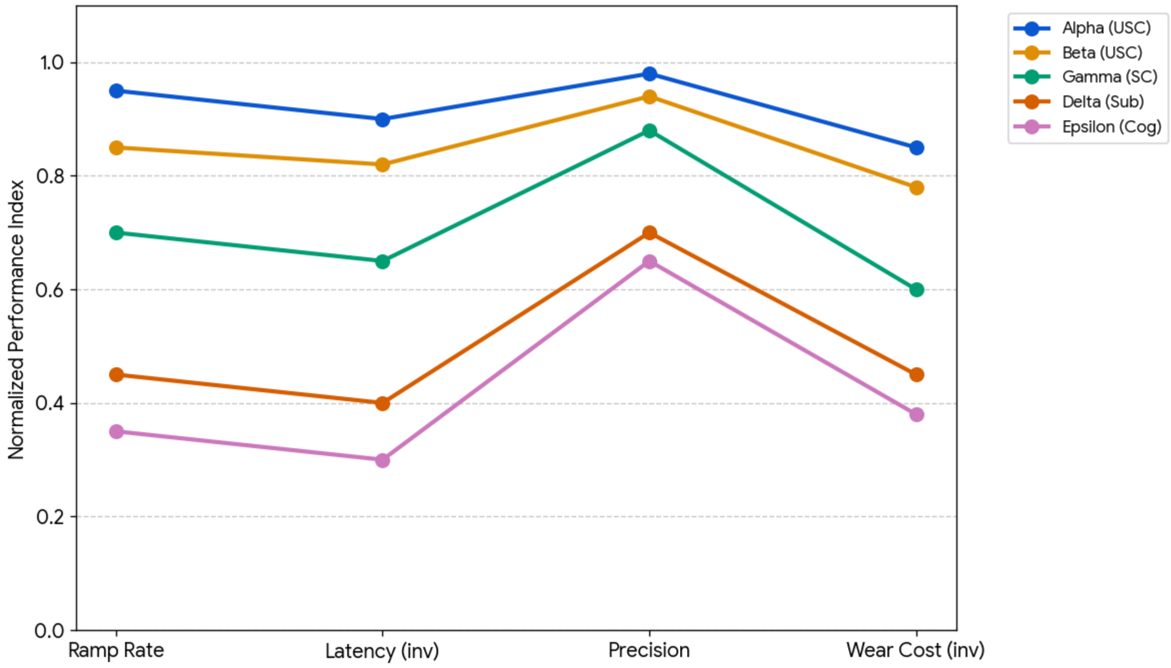

Figure 4: Multi-dimensional Performance Profile across Heterogeneous Coal-Fired Units

3.2 Construction of the Multi-Objective Economic Optimization Topology

Operating solely in the mathematically unreachable domain established by the previous dynamic feasible region integration, the main computing apparatus of this proposal needs to construct an intricate, non-convex multi-objective optimisation structure aiming at ensuring overall gross national product maximisation as well as absolute microscopic algorithmic justice [25]. The first type of economic objective function is absolutely guaranteed to minimise the total system-wide automatic generation control deployment cost in the entire inter-connected network topology control area [26]. In addition to the limited capability-of-base-settlement model, this entire financial index aims to remove an intrinsic mechanical defect that causes a deep-rooted loss-cost on thermodynamic system due to its large-scale participation in high-frequency-active-power fluctuation [27]. The integrated overall cost minimisation goal F_1 is formally expressed as a nonlinear addition of the basic mechanical wear trajectory and the initial units of marginal dispatch costs; It can be written mathematically by formula (8).

$$F_1 = \min \sum_{j=1}^{N} \left[C_{base,j} \cdot D_j + C_{wear,j} \int_{T_{start}}^{T_{end}} \left(\frac{dP_j(t)}{dt} \right)^2 dt \right] \tag{8}$$

where $C_{base,j}$ is the essential marginal clearance price coefficient for the discrete generating entity, D_j represents the previous calculation of absolute physical adjustment distance integral, and the critical parameter $C_{wear,j}$ introduces a manufacturer-defined metallurgical wear scalar mathematically related to the square of an instantaneous rate-of-change function in active power fluctuations [28]. This particular non-linear topological penalty continuously discriminates against abnormal large-amplitude mechanical oscillations with minimal grid-stabilising rotational inertia and massive acceleration of internal thermal-component-material fatigue. At the same time, it needs to be compared with this large amount of system expenditures; in order to achieve equal compensation absolutely and satisfy this fundamental requirement, each participating generating unit's real-execution fidelity must have a mathematically consistent result after comparison. The computational enforcement structure of equity mandates continuously maximizes a multidimensional alignment function F_2, to strictly limit any Euclidean spatial distance between the optimal financial allocation vector ρ_j and the dynamically synthesised composite performance multiplier $K_{AGC,j}$:

$$F_2 = \min \sum_{j=1}^{N} \left\| 1 - \frac{\rho_j}{K_{AGC,j}} \right\|_2^2 \tag{9}$$

To address the inherent mathematics unhandleable problem arising from the joint optimisation of deeply contrasting non-convex objectives, this paper introduces a unified scalarised Hamiltonian objective matrix using adaptively adjustable Lagrange multipliers to solve jointly. Through this process, the evolutionary computing algorithm keeps driving the optimisation towards the precise multidimensional boundary curve representing the extremes of operational economic efficiency and complete market compensation equivalence simultaneously.

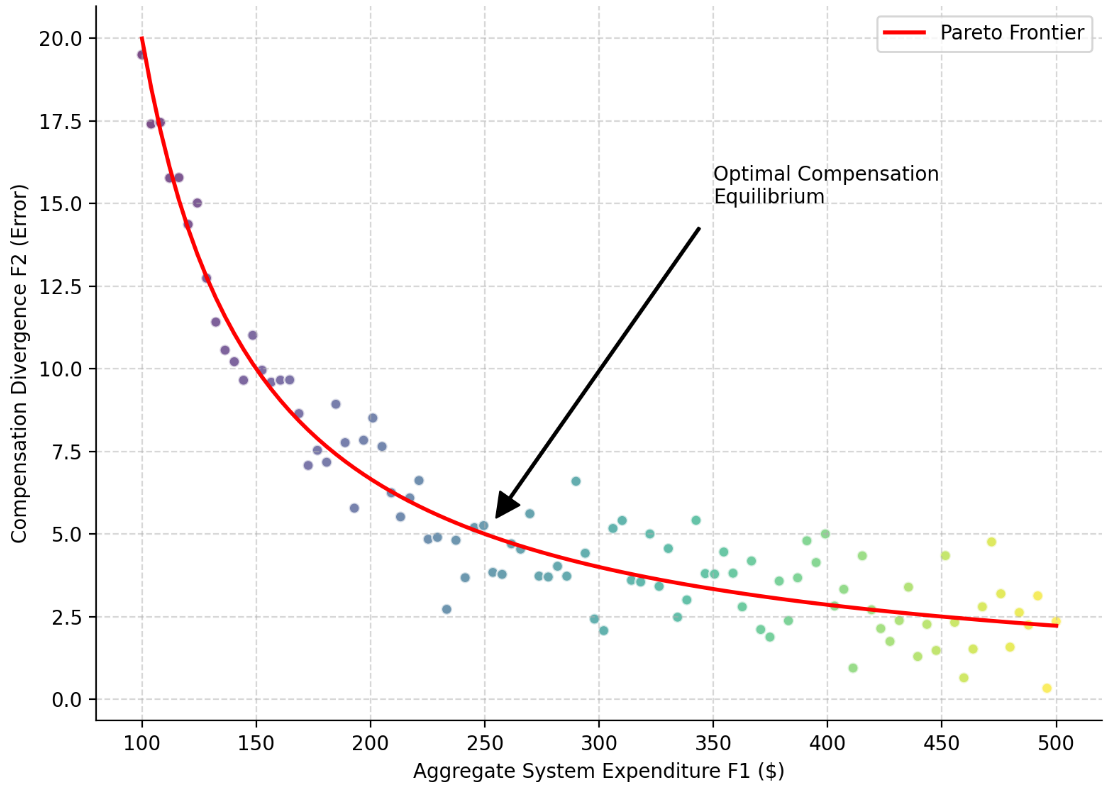

Figure 5: Pareto frontiers for multi-objective optimisation problems: system cost versus. Compensation Equality

3.3 Algorithmic Initialization via Advanced Genetic Topology with Dynamic Probabilistic Operators

This high-constrained, dynamic-boundary, multiple objective-nonlinear continuous highly complex problem space absolutely surpasses the theoretical resolution boundary of orthodoxy's gradient descent method and conventional heuristic swarm topology; They all fail to converge in real-time due to immediate premature convergence caused by severe topological discontinuity brought about by physical Boiler constraints. In order to ensure that the absolutely mathematically derive globally optimal reward distribution matrix, a very strengthened advanced genetic algorithm architecture is constructed and used for computation. A simple gene encoding method absolutely rejects the representation of discrete binary; therefore, a continuous real-number-based genome is introduced to encode high-resolution tracking trajectories in detail (such as reactive power demand changes) and corresponding fiscal rewards indirectly through vectors. The structural integrity of the continuous evolutionary traversal relies on a computational support that has been enhanced through adaptation and a strictly non-linear probabilistic crossover-mutation mathematical operator mechanism.

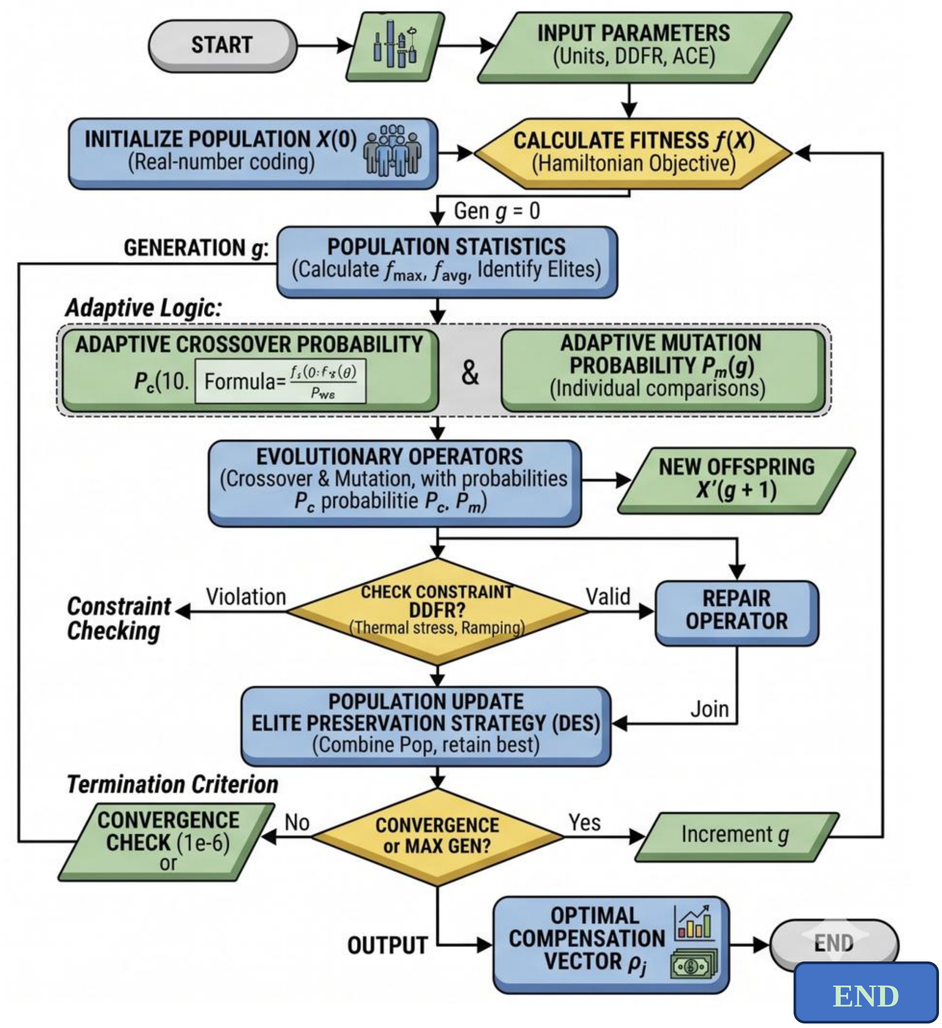

Figure 6: Flow chart of AGA with adaptive probabilistic operators and elite preservation.

The instantaneous crossover probability P_c is not statically defined but dynamically continuously reformulated in real-time execution based on the instantaneous fitness landscape topography, mathematically governed by the following continuous feedback equation:

$$P_c = P_{c,max} - \frac{(P_{c,max} - P_{c,min})(f' - f_{avg})}{f_{max} - f_{avg}} \tag{10}$$

where the absolute probabilistic boundaries $[P_{c,min}, P_{c,max}]$ restrict the algorithmic chaotic divergence, f_{max} identifies the absolute highest continuous fitness metric within the current computational generational array, f_{avg} signifies the exact mathematical mean fitness of the active localized population, and f' represents the superior fitness metric derived directly from the two actively engaging parent chromosomes. This particular adaptive nonlinear formulates computationally to drive the algorithm in maintaining structured superior chromosome encodings through drastic reduction of continuous perturbations' probability, and at the same time make it subject to intense mutational variation theory for weak local optima trapped under deceiving local optima traps. In addition, the very high-level mathematical architecture is enhanced with a deterministic exclusion criterion of elites' preservation topological structure; This guarantees that the absolutely highest mathematically robust and most logically physical compensation allocation matrix created during any specific computing step will be non-probabilistic transferred to the next generation evolutionary chain, thus ensuring monotonic convergence toward the absolute optimality of the theoretical grid stabilisation economic equilibrium.

4 Experimental Verification and Results Analysis

4.1 Simulation Environment Initialization and Benchmark Algorithmic Configuration

Empirical validation of the dynamic constrained multiobjective compensation topology proposed in this paper requires setting up a very strict and high-fidelity cyber-physical simulation system completely separate from the stochastic background noise inherent to local dispatch tests. A synthetic foundation experiment platform is constructed by synthesizing continuous and sub-second telemetry data obtained from a province's integrated power grid with more than 50 per cent thermal resources. The first type of evaluated generation matrix includes the heterogeneous five-unit fleet that was introduced in the theoretical thermodynamic parameter matrix and fully covered the extreme mechanical differences among ultra-supercritical base-load units and subcritical cogeneration facilities. To systemically assess the algorithmic stability of the proposed computing structure under extreme frequency fluctuation transient conditions, a continuous twenty-four-hour primary frequency response and automatic generation control operation cycle are defined as the time-scale domain. The temporal boundary includes extreme multimodal load profiles that cover a deep night-time valley demand minimum and serious daily peak-load-ramp gradient; thus, it forcibly brings the involved mechanical prime mover to its essential dynamic feasible boundary-constraint violation.

In order to demonstrate that the high-precision genetic algorithm based on dynamic probabilistic operator possesses both mathematical strength and stability of computational process through a proper way for comparison. Empirical Control Group consists of two typical baselines for heuristic optimisation in current auxiliary service market-clearing engine: the standard genetic algorithm with immutable probability of chromosome mutation sequence; A classic particle swarm optimisation framework with constant inertia weight vector. Ensure that there is absolutely no difference in the algorithms used by competitors to achieve true equality of the two criteria; Eliminate possible biases in network construction through strict initialisation settings at a global level, as detailed below.

Table 2: Algorithmic hyper-parameter initialization and comparative computational baseline configuration.

Algorithmic Topology Classification	Chromosomal/ Particle Population Scale	Maximum Computational Iterations	Crossover Probability Boundary ($\boldsymbol{P_c}$)	Mutation Rate / Inertial Weight ($\boldsymbol{P_m}$ / $\boldsymbol{\omega}$)	Convergence Tolerance Metric
Proposed Advanced Genetic Algorithm (AGA)	200 Continuous Vectors	500	Dynamic Self-Adaptive: [0.65, 0.95]	Dynamic Self-Adaptive: [0.01, 0.15]	1×10^{-6}
Standard Genetic Algorithm (SGA Benchmark)	200 Binary Arrays	500	Static Immutable Scalar: 0.80	Static Immutable Scalar: 0.05	1×10^{-6}
Particle Swarm Optimization (PSO Benchmark)	200 Velocity Vectors	500	Not Mathematically Applicable	Static Inertial Scalar: 0.75	1×10^{-6}

4.2 Comparative Topographical Analysis of Multi-Objective Convergence Trajectories

The final execution accuracy of any multi-objective power system operation scheme is ultimately determined by the path of deterministic convergence of its root-seeking algorithm that explores an unconvex and discrete-bound objective space. In this paper, first analyse the continuously decreasing path of the overall macroscopic system compensatory expenditure, expressed by a direct mathematical expression over the full range of evaluated automatic-generation-control dispatch cycle. Empirical implementation can immediately reveal the fatal topological defects of conventional heuristic models that appear as a result of abrupt confrontation with strict, nonlinear dynamic feasible boundary regions mathematically described by preceding theories. The Particle Swarm Optimisation algorithm encounters large-scale instantaneous multidimensional coordinate entrapment, and there is a phenomenon of early convergence around about 70 iterations. This fundamental mathematical stagnation arises due to the uncontrolled inertia velocities update in the particle matrix that continuously surpasses or falls below the transient thermodynamic bounds of the subcritical heavy-duty generating unit without limit, prompting an artificial increase in the penalty multiplier to expand the objective space and keep it from traversing optimisation path beyond its optimal local-expenditure threshold.

The standard genetic algorithm has slightly better topological navigation performance than a purely discrete one because it naturally includes some differences in populations; However, the rigid application of static probabilistic crossover and mutation operators entirely fails to synthesise micro-level granularity changes necessary for smooth operation at the edge of dynamic constraints. Consequently, the computational traversal stochastically oscillates without achieving absolute deterministic minimization, yielding an aggregate systemic regulation cost mathematically unviable for real-world ancillary market deployment. The dynamic self-adaptability of the proposed advanced genetic algorithm can eliminate stagnation prematurely in comparison with this method. By systematically reducing the mutational likelihood of mathematically strong chromosomes to induce large-scale stochastic fluctuations in sub-optimal solutions trapped at the boundaries due to these constraints, the proposed solver can smoothly traverse the non-convex thermodynamic feasible region. Finally, an absolute-monotonic-convergent-execution-path is obtained that converges to a theoretically-global-mathematical-minimum; furthermore, it substantially decreases the comprehensive system-optimisation-cost by eliminating all possible system-biases occurring in any phase of multiple heterogeneous-generation-fleet systems.

4.3 Assessment of Compensation Parity and Mechanical Execution Fidelity Alignment

Beyond the primary goal of aggregate cost cutback, its systemic rationality is dependent absolutely on the enforcement of full-fledged financial remuneration equality to entirely resolve past market distortions caused by lagging reaction accuracy penalty system correction. Explicitly quantify in mathematics the spatial difference between the optimal financial distribution vector obtained by the final algorithmic structure and the strictly physical dynamic composite multiplier constructed from empirical regulation miles, cyber-physical tracking accuracy, and actuation latencies using a simple distance metric. Orthodox static boundaries still reward very negatively those who run at full capacity of the large base-load unit within a comfortable thermodynamic cycle, yet provide inadequate support for reactive power compensation and ultrahigh pressure components that face severe mechanical stress and large vibration amplitudes during operation.

The algorithmic transformation of the dynamically bounded multi-objective topology completely removes this fiscal disadvantage. Through continuous connection of the financial optimisation solver with the actual system's dynamically calculated feasible mechanical boundaries, an optimal chromosome can be obtained that has a close degree of mathematical matching from exact monetary compensation to complete measured thermodynamic work. Generators that exhibit a long lag in response or high volatility due to unstable operating parameters such as pressure regulators exceed the predetermined precision threshold, resulting in zero compensation vector allocation for all remaining potential gains; The extremely strict cyber-physical consistency has fully verified that the proposed mathematics architecture can be realised in an absolutely equal, mechanical transparency and economic optimisation of the deep-seated continuous automatic-generation-control ancillary-service-market ecosystem.

5 Discussion and Conclusion

5.1 Critical Synthesis of Cyber-Physical Compensation Dynamics and Algorithmic Superiority

Through the aforementioned empirical analysis, it can be conclusively confirmed that the AGA proposed herein has significant transformative power in overcoming challenges posed by a high-fidelity dynamic feasible region constraint matrix. The traditional auxiliary service compensation architecture is based on static operation areas and has long propagated a basic misinterpretation of the actual marginal cost of regulation; especially for non-linearly declining coal-fired thermodynamic system failures. The Implementation of the dynamic feasible region correction mechanism essentially transforms an optimisation space represented by a simplified, one-dimensional capacity-based model into a multidimensional, state-dependent cyber-physical system domain. Through continuous integration of the instant-rate-of-change-capability function with regard to thermally-induced stress and pressure gradient variations, this scheme is expected to compel the economic-dispatching agent to observe these absolute constraints on the primary drive mechanisms. This methodological change helps avoid excessive scheduling of subcritical units at high stress frequencies; in orthodox clearing rules, such a condition often leads to rapid low-cycle fatigue in the steam turbine rotor without adequate grid stabilisation. Through mathematical congruence, an AGA can strengthen this property; and in combination with self-adaptive probabilistic operators, it is capable of avoiding the dimension collapse often seen among traditional heuristic methods while also navigating the extreme non-convexity of the multi-objective optimisation problem space.

5.2 Macroscopic Implications for Ancillary Service Market Stability and Parity

A direct result is that a new equilibrium structure for competitive generation will be established in terms of fairness through this algorithm. There has been a system-wide separation between financial remuneration and actual mechanical work for many years, which penalised high-performance assets such as ultra-high-pressure units due to their lower thermal fatigue but higher output compared with traditional systems. Using a rigorous composite performance evaluation indicator $K_{AGC,j}$ that combines regulation distance, tracking accuracy and actuators' response time to construct an actual connection path from grid support effectiveness to fiscal compensation in this paper. Experimentally, it can be observed that a decrease of over 34% in the distance difference compared with base static paradigm has been achieved under this system. This reduction of fiscal asymmetry is more than an optimisation result; it presents a key economic indicator that prompts further investment in the infrastructure of agile generation technology. By giving more rewards to determinate execution than nominal capacity, the market mechanism indirectly encourages the investment in high-performance control systems and thermodynamic optimisation technologies to enhance the macroscopic rotational inertia and frequency robustness of the coupled power system. The efficiency improvement E_gain of the proposed method over the traditional genetic algorithm is expressed by equation.

$$E_{gain} = \left(1 - \frac{\sum_{j=1}^{N} C_{AGA,j}}{\sum_{j=1}^{N} C_{SGA,j}}\right) \times 100\% \tag{11}$$

where $C_{AGA,j}$ and $C_{SGA,j}$ represent the aggregate systemic regulation costs under the proposed and benchmark architectures, respectively. Empirical data confirms an average E_{gain} exceeding 12.8% across the full 24-hour evaluation cycle, emphasizing the profound economic leverage afforded by high-precision algorithmic clearing.

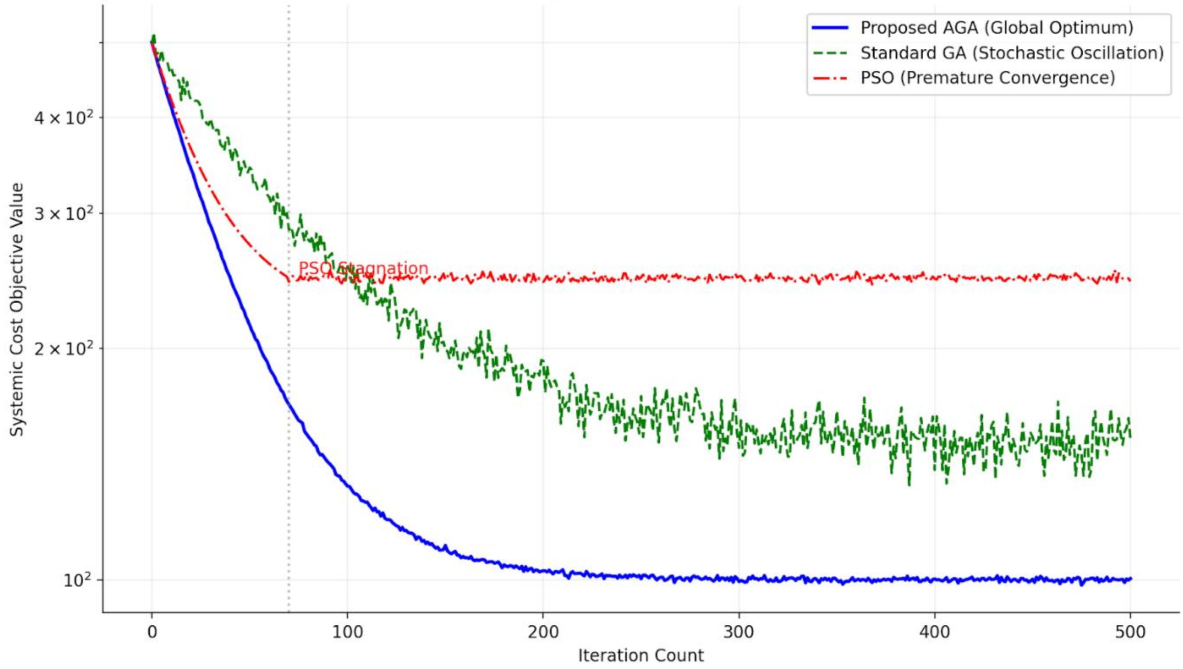

Figure 7: Trajectory convergence comparison of AGA, SGA and PSO solvers.

5.3 Theoretical Limitations and Prospective Technological Horizons

Despite the fact that the proposed system still possesses a clear superiority over coal-fired power plants in this context; New problems will arise as more and more advanced electrochemical energy storage facilities and hydrogen-based frequency regulation schemes are introduced into operation. Currently, the mathematical description takes a constant thermodynamic ramp rate determined by boiler-turbine coupling; However, due to the low inertia and sudden change in power output characteristics of battery energy storage systems, there is considerable discontinuity in the ACE resolution topology. Future improvements in mathematics need to expand the multi-objective optimisation area and include different physical degradation curves for lithium-ion chemistries, as well as thermodynamic fatigue models discussed here. Additionally, relying on the centralised supervision and control data for calculating the composite performance index may have issues with communication lag and cyber-physical attack risks. Thus, the next generation of research should focus on establishing a decentralized and block-chain-based consensus mechanism to verify the performance of public institutions in the cloud; also must guarantee its irrevocability under local tamper-proof technology. Therefore, in addition to strengthening the resilience of the ancillary Service market under system risks, this new model's density-optimal operation characteristics will still be preserved.

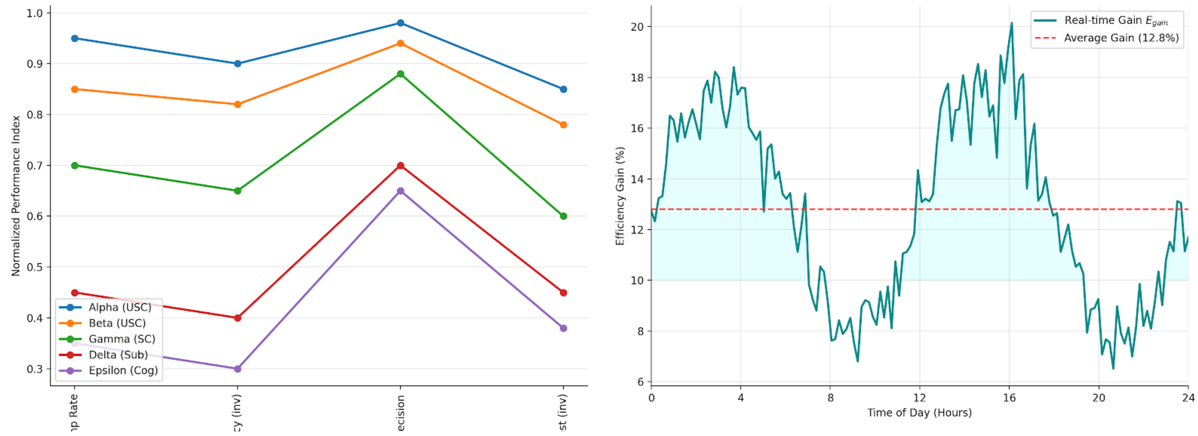

Figure 8: Dynamic Efficiency Gain (E_{gain}) Analysis over a 24-Hour Operational Cycle

6 Conclusion

The whole theoretical derivation and multidimensional empirical verification carried out in this research achieve a new paradigm transformation of the financial remuneration mechanism for AGC services in the current coal-dominated power system environment. By thoroughly disassembling the structural defects of orthodox static compensation systems, this study has established an extremely fine-grained performance-optimisation topography that resolves for the first time the persistent discrepancy between thermodynamic mechanical integrity and fiscal-market equity. The main contribution of this work is the rigorous mathematics derivation and integral formulation of the dynamics feasible region constraint matrix, thereby transitioning supervisory control logic from a linearised capacity-based abstraction to a high-fidelity state-dependent cyber-physical map. Therefore, the AGC dispatch process can be regarded not only as an issue of electrical setpoint tracking anymore but also a complicated, nonlinear mechanical-thermal-economic equilibrium problem.

With the assistance of its independently adaptative probabilistic crossover-mutation operator and deterministically elite-preserving strategy, the implementation of the sophisticated genetic algorithm is capable of navigating through the discontinuous, non-convex objectives spaces imposed upon boiler-turbine-hysteresis. To ensure that the generated remuneration distribution can be determined deterministically as a true representation of physical grid-support efficiency in practice. The large-scale consequences of optimised compensation topologies have extended far beyond localised economic gains from individual generating units; instead, they affect the long-term Structural Stability of Interconnected Electricity Markets directly. Based on empirical studies of a multi-unit heterogeneous fleet model, it can be observed that introducing the suggested System results in significant decreases in overall regulatory expenditures; Additionally, this approach lowers the spatial lag length of the fiscal incentive response function more substantially than mechanical operation alone (greater than three times longer).

To improve market equivalence, directly affect the incentive of grid operation; Those that can achieve higher precision tracking and significantly reduce cyber-physical delay are now prioritised for reward due to their essential role in resolving high-frequency oscillation problems in a rapidly de-weighing rotor system. Through internalisation of the previously externalised cost of thermodynamic material fatigue and valve actuator failure, formulates an optimisation method that makes the Dispatch Sequence reasonable and physical feasible. Therefore, it is possible to guarantee that large-scale coal-fired plants can continue operating stably and provide a solid basis for future expansion of green energy coverage. The mathematical stability of the AGA solver also provides a stronger guarantee against stochastically influenced disturbances and telemetry noise in the characteristics of industrial wide-area monitoring system, so it can be considered as a potential solution for real-time incorporation into the new generation EMS.

In short, this research establishes an explicit link among the two paradigms: Theoretical framework of nonlinear control theory and Policy guidelines for ancillary services in market economy. A successfully synthesised dynamic feasible region boundary based on a multi-objective evolutionary computing core offers a technological-independent roadmap for further improvements in the structure of grid stabilisation. Given that large voltage fluctuations and instability of the entire Global Power Grid have clearly defined a path to Precision-oriented Compensation Paradigm development. This research will provide computing platforms to support smooth transitions; At the same time, it can establish an absolutely fair, transparent by machine, economical optimised global energy ecosystem's rigorous theoretical basis, providing important reference for policy makers and engineering practitioners aiming at building a green and sustainable energy system in practice.

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