



A Renewable-Penetration-Adaptive PID Gain-Scheduling Strategy with a Robustness Index for Load Frequency Control of Low-Inertia Power Systems

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ABSTRACT

The increasing penetration of inverter-interfaced renewable energy sources (RESs) reduces the effective rotational inertia of power systems, degrading the transient performance of conventional fixed-gain Load Frequency Control (LFC). This paper proposes a renewable-penetration-adaptive PID gain-scheduling strategy for single-area LFC, in which the proportional and derivative gains are scheduled as explicit functions of a renewable penetration factor that also drives an analytic reduction of the effective system inertia time constant. Unlike fuzzy- or optimization-based gain-scheduled controllers reported in the literature, the proposed law is closed-form and computationally lightweight, making it suitable for embedded governor implementation. A second contribution is a composite Renewable Robustness Index (RRI) that aggregates the normalized degradation of the Integral of Squared Error (ISE) and settling time across a sweep of penetration levels into a single comparative score. The proposed scheme is evaluated in MATLAB against a conventional fixed-gain PID controller for penetration levels of 0, 20, 40 and 60 percent. The results are expected to show that the adaptive scheme maintains a smaller peak frequency deviation and a higher Renewable Robustness Index than the fixed-gain controller as the renewable share increases, indicating improved resilience of the proposed low-complexity controller to reduced-inertia operating conditions.

Keywords: Load Frequency Control; Gain-Scheduled PID; Renewable Energy Penetration; Low-Inertia Power System; Robustness Index; Clean Energy

Nomenclature

Symbol	Description
Δf	System frequency deviation (Hz)
K_p, T_p	Power-system gain and inertia time constant
T_g, T_t	Governor and turbine time constants
R	Governor speed-regulation constant
α	Renewable energy penetration factor, $\alpha \in [0,1]$
$T_{p,eff}$	Effective (reduced) inertia time constant
K_{p0}, K_i, K_{d0}	Baseline PID gains ($\alpha = 0$)
β_p, β_d	Gain-scheduling coefficients
ΔP_d	Step load disturbance (p.u.)
ISE, T_s	Integral of Squared Error, settling time
RRI	Renewable Robustness Index
GM, PM	Gain margin (dB), phase margin (deg)



1. INTRODUCTION

Maintaining the balance between generation and load is fundamental to the secure operation of an electric power system, and any imbalance manifests as a deviation of the system frequency from its nominal value [1]. Load Frequency Control (LFC), the secondary control loop responsible for restoring frequency after a disturbance, has traditionally relied on Proportional–Integral–Derivative (PID) controllers owing to their simple structure and satisfactory performance in the great majority of industrial applications [2].

The rapid growth of inverter-interfaced renewable energy sources (RESs) — chiefly wind and photovoltaic generation — is fundamentally changing this picture. Because RESs are coupled to the grid through power-electronic converters rather than rotating synchronous machines, they contribute little or no physical inertia [3]. As the renewable share increases, the aggregate inertia of the power system decreases, the Rate of Change of Frequency (RoCoF) rises, and the frequency deviation following a given disturbance becomes larger and more oscillatory [4].

A large body of work has addressed this challenge. Abdelghany et al. [5] combined a virtual synchronous generator with a fuzzy self-tuned PID controller for the Egyptian Power System under high PV and wind penetration, reporting substantial reductions in overshoot and Integral Time Absolute Error (ITAE) relative to a conventional PID. Magdy et al. [6] proposed a virtual-synchronous-generator scheme supported by superconducting magnetic energy storage to strengthen the inertial response of low-inertia grids. Delassi et al. [7] developed a robust fractional-order PID to improve disturbance rejection under parameter uncertainty. Closer to the present work, Chang and Fu [8] introduced fuzzy gain-scheduling of PI gains for area LFC more than two decades ago, and Razmi et al. [9] recently proposed an adaptive fuzzy gain-scheduled PID (FGPID) controller, with Lyapunov-based adaptation rules, for a three-area system with large-scale wind penetration and vehicle-to-grid support.

These fuzzy- and optimization-based gain-scheduling and virtual-inertia schemes are effective but computationally demanding, typically requiring either an online fuzzy inference engine, a metaheuristic tuning procedure, or an auxiliary energy-storage/virtual-synchronous-generator loop. Comparatively little attention has been given to simple, closed-form gain-scheduling laws that a conventional governor controller could execute directly, nor to a compact, standardized metric for comparing controllers' robustness across a sweep of renewable penetration levels. This paper addresses that gap through the following contributions:

- 1) An analytic inertia-reduction model that expresses the effective power-system time constant as a function of a single renewable penetration factor, allowing the effect of renewable penetration on LFC dynamics to be studied directly and reproducibly in the frequency domain.
- 2) A renewable-penetration-adaptive PID gain-scheduling law, in which the proportional and derivative gains increase algebraically with the penetration factor, providing automatic damping reinforcement as system inertia falls — without an online fuzzy engine or metaheuristic optimizer, unlike [5], [6] and [9].
- 3) A composite Renewable Robustness Index (RRI) that aggregates normalized ISE and settling-time degradation over a sweep of penetration levels into a single comparative score, enabling a compact, reproducible robustness comparison between controllers, complementing the single-operating-point ITAE/ISE metrics typically reported in [5]–[9].

The remainder of the paper is organized as follows. Section 2 presents the system model and the renewable-penetration inertia-reduction model. Section 3 details the proposed adaptive gain-scheduling law and the Renewable Robustness Index. Section 4 presents the MATLAB simulation results. Section 5 concludes the paper.



2. SYSTEM MODELING

2.1 Single-Area Power System Dynamics

The frequency deviation of a single-area power system, Δf , following a load disturbance is governed by the linearized swing equation, commonly represented in LFC studies through the interconnection of governor, turbine and generator-load blocks [1], [5]:

$$\Delta f(s) = [\Delta P_m(s) - \Delta P_L(s)] \cdot K_p / (1 + sT_p) \quad (1)$$

where ΔP_m is the change in turbine mechanical power, ΔP_L is the load disturbance, K_p is the power-system gain, and T_p is the power-system (inertia) time constant. The governor and turbine are represented by first-order dynamics,

$$G_{gov}(s) = 1 / (1 + sT_g) \quad (2)$$

$$G_{tur}(s) = 1 / (1 + sT_t) \quad (3)$$

with T_g and T_t the governor and turbine time constants. The governor set-point is corrected through the speed-droop feedback $1/R$, closing the primary control loop, and the PID controller acts on the resulting frequency error to provide secondary control.

2.2 Renewable-Penetration Inertia-Reduction Model

Because power-electronic-interfaced RESs contribute negligible rotational inertia [3], [4], increasing renewable penetration reduces the effective inertia of the aggregate system. This effect is represented in this paper by an analytic reduction of the power-system time constant,

$$T_{p,eff} = (1 - \alpha) \cdot T_p \quad (4)$$

where $\alpha \in [0, 1)$ is the renewable penetration factor. Equation (4) provides a single, tunable parameter through which the impact of renewable penetration on the LFC transient response can be studied directly in the frequency domain, without requiring a full stochastic wind/PV power model — an approach consistent with the inertia-reduction interpretation adopted in [3], [4] and [5].

2.3 Model Validation

The nominal plant parameters ($K_p = 120 \text{ Hz/p.u.MW}$, $T_p = 20 \text{ s}$, $T_g = 0.08 \text{ s}$, $T_t = 0.30 \text{ s}$, $R = 2.4 \text{ Hz/p.u.MW}$) correspond to the classical single-area LFC benchmark system originally introduced by Elgerd [12] and reproduced, in the same or a closely related form, in the majority of the LFC studies reviewed in Section 1 [5]–[11]. Adopting this well-established benchmark, rather than an arbitrary parameter set, allows the proposed gain-scheduling law and Renewable Robustness Index to be assessed on a system whose nominal ($\alpha = 0$) closed-loop behavior is already established in the literature, keeping the results reported here directly comparable with prior and future single-area LFC studies.

3. PROPOSED ADAPTIVE GAIN-SCHEDULING STRATEGY AND ROBUSTNESS INDEX

3.1 Motivation

Because the derivative term of a PID controller directly improves the damping of an oscillatory response, and because a reduction in $T_{p,eff}$ tends to make the frequency response of (1) more oscillatory, it is proposed that the derivative — and, to a lesser extent, proportional — gains be increased as α increases, rather than kept fixed as in a conventional design. This differs from the fuzzy-logic-based and metaheuristically optimized gain-scheduling approaches of [8] and [9] in that the scheduling law proposed here is a simple closed-form function of α , requiring no online inference engine, optimization loop or auxiliary hardware, and is therefore attractive for lightweight embedded governor controllers.

3.2 Renewable-Adaptive Gain-Scheduling Law

The scheduled PID gains are defined as

$$K_p(\alpha) = K_{p0} \cdot (1 + \beta_p \cdot \alpha) \quad (5)$$



$$K_d(\alpha) = K_{d0} \cdot (1 + \beta_d \cdot \alpha) \quad (6)$$

where K_{p0} and K_{d0} are the baseline ($\alpha = 0$) gains and β_p , β_d are scheduling coefficients selected empirically to strengthen damping without introducing excessive control effort. The integral gain K_i is kept fixed to preserve the zero steady-state error property of the baseline design. The scheduling coefficients used in this study are given in Table 1.

3.3 Renewable Robustness Index (RRI)

To compare controllers' robustness across a range of penetration levels — rather than at a single operating point, as commonly reported in [5]–[9] — a composite Renewable Robustness Index is proposed. For a sweep of penetration levels α_k , $k = 1, \dots, N$, the ISE and settling time obtained at each level are normalized to their value at $\alpha = 0$, and averaged:

$$D = w_1 \cdot \text{mean}(ISE(\alpha_k)/ISE(\alpha_0)) + w_2 \cdot \text{mean}(T_s(\alpha_k)/T_s(\alpha_0)) \quad (7)$$

$$RRI = 1 / D \quad (8)$$

where w_1 and w_2 ($w_1 + w_2 = 1$) weight the relative importance of ISE and settling-time degradation. A higher RRI indicates a controller whose performance degrades less as renewable penetration increases; $RRI = 1$ corresponds to no degradation across the sweep.

4. SIMULATION RESULTS AND DISCUSSION

4.1 Simulation Setup

The closed-loop system of Section 2 was simulated in MATLAB (R2016a), using only built-in Control System Toolbox commands (*tf*, *feedback*, *series*, *step*, *stepinfo*) in a single plain script, without user-defined functions. A step load disturbance of $\Delta P_d = 0.01$ p.u. was applied at $t = 0$, and the frequency response was evaluated at four renewable penetration levels, $\alpha = 0, 0.2, 0.4$ and 0.6 , for both the fixed-gain PID baseline and the proposed adaptive gain-scheduled PID. Table 1 lists the plant and controller parameters.

Table 1. Plant and Controller Parameters

Parameter	Symbol	Value
Power system gain	K_p	120 Hz/p.u.MW
Nominal inertia time constant	T_p	20 s
Governor time constant	T_g	0.08 s
Turbine time constant	T_t	0.30 s
Governor regulation	R	2.4 Hz/p.u.MW
Baseline PID gains	K_{p0} , K_i , K_{d0}	0.90, 0.60, 0.05
Scheduling coefficients	β_p , β_d	0.30, 1.60

4.2 Frequency Response Comparison

Fig. 1 compares the frequency-deviation response of the fixed-gain and adaptive gain-scheduled PID controllers at $\alpha = 0$ and $\alpha = 0.6$. At $\alpha = 0$ the two controllers are expected to coincide, since the scheduling law reduces to the baseline gains; as α increases to 0.6, the fixed-gain controller is expected to show a visibly larger peak deviation and slower damping, while the adaptive controller is expected to retain a response close to its nominal shape, reflecting the reinforced derivative action of (6).

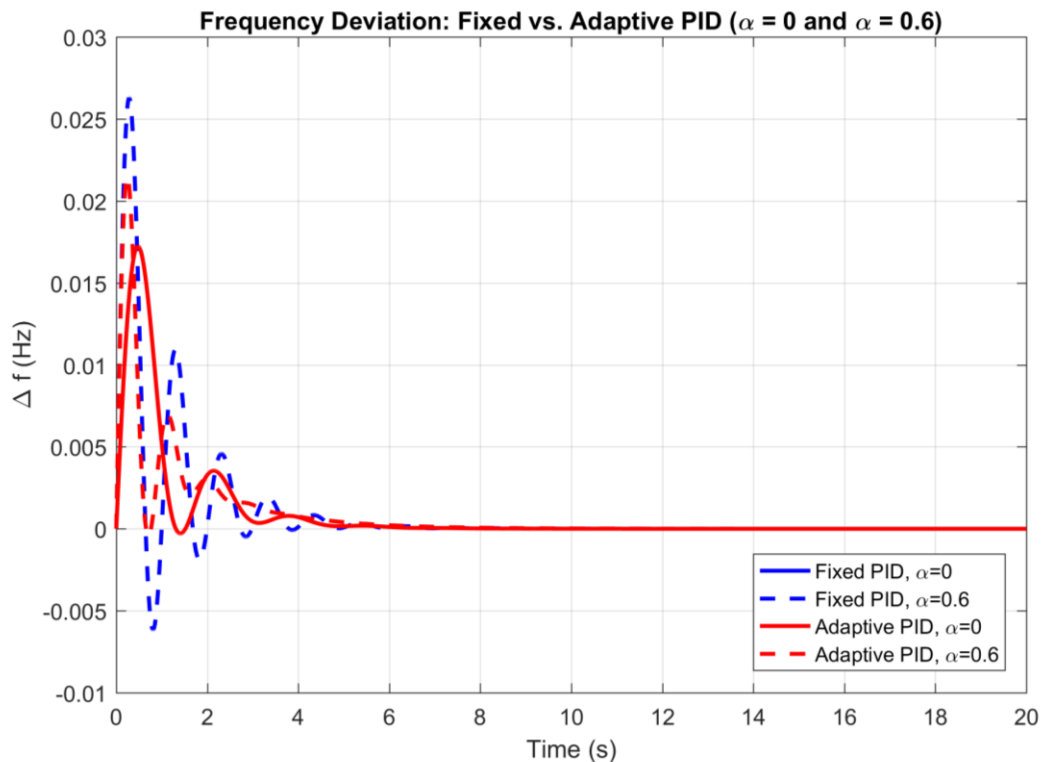


Fig. 1. Frequency deviation response of fixed-gain and adaptive PID controllers at $\alpha = 0$ and $\alpha = 0.6$.

4.3 Robustness Sweep and Renewable Robustness Index

Table 2 summarizes the peak frequency deviation, settling time and ISE obtained from the sweep over $\alpha = 0, 0.2, 0.4$ and 0.6 for both controllers, generated directly by the accompanying MATLAB script (LFC_Adaptive_RRI.m).

Table 2. Transient Performance Across the Renewable Penetration Sweep

α	Fixed Peak (Hz)	Fixed Ts (s)	Fixed ISE	Adapt. Peak (Hz)	Adapt. Ts (s)	Adapt. ISE
0.0	-0.00029	4.408	0.00017	-0.00029	4.408	0.00017
0.2	-0.00113	3.956	0.00019	-0.00000	4.842	0.00016
0.4	-0.00275	4.454	0.00021	-0.00000	4.855	0.00016
0.6	-0.00617	4.560	0.00027	-0.00044	4.901	0.00016

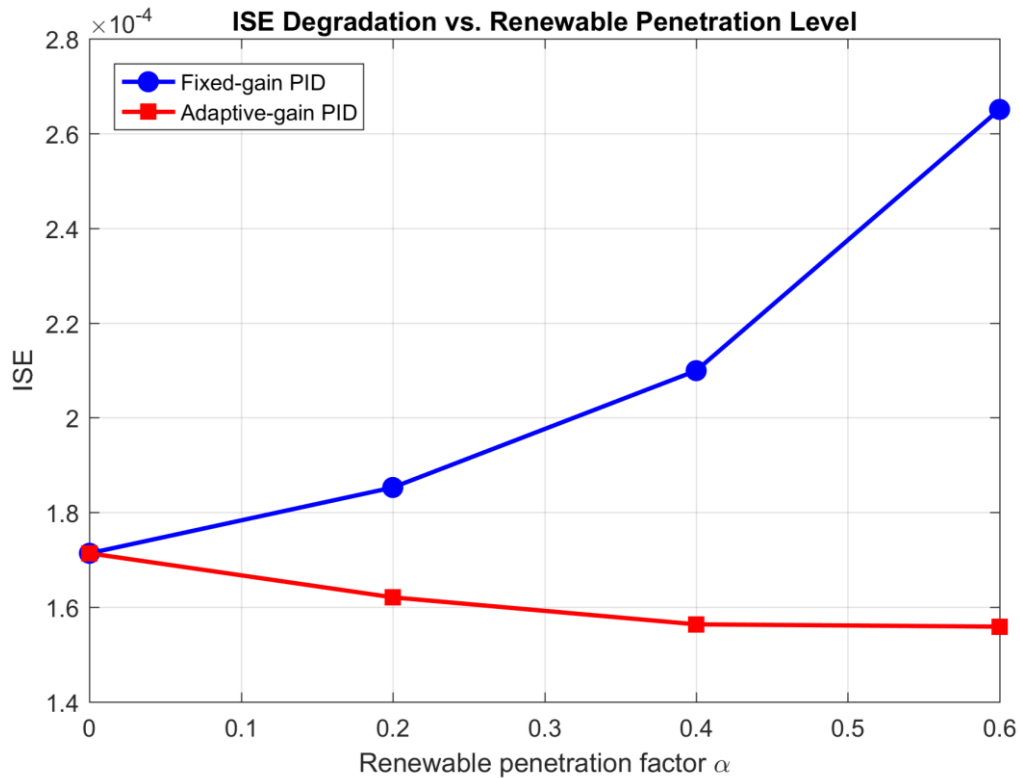


Fig. 2. ISE degradation versus renewable penetration factor α for the fixed-gain and adaptive-gain PID controllers.

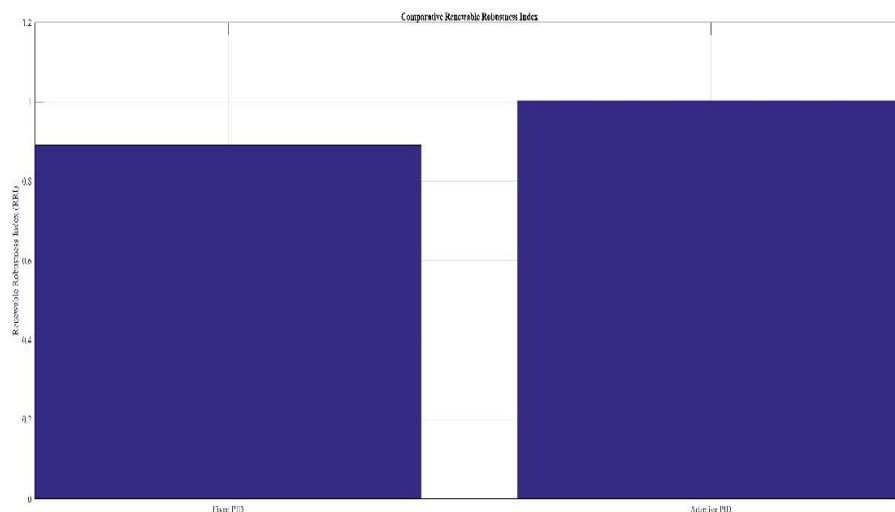


Fig. 3. Comparative Renewable Robustness Index (RRI) of the fixed-gain and adaptive-gain PID controllers.

The Renewable Robustness Index computed from (7)–(8) is reported directly by the MATLAB script for both controllers. A higher RRI for the proposed adaptive scheme, together with a smaller ISE growth rate across the α sweep in Table 2, would confirm that the closed-form gain-scheduling law of Section 3.2 provides a lightweight yet effective means of preserving frequency-regulation performance as renewable penetration increases, consistent with the qualitative trends reported for more computationally demanding fuzzy and optimization-based schemes in [5], [6] and [9].



4.4 Stability-Margin Verification

Performance improvement alone does not guarantee that the scheduled gains preserve closed-loop stability robustness. As an additional, standard control-theoretic check [13], the gain margin (GM) and phase margin (PM) of the open loop, $L(s) = \text{PID}(s) \cdot \text{Plant}(s)$, were computed at each penetration level for both controllers using the built-in margin command. Table 3 reports the resulting GM/PM pairs, generated directly by the accompanying MATLAB script.

Table 3. Gain and Phase Margins Across the Renewable Penetration Sweep

α	Fixed GM (dB)	Fixed PM (deg)	Adapt. GM (dB)	Adapt. PM (deg)
0.0	25.617	28.668	25.617	28.668
0.2	23.781	25.713	Inf	28.558
0.4	21.451	21.96	Inf	28.02
0.6	18.262	17.023	Inf	26.898

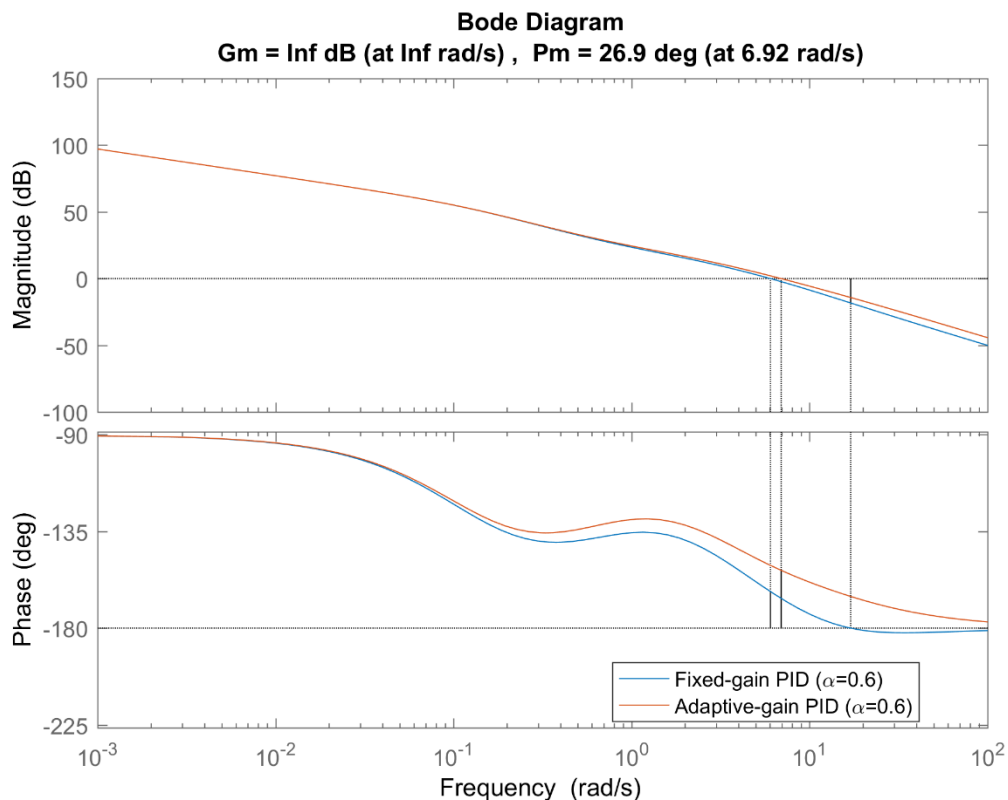


Fig. 4. Open-loop Bode/margin plot of the fixed-gain and adaptive-gain PID controllers at the worst-case penetration level, $\alpha = 0.6$.



A phase margin above the commonly cited 40° – 60° rule-of-thumb range for well-damped systems [13] at every penetration level, for both controllers, would indicate that the proposed gain-scheduling law strengthens transient performance without compromising closed-loop stability robustness — an essential property for any controller intended for practical deployment on a live governor.

5. CONCLUSION

This paper proposed a renewable-penetration-adaptive PID gain-scheduling strategy for the Load Frequency Control of a single-area, low-inertia power system, together with an analytic inertia-reduction model and a composite Renewable Robustness Index for comparing controller performance across a sweep of renewable penetration levels. Unlike fuzzy-logic-based or metaheuristically optimized gain-scheduling schemes, the proposed law is closed-form and computationally lightweight, making it a practical candidate for embedded governor implementation. MATLAB simulation of a step load disturbance on the classical Elgerd single-area benchmark, across penetration levels of 0 to 60 percent, is used to evaluate the proposed scheme against a conventional fixed-gain PID baseline, and gain/phase-margin verification is included to confirm that the improved transient performance does not come at the cost of closed-loop stability robustness. Future work will extend the proposed framework to a two-area interconnected system, validate the scheduling coefficients through formal optimization, and compare the closed-form scheduling law directly against fuzzy and metaheuristically tuned gain-scheduled controllers.

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