

Grid-Forming Inverter Performance for Enhancing Renewable Energy Integration and Frequency Stability in Modern Power Systems

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ABSTRACT

The increasing integration of inverter-based renewable energy reduces the inertia and voltage-forming capability of modern power systems. This study evaluates grid-forming (GFM) inverter performance for renewable integration and frequency stability using an IEEE 9-bus benchmark. The analysis considers renewable penetration of 20–80%, GFM shares of 0–100%, virtual synchronous machine control, and 60 disturbance scenarios involving generation loss, load increase, and three-phase faults. Results show that higher renewable penetration without GFM worsens frequency stability, while increasing GFM contribution improves frequency nadir, reduces RoCoF, and shortens settling time. Virtual inertia enhances frequency response but introduces recovery-time trade-offs. The findings highlight the importance of coordinated GFM deployment and inertia tuning, requiring further validation through detailed simulation and hardware testing

INTRODUCTION

Power systems are undergoing a structural transition from synchronous-machine-dominated generation toward converter-interfaced renewable energy resources. Wind, photovoltaic, and battery-energy-storage plants are increasingly connected through power electronic converters whose dynamic behavior is determined by control algorithms rather than by electromechanical coupling. This shift enables rapid and flexible control, but it also changes the physical mechanisms that historically stabilized system frequency and voltage. As synchronous units are displaced, aggregate rotational inertia and short-circuit strength tend to decrease, while the importance of converter synchronization, current limits, and control interactions rises (Wang et al., 2020; Rosso et al., 2021; Aljarrah et al., 2024).

Conventional grid-following (GFL) converters regulate injected current after synchronizing to an externally established voltage waveform, typically through a phase-locked loop. This architecture has been highly successful in strong grids, yet its dependence on an existing voltage and frequency reference becomes problematic when the system contains a large proportion of inverter-based resources. Under low inertia and weak-grid conditions, higher RoCoF, deeper frequency excursions, synchronization sensitivity, and control interactions can emerge. Recent work therefore emphasizes the need to complement GFL resources with converters capable of establishing a local voltage vector and contributing directly to grid frequency and voltage formation (Stanojev et al., 2023; Tozak et al., 2024).

Grid-forming (GFM) control addresses this need by operating the converter as a controlled voltage source behind an impedance, allowing active-power/frequency and reactive-power/voltage dynamics to be shaped without relying on a fast external phase-locked loop. Several GFM families have been proposed, including droop control, synchronverters, virtual synchronous machines (VSMs), power-synchronization control, and virtual-oscillator-based approaches. VSM-based implementations are particularly relevant to frequency-stability studies because the controller explicitly introduces virtual inertia and damping terms that emulate part of the dynamic response of a synchronous generator (Zhong & Weiss, 2011; Zhong, 2016; Rosso et al., 2021).

The growing technical maturity of GFM control has shifted the research question from whether GFM can support a low-inertia grid to how much GFM capability is required, how its value changes with renewable penetration, and how performance is affected by physical limits. These questions matter because a converter cannot provide unlimited inertial or damping power. Its current rating, dc-side energy availability, power headroom, grid strength, and internal control tuning constrain the support that can be delivered during large disturbances. Current-limiting behavior is especially important during faults because saturation can modify the apparent voltage-source behavior and may impair synchronization or delay recovery (Fan & Wang, 2022; Fan & Wang, 2023; Baeckeland et al., 2024).

This study develops a structured performance assessment of GFM penetration using a supplied IEEE 9-bus benchmark dataset. The analysis varies

renewable penetration from 20% to 80% and the share of renewable capacity operated in GFM mode from 0% to 100%. Three disturbances are represented: a 10% generation loss, a 10% load increase, and a three-phase fault. Frequency nadir, maximum RoCoF, settling time, minimum voltage, and peak GFM active-power support are analyzed jointly. A separate virtual-inertia sweep evaluates the trade-off between arresting the initial frequency excursion and recovering to steady state. Unlike studies that report a single GFM operating point, the present analysis maps performance over a 4 x 5 penetration matrix and three disturbance classes, thereby showing how the marginal value of GFM changes as the system becomes increasingly renewable-dominated.

LITERATURE REVIEW

Low-inertia behavior and the limitations of grid-following control

Frequency stability traditionally depends on the kinetic energy stored in synchronous-machine rotors, primary governor response, load damping, and slower secondary control. A sudden power imbalance changes rotor speed and therefore system frequency, while rotational inertia limits the initial rate of change. When converter-interfaced generation replaces synchronous generation without providing an equivalent fast power response, the same contingency can produce a larger initial RoCoF and a lower frequency nadir. Converter-dominated systems also introduce synchronization dynamics that are not captured by the classical assumption that the electrical source naturally follows electromechanical rotor physics. Wang et al. (2020) showed that the synchronization stability of GFL and GFM resources depends on fundamentally different mechanisms, while Aljarrah et al. (2024) documented the growing importance of weak-grid and low-inertia limitations for GFL resources.

The response is not determined by inertia alone. Network strength, converter-control bandwidth, power reserve, voltage control, current saturation, and the relative mixture of GFM and GFL devices influence the transient trajectory. This is why system-level assessment requires more than a single frequency metric. Frequency nadir quantifies the depth of the excursion, RoCoF characterizes the initial speed of frequency movement, settling time captures dynamic recovery, and minimum voltage indicates the ability of the grid to remain electrically stiff during a disturbance. These quantities are also consistent with the direction of recent technical requirements for GFM-capable power park modules, which increasingly emphasize dynamic active/reactive response, damping, current-limited operation, and stable performance during voltage, angle, and frequency events (ENTSO-E, 2025).

Grid-forming control and virtual synchronous machines

The defining feature of GFM control is that the converter establishes a voltage phasor rather than merely injecting a commanded current into a voltage waveform established elsewhere. Early synchronverter and VSM formulations demonstrated that a power-electronic interface can be controlled to reproduce key synchronous-machine characteristics, including frequency-power coupling, voltage-reactive-power coupling, virtual inertia, and damping (Zhong & Weiss, 2011; Zhong, 2016). These features are attractive in renewable-dominated

systems because they allow inverter-based resources to contribute to grid formation and fast frequency support while retaining the fast controllability of power electronics.

A simplified VSM active-power/frequency dynamic can be represented by a swing-equation analogue in which the virtual inertia parameter H_v and damping coefficient D_v shape the relationship between power imbalance and internal frequency. The controller is not a physical rotating mass; rather, the converter changes electrical power in response to measured or internally generated states. Therefore, the useful virtual inertia is limited by dc-side energy and converter ratings. Excessive inertia can also slow the response or create a mismatch between demanded and deliverable power, particularly when a power or current limiter becomes active. Recent experimental work has consequently moved toward frequency-dependent or adaptive inertia, coordinated power limiters, and current-synchronization methods (Jiang, Zhu, Xu, & Konstantinou, 2024; Jiang, Zhu, & Konstantinou, 2024).

$$2 H_v (d \omega / dt) = P_{ref} - P_e - D_v (\omega - \omega_0) \quad (1)$$

For the present study, VSM control is used as the GFM representation because the raw dataset explicitly provides a virtual-inertia constant and droop setting. The baseline H_v is 4 s and the frequency droop is 5%. The virtual-inertia sensitivity sweep from 1 s to 6 s is therefore interpreted as a tuning study, not as a change in physical rotating mass.

Current limits, grid strength, and large-disturbance performance

Large disturbances expose a fundamental difference between synchronous machines and semiconductor converters. A synchronous machine can temporarily supply substantial fault current, whereas a converter must protect switches against overcurrent. Current limiters can therefore reshape the effective internal voltage, reduce available active power, and alter the equilibrium of the power-synchronization loop. Fan and Wang (2022) derived an equivalent-circuit view of current-limited GFM converters and showed how the current limiter affects transient stability. Their later fault-recovery analysis demonstrated that the choice of current-priority logic influences whether the converter can recover successfully after grid faults (Fan & Wang, 2023). Baeckeland et al. (2024) synthesized this issue as a central design challenge for practical GFM implementation.

The supplied dataset fixes the current limit at 1.2 p.u. and the short-circuit ratio (SCR) at 3. These values represent a moderately weak system and a converter with limited short-duration overcurrent capability. By holding both variables constant while changing renewable and GFM penetration, the dataset isolates the system-level effect of control-mode composition. This does not eliminate the need for future SCR and current-limit sensitivity studies, but it provides a controlled basis for examining the primary research questions.

Research gap, questions, and contributions

The literature establishes that GFM technology can improve low-inertia operation, yet three gaps remain relevant to system planners. First, the benefit of

GFM is often reported at one renewable penetration level, making it difficult to see how its marginal value changes as synchronous generation is progressively displaced. Second, frequency and voltage performance are frequently discussed separately even though current-limited converters couple active-power support and voltage behavior during severe events. Third, virtual-inertia tuning is often presented as beneficial without explicitly showing the recovery-time penalty that can accompany higher inertia settings. The present scenario matrix is designed to address these gaps in a compact and transparent way.

The study is guided by three questions. RQ1 asks how increasing renewable penetration changes frequency and voltage stability when renewable converters remain entirely grid-following. RQ2 asks how progressively increasing the GFM share changes frequency nadir, RoCoF, settling time, minimum voltage, and active-power support under generation loss, load increase, and three-phase fault conditions. RQ3 asks how virtual inertia modifies the trade-off between the initial frequency arrest and the subsequent settling process. The principal contribution is therefore a multi-disturbance penetration map that connects renewable share, GFM share, and virtual-inertia tuning to quantitative dynamic-performance metrics.

METHODOLOGY

Research design and analytical boundary

The study uses a quantitative, scenario-based dynamic-performance design. The underlying data are supplied in a structured workbook containing 60 operating scenarios, 1,860 time-series records plus headers, and a six-case virtual-inertia sensitivity dataset. The workbook identifies the data as intended for method development, plotting, statistical workflow, and manuscript drafting. Accordingly, this article treats the dataset as a synthetic simulation benchmark rather than as independently verified MATLAB/Simulink, PSCAD, or hardware results. This distinction is important: the scenario relationships can be analyzed rigorously, but the numerical values should be validated against a documented dynamic model before they are used for grid-code compliance or investment decisions.

The benchmark system is the IEEE 9-bus network on a 100 MVA base with a nominal frequency of 50 Hz. Renewable penetration is varied across 20%, 40%, 60%, and 80%. Within each renewable level, the GFM share is varied across 0%, 25%, 50%, 75%, and 100% of renewable capacity. A 0% GFM share therefore represents a renewable fleet operating entirely in GFL mode, while 100% means all renewable inverter capacity is assigned GFM control. The effective GFM penetration relative to the whole system is calculated as the product of renewable penetration and the GFM share of renewable capacity.

$$\text{Effective GFM (\%)} = \text{RE penetration (\%)} \times \text{GFM share of RE (\%)} / 100 \quad (2)$$

Table 1. Benchmark configuration and controlled variables

Parameter	Value
Test system	IEEE 9-bus
Base power	100 MVA
Nominal frequency	50 Hz
Renewable penetration	20%, 40%, 60%, 80%
GFM share of renewable capacity	0%, 25%, 50%, 75%, 100%
GFM control	Virtual synchronous machine (VSM)
Base virtual inertia	4 s
Frequency droop	5%
Current limit	1.2 p.u.
Short-circuit ratio	3
Disturbances	10% generation loss; 10% load increase; three-phase fault
Disturbance application time	5 s

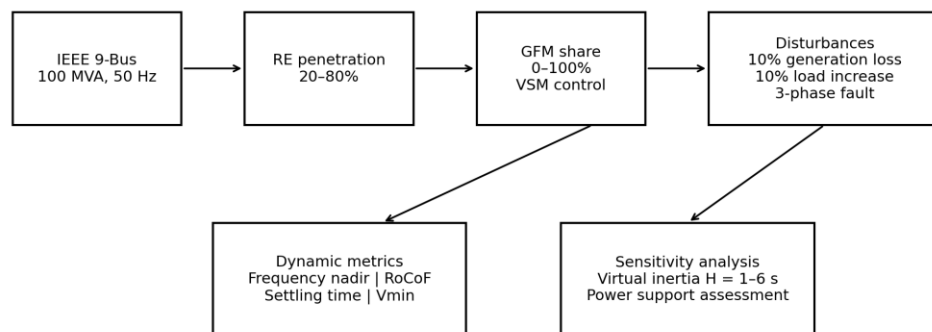


Figure 1. Scenario-based methodology for the GFM performance assessment.

Disturbance matrix and performance metrics

Each of the 20 renewable/GFM combinations is evaluated under three disturbances, producing 60 scenarios. Generation loss and load increase are both represented as 10% active-power disturbances applied at $t = 5$ s. The three-phase fault is encoded in the dataset with a disturbance magnitude of 100%. Because the workbook does not provide the exact faulted bus, fault impedance, or clearing time, the fault results are interpreted as system-level stress indicators rather than protection-grade electromagnetic-transient verification. This

boundary is retained explicitly rather than filled with assumptions that are not supported by the source data.

Five outputs are used. Frequency nadir is the lowest system frequency following the disturbance. Maximum RoCoF is taken directly from the scenario table because the supplied time-series is sampled at 0.5 s, which is too coarse to reconstruct the fastest initial derivative reliably. Settling time is the recovery duration provided in the benchmark. Minimum bus voltage captures the deepest voltage depression, and peak GFM active-power support quantifies the additional fast power contribution relative to the 100 MVA system base. The frequency-deviation and RoCoF metrics can be summarized by Equations (3) and (4).

$$\Delta f_{\text{nadir}} = f_0 - f_{\text{nadir}} \quad (3)$$

$$\text{RoCoF}_{\text{max}} = \max |df/dt| \quad (4)$$

The analysis is deterministic. Because the dataset contains one result for each scenario rather than repeated stochastic trials, inferential statistics such as p-values and confidence intervals would imply a replication structure that is not present. The study therefore uses scenario contrasts, relative improvements, slopes, and parameter-sensitivity trends. Percentage improvement in a performance metric is calculated relative to the corresponding 0%-GFM case at the same renewable penetration and disturbance type.

Virtual-inertia sensitivity

A separate six-case sensitivity dataset holds renewable penetration at 60%, GFM share at 50% of renewable capacity, effective GFM penetration at 30%, and droop at 5%, while H_v is swept from 1 s to 6 s. Frequency nadir, maximum RoCoF, and settling time are evaluated. This design isolates the tuning effect of virtual inertia from the penetration effect and makes it possible to identify whether increasing H_v produces a monotonic benefit or a dynamic trade-off.

RESEARCH RESULT

Frequency-stability degradation as renewable penetration increases

The GFL-only cases provide a baseline for RQ1. Under the 10% generation-loss disturbance, raising renewable penetration from 20% to 80% decreases the frequency nadir from 49.550 Hz to 48.806 Hz, an additional excursion of 0.744 Hz. Over the same range, maximum $|\text{RoCoF}|$ rises from 0.552 Hz/s to 1.447 Hz/s, an increase of approximately 162.1%, while settling time expands from 4.18 s to 7.66 s, an increase of approximately 83.3%. Minimum voltage decreases from 0.967 p.u. to 0.911 p.u. These results illustrate the increasingly severe dynamic response of the GFL-dominated benchmark as renewable penetration rises.

The same pattern is preserved for the other disturbance classes. For the 10% load increase, the GFL-only frequency nadir falls from 49.649 Hz at 20% renewable penetration to 49.069 Hz at 80%, while $|\text{RoCoF}|$ rises from 0.420 Hz/s to 1.100 Hz/s and settling time increases from 3.68 s to 6.74 s. Under the three-phase-fault benchmark, the corresponding nadir falls from 49.739 Hz to 49.307

Hz, $|\text{RoCoF}|$ increases from 0.508 Hz/s to 1.331 Hz/s, and minimum voltage declines from 0.502 p.u. to 0.448 p.u. The consistency across disturbances supports the interpretation that high renewable penetration requires a progressively stronger grid-forming contribution if frequency and voltage stiffness are to be preserved.

Effect of GFM penetration under generation loss

Figure 2 shows the generation-loss frequency nadir across the full penetration matrix. For every renewable level, increasing the GFM share improves the nadir monotonically. The improvement is modest at 20% renewable penetration but becomes substantially larger at 60% and 80%. At 20% renewable penetration, moving from 0% to 100% GFM improves the nadir by 0.177 Hz, from 49.550 Hz to 49.727 Hz. At 80% renewable penetration, the same change improves the nadir by 0.671 Hz, from 48.806 Hz to 49.477 Hz. The GFM contribution is therefore not merely additive; its system-level value increases as the benchmark becomes more inverter-dominated.

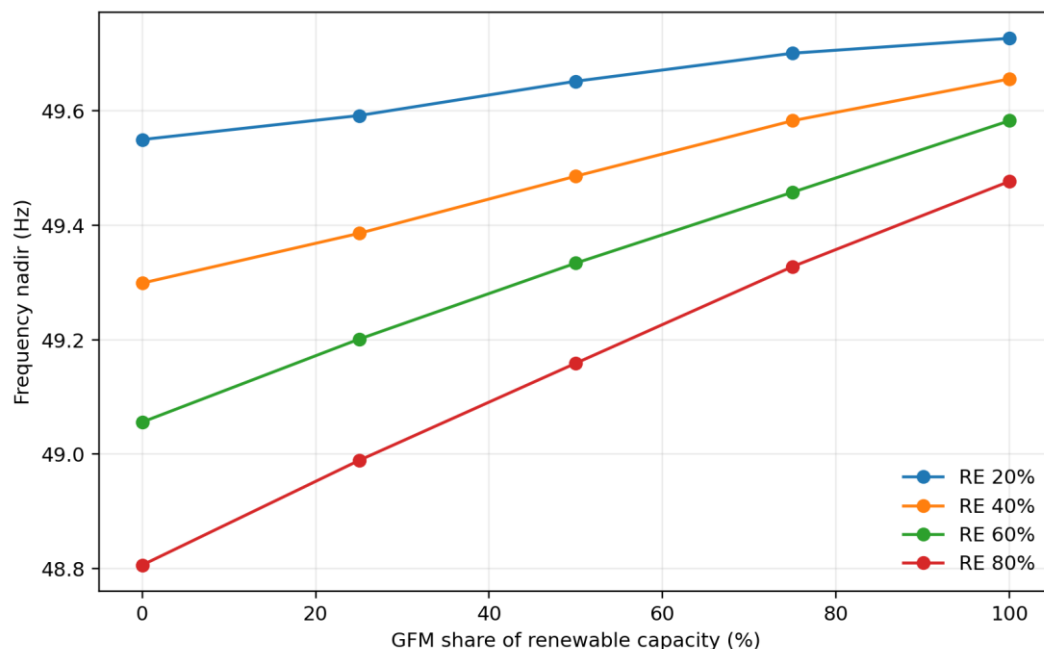


Figure 2. Frequency nadir versus GFM share under a 10% generation-loss disturbance.

The RoCoF trend is even clearer. At 80% renewable penetration, maximum $|\text{RoCoF}|$ decreases from 1.447 Hz/s in the GFL-only case to 0.720 Hz/s with 100% GFM renewable capacity, corresponding to a 50.2% reduction. At 60% renewable penetration the reduction is 50.5%, from 1.140 Hz/s to 0.564 Hz/s. By comparison, the 20% renewable case improves by 38.8%, from 0.552 Hz/s to 0.338 Hz/s. Figure 3 demonstrates that GFM penetration increasingly substitutes for the missing fast frequency stiffness as synchronous contribution declines.

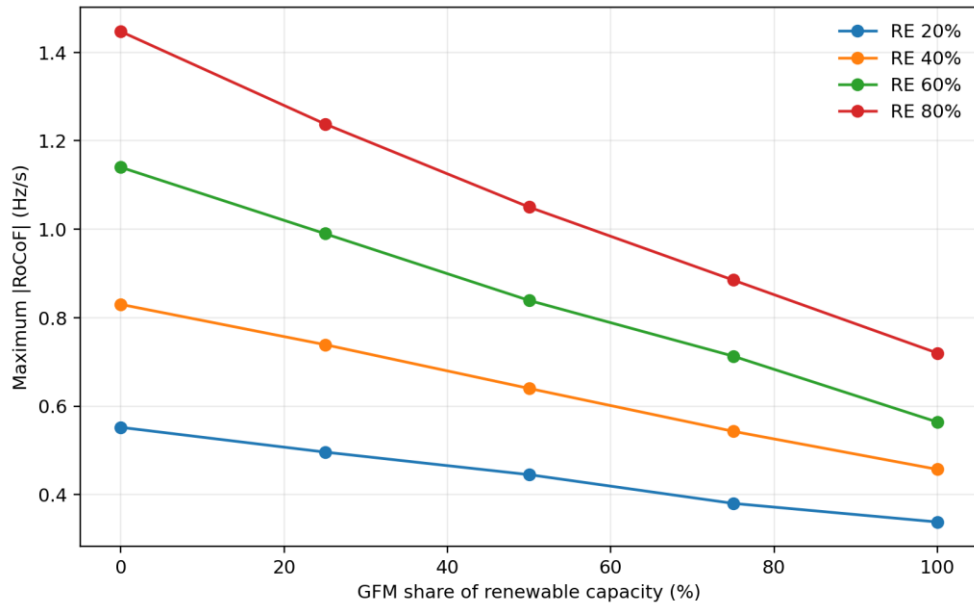


Figure 3. Maximum $|\text{RoCoF}|$ versus GFM share under a 10% generation-loss disturbance.

Settling time follows a similar but not identical pattern. At 80% renewable penetration it decreases from 7.66 s to 4.87 s as the GFM share increases from 0% to 100%, a 36.4% reduction. At 60%, the reduction is 35.3%; at 40%, 29.5%; and at 20%, 21.8%. These results indicate that the benchmark attributes both arresting and recovery benefits to GFM penetration. The time-domain traces in Figure 5 further show that at 80% renewable penetration the 100%-GFM case experiences a markedly shallower frequency dip and faster return toward nominal than the GFL-only case.

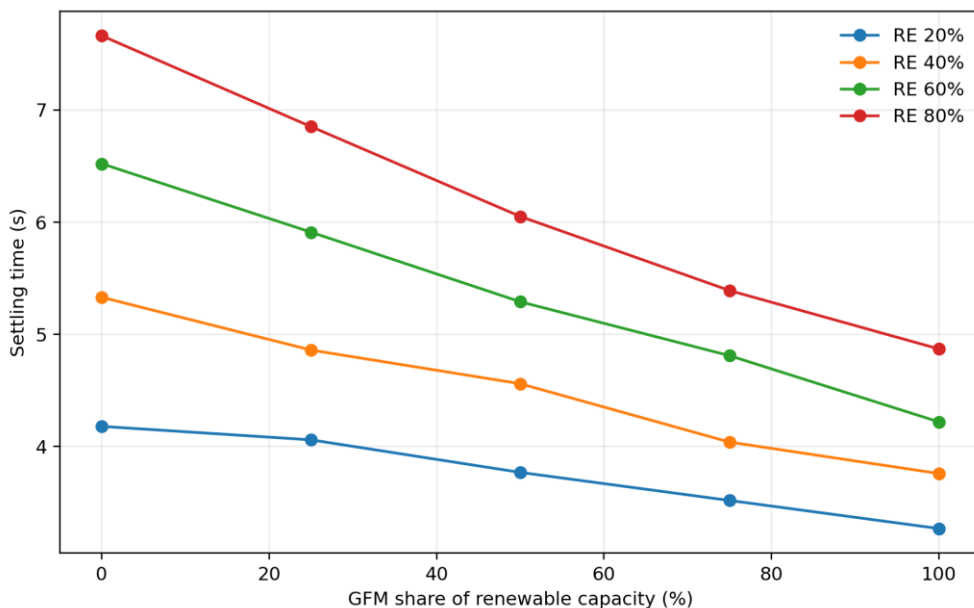


Figure 4. Settling time versus GFM share under a 10% generation-loss disturbance.

Table 2. Generation-loss performance across renewable and GFM penetration levels

RE (%)	GFM of RE (%)	Eff. GFM (%)	Nadir (Hz)	RoCoF (Hz/s)	T _s (s)	V _{min} (p.u.)	P _{GFM peak} (% base)
20	0	0	49.550	0.552	4.18	0.967	0.00
20	25	5	49.592	0.496	4.06	0.970	0.60
20	50	10	49.652	0.445	3.77	0.971	1.30
20	75	15	49.701	0.380	3.52	0.972	1.80
20	100	20	49.727	0.338	3.27	0.977	2.60
40	0	0	49.299	0.830	5.33	0.949	0.00
40	25	10	49.386	0.739	4.86	0.952	1.40
40	50	20	49.486	0.640	4.56	0.957	2.60
40	75	30	49.583	0.543	4.04	0.962	4.10
40	100	40	49.656	0.457	3.76	0.965	5.40
60	0	0	49.056	1.140	6.52	0.931	0.00
60	25	15	49.201	0.990	5.91	0.939	1.90
60	50	30	49.334	0.839	5.29	0.941	3.80
60	75	45	49.458	0.713	4.81	0.947	5.80
60	100	60	49.583	0.564	4.22	0.953	8.00
80	0	0	48.806	1.447	7.66	0.911	0.00
80	25	20	48.989	1.238	6.85	0.920	2.60
80	50	40	49.159	1.050	6.05	0.930	5.30
80	75	60	49.328	0.885	5.39	0.936	7.80
80	100	80	49.477	0.720	4.87	0.937	10.20

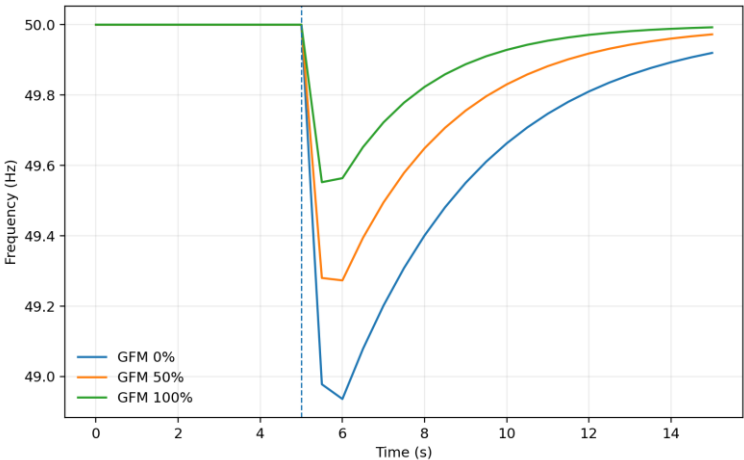


Figure 5. Representative frequency trajectories at 80% renewable penetration for 0%, 50%, and 100% GFM share under generation loss.

Cross-disturbance performance and voltage support

The benefit of GFM is not limited to generation-loss events. Table 3 compares the 0%-GFM and 100%-GFM endpoints for each renewable penetration and disturbance. At 80% renewable penetration, the 10% load-increase case improves from a frequency nadir of 49.069 Hz to 49.592 Hz, while $|\text{RoCoF}|$ decreases by 50.3% and settling time by 36.4%. Under the three-phase fault, the frequency nadir improves from 49.307 Hz to 49.697 Hz and $|\text{RoCoF}|$ decreases from 1.331 Hz/s to 0.662 Hz/s. These results show that the GFM benefit persists even when the disturbance is dominated by voltage stress rather than a sustained active-power deficit.

Voltage support under the fault condition is more modest in absolute terms because the sag remains severe. At 80% renewable penetration, minimum voltage rises from 0.448 p.u. in the GFL-only case to 0.493 p.u. with 100% GFM, a relative increase of approximately 10.0%. At lower renewable penetration the minimum voltage is also improved progressively with GFM share, as shown in Figure 6. The result should not be interpreted as fault-ride-through compliance because the benchmark does not encode fault duration or location; instead, it shows that the scenario generator assigns a stronger voltage response to higher GFM participation while respecting the 1.2 p.u. current-limit assumption.

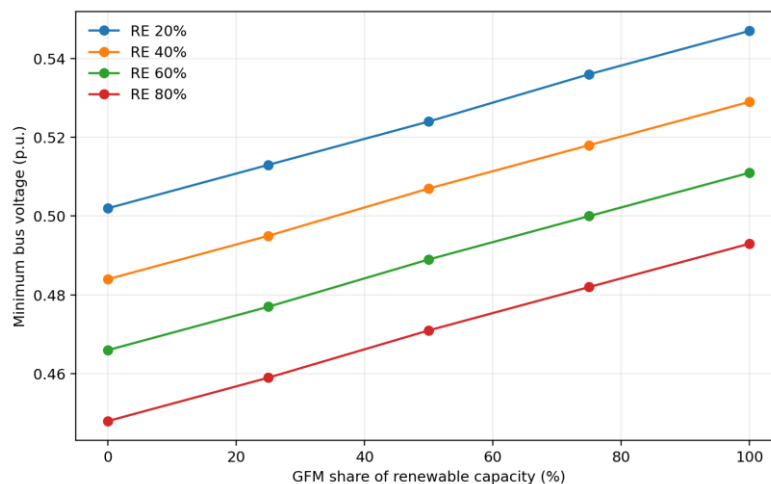


Figure 6. Minimum bus voltage versus GFM share during the three-phase-fault benchmark.

Table 3. Improvement from 0% to 100% GFM share at constant renewable penetration

RE (%)	Disturbance	Nadir gain (Hz)	RoCoF reduction (%)	Settling reduction (%)	V_min gain (%)	Peak support (% base)
20	Generation Loss	0.177	38.8	21.8	1.0	2.60
20	Load Increase	0.138	38.8	21.7	1.0	2.13

RE (%)	Disturbance	Nadir gain (Hz)	RoCoF reduction (%)	Settling reduction (%)	V_min gain (%)	Peak support (% base)
20	3-Phase Fault	0.103	38.8	21.7	9.0	2.14
40	Generation Loss	0.357	44.9	29.5	1.7	5.40
40	Load Increase	0.279	45.0	29.4	1.7	4.43
40	3-Phase Fault	0.207	45.0	29.4	9.3	4.42
60	Generation Loss	0.527	50.5	35.3	2.4	8.00
60	Load Increase	0.411	50.5	35.4	2.3	6.56
60	3-Phase Fault	0.306	50.5	35.3	9.7	6.57
80	Generation Loss	0.671	50.2	36.4	2.9	10.20
80	Load Increase	0.523	50.3	36.4	2.8	8.36
80	3-Phase Fault	0.390	50.3	36.5	10.0	8.44

Peak GFM power support increases with both renewable penetration and the share operated in GFM mode. In the 80% renewable, 100%-GFM case, peak support reaches 10.2% of system base under generation loss, 8.36% under load increase, and 8.44% under the fault case. On a 100 MVA base these percentages correspond numerically to approximately 10.2, 8.36, and 8.44 MW if the active-power base is interpreted as 100 MW. This scaling emphasizes a practical condition: higher GFM penetration only produces meaningful frequency support if the dc-side source has sufficient headroom and energy. The present benchmark provides the power-support output but does not specify state of charge, curtailment, or dc-source dynamics, so those energy constraints remain outside the current analytical boundary.

Virtual-inertia sensitivity and the recovery trade-off

The virtual-inertia sweep addresses RQ3. Increasing H_v from 1 s to 6 s improves the frequency nadir from 49.200 Hz to 49.361 Hz and reduces maximum $|\text{RoCoF}|$ from 1.020 Hz/s to 0.790 Hz/s, a 22.5% reduction. Figures 7 and 8 show that both metrics improve monotonically, but the incremental gain becomes smaller as H_v increases. From $H_v = 4$ s to 6 s, for example, the nadir improves by only 0.027 Hz while $|\text{RoCoF}|$ decreases from 0.839 to 0.790 Hz/s.

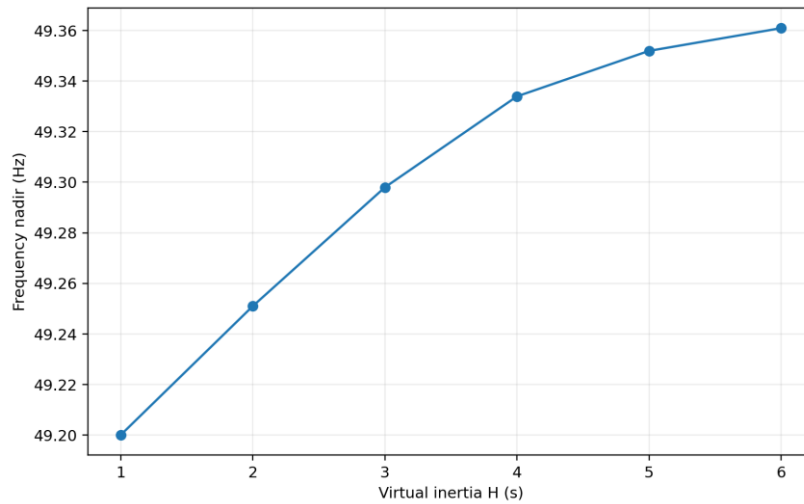


Figure 7. Frequency nadir sensitivity to virtual inertia at 60% renewable penetration and 50% GFM share.

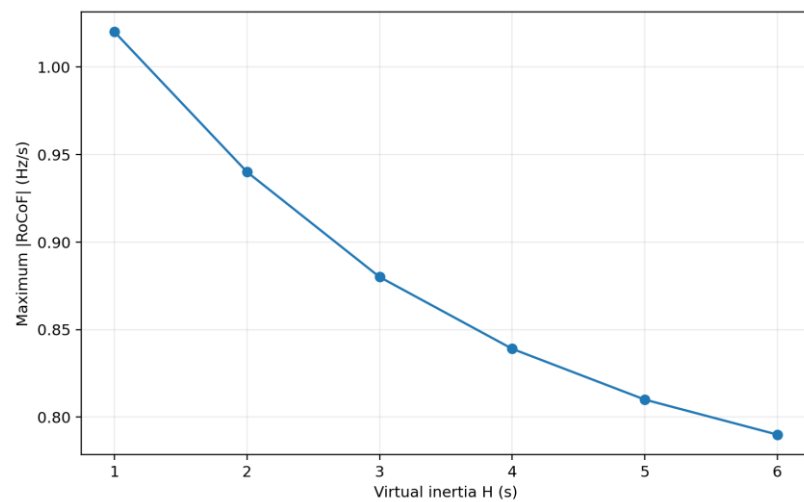


Figure 8. Maximum |RoCoF| sensitivity to virtual inertia at 60% renewable penetration and 50% GFM share.

The benefit is accompanied by slower settling. Settling time increases from 4.86 s at $H_v = 1$ s to 5.80 s at $H_v = 6$ s, a 19.3% increase. This non-negligible penalty prevents the virtual-inertia parameter from being treated as a simple "more is better" setting. A high H_v reduces the initial frequency acceleration but makes the controller sustain the inertial behavior longer, delaying final recovery in the supplied benchmark. The result is consistent with the broader control-design literature, which emphasizes coordinated inertia, damping, and power limits rather than maximizing one parameter independently (Elwakil et al., 2023; Jiang, Zhu, & Konstantinou, 2024).

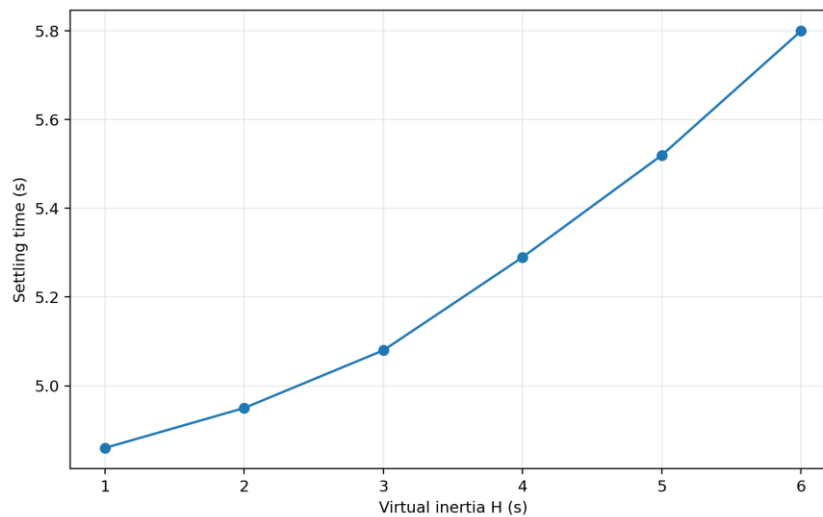


Figure 9. Settling-time sensitivity to virtual inertia at 60% renewable penetration and 50% GFM share.

Table 4. Virtual-inertia sensitivity at 60% renewable penetration and 50% GFM share

H_v (s)	Nadir (Hz)	RoCoF (Hz/s)	Settling time (s)
1	49.200	1.020	4.86
2	49.251	0.940	4.95
3	49.298	0.880	5.08
4	49.334	0.839	5.29
5	49.352	0.810	5.52
6	49.361	0.790	5.80

DISCUSSION

GFM value increases as the grid becomes more renewable-dominated

The most important system-level finding is that the incremental value of GFM increases with renewable penetration. At 20% renewable penetration the GFL-only benchmark is still comparatively stiff, so converting the renewable fleet from GFL to GFM yields a 0.177 Hz improvement in generation-loss nadir. At 80% renewable penetration the same control-mode transition produces a 0.671 Hz improvement. This pattern supports the engineering intuition that GFM is most valuable when the grid has lost a large fraction of the synchronous mechanisms that previously established frequency and voltage. It also aligns with recent planning studies that assess GFM placement and penetration using frequency deviation, RoCoF, and damping rather than treating each converter as an isolated device (Liyanage et al., 2025).

The trend does not imply that every renewable converter must always operate as GFM. A mixed GFM/GFL fleet can exploit complementary strengths: GFM devices provide local voltage/frequency formation and damping, while GFL devices retain mature current-control behavior and can follow the stronger reference created by the GFM population. The data show continuous

improvement at 25%, 50%, and 75% GFM shares rather than an abrupt threshold, which suggests a planning problem centered on sufficient GFM coverage rather than a binary technology replacement. Determining the minimum acceptable share would require explicit stability criteria, location sensitivity, reserve constraints, and contingency probabilities, which are not encoded in the present dataset.

Frequency support is constrained by deliverable power and current

The results also show that improved frequency behavior is accompanied by increasing peak GFM active-power support. This is physically important. Virtual inertia cannot be created without an energy exchange: the converter must temporarily increase or decrease electrical power relative to its pre-disturbance operating point. At 80% renewable penetration, the benchmark requires 10.2% of system base in peak GFM support during generation loss when all renewable capacity is grid-forming. If the renewable sources were operating at their maximum available power with no storage or curtailment, that support could not be delivered. Practical GFM deployments therefore need BESS, dc-side energy buffers, deloading, or another source of headroom. This is one reason why modern GFM specifications increasingly discuss active-power capability together with converter dynamics rather than as separate issues.

The 1.2 p.u. current limit creates a second constraint. Under a severe voltage sag, the converter may be unable to maintain both the requested active-power support and its internal voltage magnitude. Current limiting can shift the device away from ideal voltage-source behavior and may threaten synchronization if the power-synchronization loop continues to demand an infeasible power transfer. The recent literature has therefore proposed current-synchronization control, adaptive references, virtual impedance, and other schemes that explicitly coordinate GFM dynamics with semiconductor protection (Narula et al., 2023; Jiang, Zhu, Xu, & Konstantinou, 2024; Baeckeland et al., 2024). The moderate voltage improvement observed in the fault cases should be understood in this context.

Virtual inertia must be tuned with damping and recovery objectives

The virtual-inertia sweep reveals a classic multi-objective tuning problem. Increasing H_v reduces the initial RoCoF and raises the nadir, but it also lengthens settling time. If the operational objective is to prevent under-frequency protection or limit RoCoF, a higher H_v is beneficial. If the objective includes rapid recovery and minimal prolonged power deviation, excessive inertia may be undesirable. The most appropriate H_v therefore depends on grid strength, available energy, damping, droop, converter rating, and the disturbance spectrum. The dataset places $H_v = 4$ s near the middle of the tested range; from that point, further increases produce diminishing nadir gains while continuing to increase settling time.

This trade-off is compatible with advanced GFM control research. Fixed-parameter VSMs are increasingly supplemented by adaptive or frequency-dependent inertia and damping so that the converter behaves with strong inertia during the first instants of a disturbance but transitions toward faster recovery once the critical RoCoF interval has passed. Bandwise power-synchronization

control similarly separates frequency components so that damping and power-limiting objectives can be coordinated during severe events (Jiang, Zhu, & Konstantinou, 2024). The present sensitivity data provide a system-level motivation for those controller developments.

Interpretation of the synthetic benchmark and reproducibility requirements

The analysis is intentionally explicit about the status of the source data. The workbook provides internally consistent scenario metrics and time-series traces, but it does not include the underlying differential-algebraic equations, converter inner-loop parameters, network branch data as modified for renewable substitution, renewable unit placement, fault location, fault clearing time, secondary frequency-control logic, or dc-side source models. The 0.5 s time-series sampling interval is also insufficient for independently reconstructing the reported maximum RoCoF. These omissions do not prevent comparative analysis, but they limit reproducibility if the numerical values are presented as definitive simulation results.

A publication-ready validation should therefore recreate the 60 scenarios in a documented RMS or electromagnetic-transient environment, state the exact bus allocation of GFM and GFL resources, define fault impedance and clearing time, specify VSM damping and inner-loop bandwidths, and model the dc-side energy source and current limiter explicitly. EMT simulation is particularly important for severe faults and converter current saturation, whereas RMS models may be sufficient for slower frequency events if the GFM model is appropriately validated. Hardware-in-the-loop or power-hardware-in-the-loop testing would provide the strongest confirmation of the proposed performance trends.

CONCLUSIONS AND RECOMMENDATIONS

This study assessed the performance of grid-forming inverters for renewable-energy integration and frequency stability using a 60-scenario IEEE 9-bus synthetic dynamic benchmark. The results show a clear degradation in the GFL-only system as renewable penetration rises: under 10% generation loss, increasing renewable penetration from 20% to 80% lowers frequency nadir from 49.550 Hz to 48.806 Hz, raises maximum $|\text{RoCoF}|$ from 0.552 Hz/s to 1.447 Hz/s, and increases settling time from 4.18 s to 7.66 s. Increasing the GFM share reverses this degradation. At 80% renewable penetration, moving from 0% to 100% GFM improves the generation-loss nadir to 49.477 Hz, cuts $|\text{RoCoF}|$ by 50.2%, shortens settling time by 36.4%, and raises minimum voltage from 0.911 p.u. to 0.937 p.u. Comparable benefits appear under the load-increase and three-phase-fault benchmarks.

The virtual-inertia study demonstrates that GFM tuning is not monotonic across all objectives. Increasing H_v from 1 s to 6 s improves nadir by 0.161 Hz and reduces $|\text{RoCoF}|$ by 22.5%, but increases settling time by 19.3%. The recommended design principle is therefore to coordinate GFM penetration, virtual inertia, damping, droop, current limits, and available active-power headroom rather than maximizing virtual inertia alone. For systems approaching

60-80% renewable penetration, the benchmark indicates that a substantial GFM share can materially improve frequency and voltage resilience. However, the reported numerical thresholds should be treated as preliminary because the supplied dataset is synthetic; detailed model-based and hardware validation is required before adopting the results as operational limits.

ADVANCED RESEARCH

Future work should convert the present benchmark into a reproducible multi-fidelity validation framework. First, the IEEE 9-bus cases should be rebuilt in MATLAB/Simulink, DIgSILENT PowerFactory, or PSCAD with documented generator replacement, renewable placement, VSM inner and outer loops, current-limiter logic, and dc-side energy constraints. Second, short-circuit ratio should be varied to quantify GFM performance in weak and strong grids rather than holding SCR at 3. Third, current-limit values and priority logic should be swept during faults to distinguish frequency-support limits from synchronization limits. Fourth, stochastic renewable and load trajectories should be introduced so that scenario probabilities and uncertainty bounds can be reported. Fifth, the analysis should be extended to the IEEE 39-bus or larger systems to study spatial GFM placement, inter-area oscillations, and location-dependent frequency stiffness. Finally, real-time digital simulation and controller-/power-hardware-in-the-loop experiments should verify that the system-level trends survive realistic sampling, delay, saturation, and measurement noise.

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REFERENCES

- Aljarrah, R., Fawaz, B. B., Salem, Q., Karimi, M., Marzooghi, H., & Azizipanah-Abarghooee, R. (2024). Issues and challenges of grid-following converters interfacing renewable energy sources in low inertia systems: A review. *IEEE Access*, 12, 5534-5561. <https://doi.org/10.1109/ACCESS.2024.3349630>
- Baeckeland, N., Chatterjee, D., Lu, M., Johnson, B., & Seo, G.-S. (2024). Overcurrent limiting in grid-forming inverters: A comprehensive review and discussion. *IEEE Transactions on Power Electronics*, 39(11), 14493-14517. <https://doi.org/10.1109/TPEL.2024.3430316>
- Elwakil, M. M., El Zoghaby, H. M., Sharaf, S. M., et al. (2023). Adaptive virtual synchronous generator control using optimized bang-bang for islanded microgrid stability improvement. *Protection and Control of Modern Power Systems*, 8, 57. <https://doi.org/10.1186/s41601-023-00333-7>
- ENTSO-E. (2025). Grid forming capability of power park modules: Phase II technical report on grid-forming requirements. European Network of Transmission System Operators for Electricity.
- Fan, B., & Wang, X. (2022). Equivalent circuit model of grid-forming converters with circular current limiter for transient stability analysis. *IEEE Transactions on Power Systems*, 37(4), 3141-3144. <https://doi.org/10.1109/TPWRS.2022.3173160>
- Fan, B., & Wang, X. (2023). Fault recovery analysis of grid-forming inverters with priority-based current limiters. *IEEE Transactions on Power Systems*, 38(6), 5102-5112. <https://doi.org/10.1109/TPWRS.2022.3221209>
- Jiang, S., Zhu, Y., Xu, T., & Konstantinou, G. (2024). Current-synchronization control of grid-forming converters for fault current limiting and enhanced synchronization stability. *IEEE Transactions on Power Electronics*, 39(5), 5271-5285. <https://doi.org/10.1109/TPEL.2024.3361917>

- Jiang, S., Zhu, Y., & Konstantinou, G. (2024). Bandwise power-synchronization loop for frequency response improvement in grid-forming converters. *IEEE Transactions on Power Electronics*, 39(9), 10693-10698. <https://doi.org/10.1109/TPEL.2024.3406564>
- Liyanage, C., Meegahapola, L., Nutkani, I., & Jalili, M. (2025). Strategic placement of grid-forming inverters considering spatiotemporal dynamics and composite stability index. *IEEE Open Journal of the Industrial Electronics Society*, 6, 290-308. <https://doi.org/10.1109/OJIES.2025.3538480>
- Narula, A., Imgart, P., Bongiorno, M., Beza, M., Svensson, J. R., & Hasler, J. P. (2023). Voltage-based current limitation strategy to preserve grid-forming properties under severe grid disturbances. *IEEE Open Journal of Power Electronics*, 4, 176-188. <https://doi.org/10.1109/OJPEL.2023.3246728>
- Pan, D., Wang, X., Liu, F., & Shi, R. (2020). Transient stability of voltage-source converters with grid-forming control: A design-oriented study. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 8(2), 1019-1033. <https://doi.org/10.1109/JESTPE.2019.2946310>
- Rosso, R., Wang, X., Liserre, M., Lu, X., & Engelken, S. (2021). Grid-forming converters: Control approaches, grid-synchronization, and future trends - A review. *IEEE Open Journal of Industry Applications*, 2, 93-109. <https://doi.org/10.1109/OJIA.2021.3074028>
- Stanojev, O., Markovic, U., Aristidou, P., & Hug, G. (2023). Improving stability of low-inertia systems using virtual induction machine synchronization for grid-following converters. *IEEE Transactions on Power Systems*, 38(3), 2290-2303. <https://doi.org/10.1109/TPWRS.2022.3187789>
- Tozak, M., Taskin, S., Sengor, I., & Hayes, B. P. (2024). Modeling and control of grid forming converters: A systematic review. *IEEE Access*, 12, 107818-107843. <https://doi.org/10.1109/ACCESS.2024.3437236>

- Wang, X., Taul, M. G., Wu, H., Liao, Y., Blaabjerg, F., & Harnefors, L. (2020). Grid-synchronization stability of converter-based resources - An overview. *IEEE Open Journal of Industry Applications*, 1, 115-134. <https://doi.org/10.1109/OJIA.2020.3020392>
- Xu, T., Jiang, S., & Konstantinou, G. (2024). Comparison of the performance of grid-forming converters with different combinations of control methods and current limiters. In *2024 IEEE 10th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)* (pp. 3268-3273). <https://doi.org/10.1109/IPEMC-ECCEAsia60879.2024.10567581>
- Zhong, Q.-C. (2016). Virtual synchronous machines: A unified interface for grid integration. *IEEE Power Electronics Magazine*, 3(4), 18-27. <https://doi.org/10.1109/MPEL.2016.2614906>
- Zhong, Q.-C., & Weiss, G. (2011). Synchronverters: Inverters that mimic synchronous generators. *IEEE Transactions on Industrial Electronics*, 58(4), 1259-1267. <https://doi.org/10.1109/TIE.2010.2048839>