A REVIEW AND DISCUSSION OF THE GRID CODE REQUIREMENTS FOR VARIABLE RENEWABLE ENERGY INTEGRATION IN ETHIOPIA

Summary

With the integration of inverter-based variable renewable energy resources (VRE) that are crucial to meeting ambitious electrification targets, Ethiopia needs robust policy directions and regulatory frameworks that address the challenges posed by these resources, build confidence, and incentivize private-sector investment in the power sector. This study presents the evaluation of the existing Ethiopian national grid codes' adequacy for supporting VRE integration using a comparative benchmarking framework against internationally recognized standards and selected African grid codes. A mixed-methods approach combining qualitative content analysis and quantitative scoring is employed to assess compliance across key technical domains such as fault ride-through (FRT), frequency response, voltage regulation, and inverter-based resource capabilities. The results show moderate alignment with IEEE 1547-2018 (weighted score 2.4), weaker alignment with ENTSO-E RfG and German VDE-AR-N standards (score 1.7), and relatively stronger, but still incomplete, alignment with African peers Kenya's grid codes (score 2.6) and South Africa's SAREGC v2.8 (score 2.8). The study concludes that comprehensive grid code reform, aligned with global standards and adapted to local system characteristics, is essential for enabling a resilient and sustainable energy transition.

Keywords: Grid codes, variable renewable energy integration, Ethiopia, comparative benchmarking

Field of application for the findings: The findings contribute to both academic literature and policy discourse by providing a structured benchmarking methodology and actionable recommendations for emerging power systems.

Addressed audience: ***Poster presentation***

1. Introduction

Ethiopia possesses one of Africa's largest renewable resource bases and has set ambitious targets to add a substantial amount of variable renewable energy resources such as wind and solar power generation systems by 2030 under the National Sustainable Energy Development Strategy (N-SEDS) and National Electrification Program 2. 0 (NEP 2.0) to achieve universal electricity access while reducing overdependence on hydropower (MoWE, 2024; MoWIE, 2019). Nonetheless, the Ethiopian National Transmission Grid Code (No. 865/2022) and Distribution Grid Code (No. 866/2022) remain limited to basic provisions, such as 150 ms low-voltage ride-through at zero voltage, limited reactive support, and no mandatory synthetic inertia or under-frequency droop response (Ethiopian Energy Authority (EEA), 2022; Ethiopian Energy Authority, 2022). These shortcomings create technical barriers to high VRE penetration, increasing risks of instability, curtailment, and delayed Independent Power Producer (IPP) projects in a hydro-dominant system already vulnerable to climate-induced variability.

Extensive studies have been conducted on grid-code requirements and their evolutions in mature markets (IEEE 1547-2018 in the United States (IEEE, 2018), ENTSO-E Requirements for Generators and Germany's VDE-AR-N series in Europe (European Union, 2016; VDE, 2011), GB/T standards in China (GB/T19964, 2012)) (Diez-Maroto et al., 2016; Mohseni and Islam, 2012; Roberts, 2018). Furthermore, some African peers (Kenya's grid codes (EPRA, 2024, 2021) and South Africa's SAREGC v2.8 (NESRA, 2014)) (Cabrera-Tobar et al., 2016; Nhlapo and Awodele, 2020) have made substantial progress on their grid code development. However, Ethiopia-specific comparative analyses are notably limited. Khan et al. (2022) offered the most comprehensive review to date, mapping basic LVRT, limited reactive support, and over-frequency curtailment in Ethiopia's 2022 codes while recommending alignment with IEEE 1547-2018 and Danish practices (Khan et al., 2022). However, their work stopped short of quantitative multi-jurisdictional benchmarking or prescriptive reform pathways tailored to Ethiopia's 2030 electrification targets and ambitions to be a regional power hub. No peer-reviewed study has yet systematically compared Ethiopia's codes across the full suite of technical parameters, including LVRT/HVRT envelopes, frequency response, RoCoF withstand, reactive power modes, plant categorization, synthetic inertia, and grid-forming requirements, against both mature international standards and regionally relevant African frameworks.

Closing this gap is of paramount importance for Ethiopia's grid-code deficiencies directly impede achieving the country's grand universal electrification program (96% access by 2030), the Eastern Africa Power Pool's export ambitions (1.5 GW by 2030), and the country's contribution to global decarbonization efforts (MoWE, 2024). Thus, this study delivers the first comprehensive, Ethiopia-centered benchmarking matrix and evidence-based reform roadmap, bridging the documented literature void. By providing technically rigorous, policy-ready recommendations that integrate IEEE, ENTSO-E, and African best practices, the research will furnish a replicable analytical framework for other emerging economies, thereby advancing both theoretical understanding of grid-code evolution in developing contexts and practical pathways for sustainable VRE integration.

2. Results and Discussion

2.1 Results

The results are derived from a systematic parameter-by-parameter extraction and comparative evaluation of the primary grid-code documents stated above. A nine-parameter coding framework, as indicated in Table 1, was applied to produce the benchmarking matrix. Alignment was scored qualitatively (full = 3, partial = 2, divergence = 1, absence = 0) and weighted against Ethiopia's system characteristics (hydro dominance, weak grid segments, climate vulnerability, and 2030 VRE integration targets).

Table 1: Benchmarking Matrix – Key Technical Parameters for VRE Integration

Parameter	**Ethiopia (ENTGC 865/2022 & ENDGC 866/2022)**	**IEEE 1547-2018**	**ENTSO-E RfG + Germany VDE-AR-N**	**Kenya KNTGC (2025)**	**South Africa SAREGC v2.8**
LVRT	0 pu for 150 ms (category-dependent curves; partial reactive injection)	Category III: 0 pu for 150 ms + smart functions	Zero voltage 150 ms + full reactive current injection	0 pu ≥150 ms + reactive maximization ≥600 ms	0 pu ≥150 ms (Cat. C) + reactive support
HVRT	Limited (120% for 2 s in δ category only)	Up to 1.2–1.3 pu	Up to 120% with dynamic support	Up to 1.2 pu ≥2 s	Up to 120% ≥2 s
Frequency Ride-Through	47–51.5 Hz; RoCoF ≤1.5 Hz/s	57–63 Hz (60 Hz)	47.5–51.5 Hz extended	47.5–51.5 Hz; RoCoF ≤1.0 Hz/s	49–51 Hz; RoCoF ≤1.5 Hz/s
Frequency Droop Response	Over-frequency only (>50.5 Hz); no mandatory under-frequency or P-Δ (≥3%)	Default 5% droop + frequency-watt	2–12% droop (FSM); synthetic inertia mandatory	4–12% adjustable droop (LFSM-O)	0–10% adjustable + P-Δ ≥3% (Cat. C)
Reactive Power Capability	Unity PF (<20 MVA); limited for larger	Volt-var, volt-watt	Q(U)/Q(P) dynamic; 0.95 lag/lead	±0.35 pu selectable modes	Category-dependent full

					envelope
Ramp Rates & Active Power Control	Controlled gradient/absolute/delta	Smart-function limits	Strict limits	1–30 MW/min adjustable	Power gradient (SO-set)
Synthetic Inertia/Grid-Forming	Absent	Optional (advanced)	Mandatory (Type C/D)	Absent	Emerging (not mandatory)
Plant Categorization	α–η by MVA	I–III by performance	A–D by size/voltage	≥10 MW / ≥33 kV focus	A (≤1 MVA), B, C (≥20 MVA)
Overall Alignment Score (weighted)	Baseline (reference)	2.4	1.7	2.6	2.8

2.2 Discussion

The comparison results reveal that Ethiopia's 2022 grid codes occupy a foundational but transitional position in the global spectrum of VRE integration standards. With an overall weighted alignment score of 2.4 against IEEE 1547-2018 and 1.7 against ENTSO-E RfG/Germany, while showing stronger regional scores of 2.6 (Kenya) and 2.8 (South Africa). The findings confirm that Ethiopia's current grid codes provide adequate baseline stability for the current hydro-dominated system but fall critically short of the dynamic, inverter-based resource (IBR) capabilities required for the ambitious VRE integration targets by 2030.

The analysis of existing Ethiopian grid codes demonstrates that Ethiopia's provisions, such as 150 ms LVRT at zero voltage with only partial reactive power support and over-frequency curtailment without mandatory under-frequency droop or P-Δ reserve, mirror early-stage codes in many developing markets. These rules ensure basic fault tolerance and power quality, but lack the granularity needed for high instantaneous VRE penetration. This limitation becomes particularly acute in a weak-grid, climate-vulnerable context where hydro variability already strains reserves, directly constraining the N-SEDS 2030 scenario and exposing the system to increased RoCoF events and potential cascading disconnections. On the other hand, a comparative analysis against internationally mature grid codes, such as IEEE 1547-2018 and ENTSO-E/Germany (and its amendments), highlights the most pronounced divergences in synthetic inertia, grid-forming inverter mandates, and dynamic reactive modes (Q(U)/Q(P)). Germany's zero-voltage LVRT envelope with full reactive-current injection and mandatory inertia emulation for Type C/D generators enables stable operation above 50 % VRE share, a capability entirely absent in Ethiopia's framework. However, regional benchmarking yields more encouraging results. Ethiopia's grid codes compare favorably with Kenya's grid codes on basic FRT envelopes but lag in adjustable droop (4–12 %) and reactive-current maximization during faults, while South Africa's SAREGC v2.8 provides the closest practical benchmark, with its Category A–C differentiation, P-Δ ≥3 % reserve, and proven ancillary-service readiness. Finally, the gap synthesis prioritizes four actionable deficiencies: (1) absence of synthetic inertia/grid-forming, (2) incomplete under-frequency response, (3) limited dynamic reactive control, and (4) insufficient performance-based categorization and model validation. Thus, the study proposes implementing the phased (short-term to long-term) roadmap, beginning with Kenya/South Africa-style FRT and droop amendments, progressing to ENTSO-E/Germany inertia requirements, and culminating in IEEE-style smart functions, which could reduce curtailment risk by 15–25 % while improving IPP bankability and EAPP export viability.

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