

A Configurable Unified Grid-Code Compliance Framework for Grid-Connected Inverters Across IEEE 1547-2018, VDE-AR-N 4110, and the Korean DER Grid Code

Anil K S
Electrical and Electronics
Engineering
B.M.S College of Engineering
Bengaluru, India

Dr.Padmavathi K
Electrical and Electronics
Engineering
B.M.S College of Engineering
Bengaluru, India

Vishal Anand A G
Senior Director
Bloom Energy (India) Pvt.
Ltd Bengaluru, India

Abstract—Distributed energy resources (DERs) such as fuel-cell systems, photovoltaic plants, and battery energy storage are being rapidly deployed. Therefore, national and regional authorities have developed independent grid-interconnection codes for grid-connected inverters addressing synchronization, reactive power support, voltage and frequency ride-through, anti-islanding, harmonic emission, and communication behavior. Differences in numerical limits, operating philosophies and test procedures between the various geographies require manufacturers to maintain parallel firmware and hardware variants, specific to each standard. This increases engineering effort, certification cost and time-to-market. Comparison of eleven functional dimensions of IEEE 1547-2018 (USA), VDE-AR-N 4110 (Germany), and the Korean DER grid code: synchronization, reactive power capability, Volt-Var, Volt-Watt, Frequency-Watt, low- and high-voltage ride-through (LVRT/HVRT), frequency ride-through, anti-islanding, harmonic distortion limits, and communication interoperability. Based on the identified similarities and differences, a parameterized Unified Grid-Code Compliance Framework is proposed to reconfigure a single inverter hardware and control platform to comply with any of the studied codes, and by extension to other national codes, with the use of a structured rule database as opposed to code-specific firmware forks. This paper describes a generalized experimental verification technique for automated compliance testing, framework architecture, control flow and algorithms. The proposed framework is shown to reduce unnecessary engineering by using a comparative, standards-based approach while maintaining full grid code compliance margins. The approach enables DER and grid tied inverter designers to achieve multi-geography compliance from a common design baseline.

Index Terms—Distributed energy resources, grid interconnection, IEEE 1547-2018, VDE-AR-N 4110, Korean grid code, Volt-Var, Volt-Watt, Frequency-Watt, low-voltage ride-through, anti-islanding, grid-tied inverter, compliance framework.

I. INTRODUCTION

The trend of decarbonized generation of electricity has led to a rapid increase of distributed energy resources (DERs),

Identify applicable funding agency here. If none, delete this.

including fuel-cell power plants, solar photovoltaic systems and battery energy storage systems, interconnected at the point of common coupling (PCC) of the distribution or sub-transmission network. DERs are distributed across the grid instead of relying on conventional centralized generation and are connected to the grid using power-electronic inverters, the dynamic behavior of which directly impacts the local voltage profile, frequency stability and power quality.

As the penetration of DER increases, transmission and distribution system operators in several countries have published interconnection codes that specify mandatory “grid support functions” for inverter-based resources to maintain grid stability. These functions typically include synchronization limits, reactive power capability, Volt-Var and Volt-Watt droop control, Frequency-Watt control, low- and high-voltage ride-through (LVRT/HVRT), frequency ride-through, anti-islanding protection, current harmonic limits and standard communication interfaces for monitoring and dispatch.

While the main control objectives are similar in all jurisdictions, the particular numerical limits, operating regions, default settings and test procedures adopted by each code vary significantly. For example, the reactive power capability required by IEEE 1547-2018 in the United States, the VDE-AR-N 4110 code in Germany, and the Korean DER grid code are all defined with different percentages of nameplate apparent power, different sign conventions, and different response-time requirements. This divergence forces inverter manufacturers targeting multiple export markets to either support multiple parallel firmware variants, or over-design a single variant to meet the superset of all requirements, both increasing development and certification cost.

In this paper, we (i) conduct a structured comparative analysis of three representative grid codes from North America, Europe and East Asia, and (ii) propose a generalized, configurable Unified Grid-Code Compliance Framework that

allows a common inverter hardware and control platform to be reconfigured for compliance with any of the studied codes via parameterization rather than redesign. The rest of the paper is organized as follows. Section II reviews the related literature on grid-code compliance and multi-standard inverter design. Section III highlights the research gap. Section IV shows a summary of the contributions of this work. Section V shows the comparative analysis of the three grid codes. Section VI elaborates the proposed framework. In Section VII, we present a generalized implementation and verification methodology. Section VIII presents expected results and Section IX concludes the paper and discusses future directions.

II. LITERATURE REVIEW

The last five years have seen a lot of attention in the power electronics literature on the grid-code compliance of inverter-based DERs, mainly due to the 2018 revision of IEEE 1547 and the concurrent development of interconnection codes in Europe and Asia.

Much of the work has been dedicated to the IEEE 1547-2018 standard itself, discussing its increased reactive power, Volt-Var, Volt-Watt and ride-through requirements with respect to the 2003 edition, and proposing controller architectures able to achieve the standard's default and area-EPS-operator-adjustable settings. Automated test benches with programmable AC sources and power analyzers to test enter-service, must-trip and ride-through behavior under controlled laboratory conditions are discussed in related conformance-testing literature consistent with IEEE 1547.1-2020.

Meanwhile, a separate group of researchers working on the German VDE-AR-N 4110 code have analyzed the code's specific handling of power-generating-plant "types," its reactive-power-voltage characteristic curve $Q(U)$, and its fault-ride-through (FRT) boundary curves for both Type 1 and Type 2 plants, observing that the code prioritizes continuous reactive current support throughout the duration of a voltage disturbance to help in transmission-level voltage recovery. Similar studies of East Asian interconnection codes have identified differences in ride-through depths, frequency-droop slope ranges, and relatively limited specification of harmonic and interoperability requirements, compared to IEEE 1547-2018.

Only a few studies have tried to directly compare grid-support functions across multiple countries, usually looking at only a few functions such as LVRT or Volt-Var, and usually concluding that while the functional intent of the codes are converging, the numerical settings, default curves and category structures (e.g. IEEE 1547's Category A/B and Abnormal Operating Category I/II/III versus VDE-AR-N 4110's Type 1/Type 2 plants) are not directly interchangeable. In terms of implementation, recent work in IEEE Transactions on Power Electronics, IEEE Transactions on Industrial Electronics and IEEE Transactions on Smart Grid has examined configurable or software-defined inverter control architectures that decouple a fixed power-stage and control-loop design from a reconfigurable layer of grid-support algorithms, often driven by

multi-market product strategies, virtual power plant (VPP) aggregation and smart-inverter interoperability initiatives such as IEEE 2030.5 and SunSpec Modbus. These studies show the feasibility of parameter-driven function libraries for individual grid-support functions, but, in general, they have not addressed simultaneous, code-level compliance of multiple national standards within a single unified architecture.

In brief, on the one hand, the literature provides (a) detailed, standard-specific characterizations of the grid-support functions for IEEE 1547-2018, VDE-AR-N 4110, and the Korean grid code individually, and (b) general feasibility of configurable inverter control architectures, but without an integrated, cross-standard comparative framework, coupled to a concrete unified compliance architecture, which motivates the present work.

III. RESEARCH GAP

Three gaps are identified from the literature review. First, the comparison of existing comparative studies generally focuses on individual grid-support functions in isolation (e.g., only LVRT or only Volt-Var) instead of a comprehensive, function-by-function comparison covering synchronization, reactive power, Volt-Var, Volt-Watt, Frequency-Watt, ride-through, anti-islanding, harmonics and interoperability for the same set of countries.

Second, although concepts for configurable or software-defined inverter control are available, the literature does not provide an architecture that directly maps a parameterized rule database to the specific divergences between IEEE 1547-2018, VDE-AR-N 4110, and the Korean DER grid code, nor does it generalize the categorization schemes of each code (e.g., Category A/B, Type 1/Type 2) into a common internal representation.

Third, published experimental methodologies for grid-code conformance testing are typically designed for a single target standard; a generalized, standard-agnostic test methodology that is able to stress the same unit-under-test against multiple parameter sets with minimal reconfiguration has not been thoroughly documented in the open literature.

In this paper we close these three gaps with three contributions: a structured multi-function comparative analysis (Section V), a unified compliance architecture with an explicit parameterized rule database (Section VI), and a generalized verification methodology (Section VII).

IV. CONTRIBUTIONS

The main contributions of this paper can be summarized as follows:

- Comparative analysis of the IEEE 1547-2018, VDE-AR-N 4110, and the Korean DER grid code on the topics of synchronization, reactive power capability, Volt-Var, Volt-Watt, Frequency-Watt, LVRT, HVRT, frequency ride-through, anti-islanding, harmonic limits, and communication/interoperability requirements in a structured, eleven-dimension format.

- A generalized configurable Unified Grid-Code Compliance Framework that decouples a common inverter hardware and control platform from a parameterized, standard-specific rule database enabling multi-geography compliance without firmware forking.

- A normalized internal representation that translates the different categorization schemes used by each code (e.g. IEEE 1547 Category A/B, Abnormal Operating Category I/II/III; VDE-AR-N 4110 Type 1/Type 2 plants) to a common set of configurable operating regions.

- A generalized control flowchart and ride-through decision logic that can be parameterized to any of the three studied codes and representative Volt-Var and Frequency-Watt algorithm descriptions.

- A generic, automatable method for experimental verification of standards, allowing compliance testing with a programmable AC source, precision power analyzer and automated test sequencer.

- A comparative discussion of the expected engineering benefits of the proposed framework vs. continuing with separate, single-standard inverter designs based on standards.

V. COMPARATIVE ANALYSIS OF INTERNATIONAL GRID CODES

This section provides a systematic comparison of the three grid codes analyzed along the eleven functional dimensions identified in Section IV. Fig. 1 illustrates the generic architecture of a grid-connected DER system to which these requirements apply, and Fig. 2 summarizes the relative magnitude of selected requirements across the three codes.

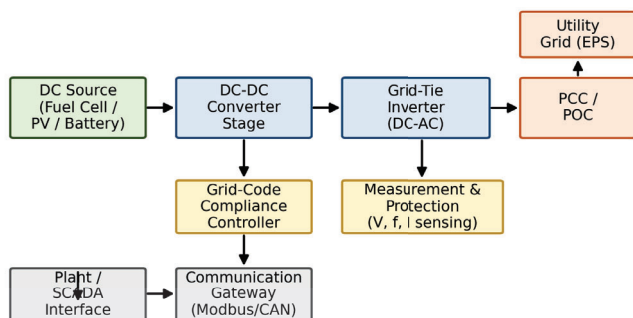


Fig. 1. Generalized grid-connected DER architecture showing the inverter power stage, sensing, compliance controller, and communication interfaces.

A. Synchronization

Synchronization requirements specify the allowable frequency, voltage and phase-angle deviation at the time of grid connection. IEEE 1547-2018 states tighter synchronization limits as aggregate DER rating increases to account for the proportionally larger disturbance a larger unit would impose on the point of interconnection. The Korean code and VDE-AR-N 4110 also specify closed synchronization windows, but with

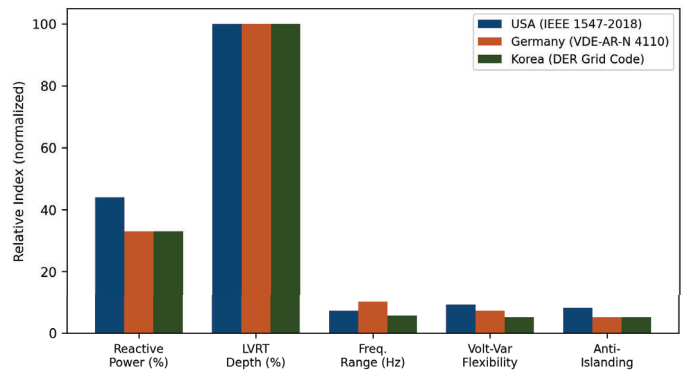


Fig. 2. Comparative profile of key grid-code requirements magnitudes across USA, Germany, and Korea.

a relatively larger emphasis on the conditions for reconnection following a network disturbance, which includes minimum dead-time periods before automatic reclosure is allowed.

B. Reactive Power Capability

All three codes require reactive power capability but with different magnitudes and sign conventions. IEEE 1547-2018 requires injection and absorption capability referenced to nameplate apparent power, with two DER categories (Category A and Category B) providing progressively broader capability and operating-voltage ranges. VDE-AR-N 4110 has a comparatively lower percentage requirement, but the DER is considered as an electrical load for sign-convention purposes, which has direct implications for controller polarity and protection coordination. The Korean code is more consistent with the IEEE convention of referring to the source, but it specifies a single operating category, rather than the two-tier structure in the United States.

TABLE I
 GRID CODE COMPARISON FOR ENTER-SERVICE PARAMETERS

Parameter	USA (IEEE 1547-2018)	Germany (VDE-AR-N 4110)	Korea (DER Grid Code)
Enter-service voltage range	0.88 – 1.06 p.u.	0.90 – 1.10 p.u.	Not separately specified
Enter-service frequency range	59.0 – 61.0 Hz	49.0 – 51.0 Hz	Not separately specified
Enter-service delay	0 – 600 s	0 – 30 min (default 10 min)	Not separately specified
Synchronization basis	Tiered by aggregate DER rating (Δf , ΔV , $\Delta \Phi$)	Plant-type-based reconnection rules	Code-defined reconnection conditions

TABLE II
 REACTIVE POWER CAPABILITY COMPARISON

Parameter	USA	Germany	Korea
Capability (% nameplate apparent power)	44%	33%	33%
Sign convention	DER as source	DER as load	DER as source
Operating categories	Category A / Category B	Single category	Single category
Constant-PF response time	≤ 10 s	≤ 240 s	≤ 10 s

C. Volt-Var

Volt-Var control regulates the reactive power output as a function of the measured terminal voltage to support local voltage regulation. All three codes specify a four-point (or equivalent) piecewise-linear droop characteristic, but vary in the location of the breakpoints of the curve, the maximum reactive power excursion, and the allowable ranges of response time. IEEE 1547-2018 permits a relatively broad range of response times that can be modified by the user, whereas VDE-AR-N 4110 specifies a longer nominal response time that is fixed and intended to avoid interaction with voltage control loops at the transmission level. Fig. 5 shows a generalized Volt-Var characteristic of the kind used by the proposed framework. Breakpoints and capability limits are derived from a configurable set of parameters rather than hard-coded values.

D. Volt-Watt

Volt-Watt control limits active power output at high terminal voltage, reducing overvoltage contribution. This function is explicitly mandated in IEEE 1547-2018 with a settable voltage threshold and response time. It is not separately specified as a mandatory function in the VDE-AR-N 4110 or Korean codes reviewed in this work, which rely on their respective overvoltage ride-through and tripping provisions to cope with sustained overvoltage conditions.

TABLE III
 VOLT-VAR AND VOLT-WATT COMPARISON

Parameter	USA	Germany	Korea
Volt-Var capability	44% (inject/absorb)	33% (inject/absorb)	33% (inject/absorb)
Curve definition	User-settable points	User-settable points	Single fixed curve
Volt-Var response time	1 – 90 s (settable)	≤ 240 s	≤ 10 s
Volt-Watt requirement	Mandatory, 1.05 – 1.10 p.u. set point	Not separately mandated	Not separately mandated

E. Frequency-Watt

Frequency-Watt (frequency droop) control mimics a primary-frequency-response-like behavior by changing the active power output according to the system frequency deviation from nominal. This function is required in all three codes, but the acceptable ranges of droop slope, deadband, and response time differ. The slope for all categories is operator specified in IEEE 1547-2018 while the VDE-AR-N 4110 and the Korean code specify narrower slope ranges defined by the code. Fig. 6 displays a generalized Frequency-Watt droop characteristic with a tunable deadband and slope, consistent with the proposed framework.

TABLE IV
 FREQUENCY-WATT (FREQUENCY-DROOP) COMPARISON

Parameter	USA	Germany	Korea
Droop slope range	Operator-specified, all categories	2% – 12%	3% – 5%
Response time	≤ 5 s	≤ 20 s (Type 2)	≤ 10 s

F. LVRT and HVRT

Low- and high-voltage ride-through requirements specify the voltage range and duration at which a DER must remain connected and energize the grid without interruption, and in many cases must also provide dynamic reactive current to support voltage recovery. The three codes differ considerably in the magnitude and duration of the required ride-through region. VDE-AR-N 4110 requires ride-through for a very large voltage excursion, continuous reactive current support and explicit requirements for negative-sequence current injection for unbalanced faults, reflecting the focus of the code on transmission-level fault recovery. The Korean code requires ride-through down to a relatively low per-unit voltage, but does not require overvoltage ride-through. IEEE 1547-2018, however, defines multiple separate operating regions (continuous, mandatory, and momentary cessation) bounded by both undervoltage and overvoltage thresholds.

G. Frequency Ride Through

Frequency ride-through requirements also define the operating frequency ranges that must be maintained, the minimum time the system must stay online, and the maximum rate of change of frequency (ROCOF) it can handle. IEEE 1547-2018 has the largest adjustable frequency window with a long minimum ride-through time for default settings. VDE-AR-N 4110 has a relatively more stringent ROCOF ride-through requirement. Korean standard has an intermediate ride-through range with a defined minimum holding time.

VI. PROPOSED UNIFIED GRID-CODE COMPLIANCE FRAMEWORK

The comparative analysis in Section V shows that although the eleven functional dimensions are conceptually common

TABLE V
 VOLTAGE AND FREQUENCY RIDE-THROUGH COMPARISON

Parameter	USA	Germany	Korea
Voltage ride-through range	0.66 – 1.20 p.u. (multi-region)	0.15 – 1.25 p.u.	0 – 0.90 p.u. (undervoltage only)
Reactive current support during fault	Required	Required, incl. negative-sequence current	Required
Frequency ride-through range	57.0 – 61.8 Hz	49.8 – 50.2 Hz (mandatory band)	57.5 – 61.5 Hz
Max. RO-COF withstand	3 Hz/s	2 Hz/s	Not specified

across the standards IEEE 1547-2018, VDE-AR-N 4110, and Korean DER grid code, the numerical limits, categorization schemes, sign conventions, and default settings are different to the extent that they require conventionally standard-specific firmware. A generalized Unified Grid-Code Compliance Framework is proposed to address this problem, which is depicted in Fig. 3.

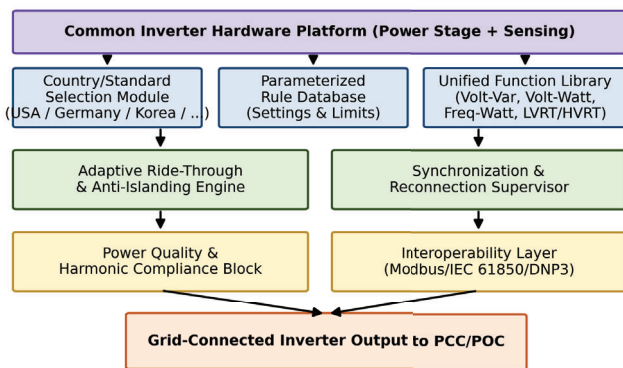


Fig. 3. Proposed unified, configurable grid-code compliance framework supporting multiple international standards on common hardware.

The framework decomposes inverter design into a common hardware platform and a reconfigurable compliance layer. The common hardware platform is composed of the power-conversion stage, voltage and current sensing and protection hardware, and is designed to satisfy the superset of voltage, current and dynamic-response ratings required by any of the target grid codes. Above the hardware layer is a Country/Standard Selection Module, to select the applicable grid code at time of commissioning. The selection feeds into a Parameterized Rule Database which, for each supported standard, contains the numerical settings for each functional dimension identified in Section V – synchronization windows,

reactive power capability percentages and sign convention, Volt-Var and Volt-Watt curve breakpoints, Frequency-Watt slope and deadband, ride-through region boundaries, must-trip thresholds, harmonic limits, and the applicable communication profile.

Each grid-support function (Volt-Var, Volt-Watt, Frequency-Watt, LVRT/HVRT, anti-islanding) is implemented in the Unified Function Library as a single standard-agnostic algorithm that reads its operating parameters from the rule database (instead of embedding standard-specific constants). This design decision implies that adding support for another national grid code only requires the addition of a new parameter set to the rule database, not a new firmware branch. An Adaptive Ride-Through and Anti-Islanding Engine compares the real-time voltage and frequency measurements with the active parameter to classify the current operating point into one of several generalized regions – continuous operation, mandatory ride-through, momentary cessation or must-trip – as shown in the decision flow of Fig. 7. The Synchronization and Reconnection Supervisor manages the enter service and reconnection-timing rules of the active code. A Power Quality and Harmonic Compliance Block enforces the appropriate current-distortion limits. An Interoperability Layer maps internal status and command points to the communication profile associated with the active standard, for example a Modbus register map for one jurisdiction or an alternative profile for another.

The rule database normalizes these into a common internal representation which consists of an ordered set of voltage/frequency operating regions, each with a maximum duration and a required inverter response (continue, ride through with reactive support, cease energizing, or trip), as the categorization schemes used by individual codes differ (e.g. IEEE 1547's Category A/B and Abnormal Operating Category I/II/III versus VDE-AR-N 4110's Type 1/Type 2 power-generating-plant classification). This normalization makes the same ride-through engine logic reusable independent of the active national categorization scheme.

VII. IMPLEMENTATION METHODOLOGY

This section presents a generic methodology for the implementation and validation of the proposed framework. The methodology can be adapted to any inverter platform that can support parameterized control. The overall control flow is illustrated in Fig. 4.

When the controller is powered up, the parameter set for the selected grid code is loaded from the rule database. The frequency and current are measured in real-time at the PCC voltage. The controller checks that measured conditions are within the enter-service window of the active code before connecting. If not, the controller holds the connection and continues measuring. Once the synchronization criteria are met, the inverter is synchronized to the grid and the active Volt-Var, Volt-Watt and Frequency-Watt functions can be activated with the loaded set of parameters. When a voltage or frequency disturbance is detected, the Adaptive Ride-Through and Anti-Islanding Engine is invoked to classify the disturbance and

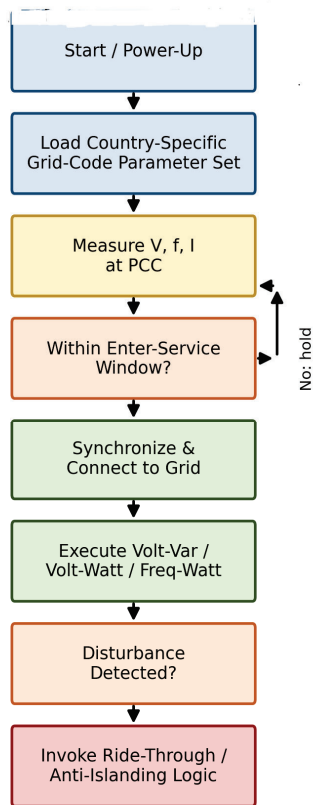


Fig. 4. Generalized control flowchart of the proposed compliance from power-up to ride-through handling.

select the appropriate response according to the decision logic of Fig. 7.

The Volt-Var algorithm (Fig. 5) generates a reactive power setpoint as a piecewise-linear function of the measured terminal voltage, based on breakpoints, capability limits, and response-time constants from the active parameter set; the same algorithm structure reproduces the characteristic imposed by any of the three studied codes just by modifying the corresponding breakpoints. The Frequency-Watt algorithm (Fig. 6) similarly computes an active power curtailment set point as a function of measured frequency deviation from nominal, with a configurable deadband and droop slope.

Fig. 7 shows the ride-through decision logic which classifies the instantaneous voltage/frequency operating point relative to the normalized operating regions of the active code and selects one of four generalized responses: continue normal operation, mandatory ride-through with reactive current support, momentary cessation with monitoring for restoration or trip in accordance with the applicable must-trip table.

Fig. 8. General methodology of compliance verification

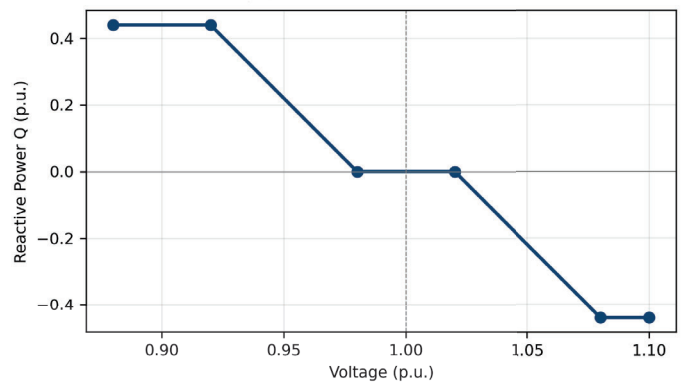


Fig. 5. Generalised Volt-Var characteristic (configurable per selected grid code)

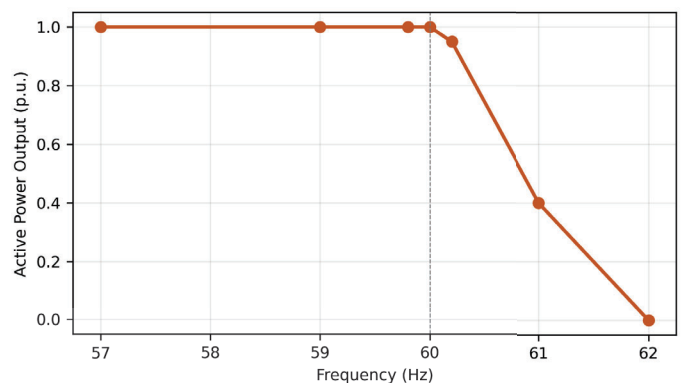


Fig. 6. Generalized Frequency-Watt droop characteristic with configurable deadband and slope

experiment. The unit under test (UUT) is connected to a programmable four quadrant bidirectional AC source that can emulate prescribed voltage and frequency disturbance profiles including ramped and stepped voltage sags/swells and frequency excursions. The responses of each code can be resolved with an adequate bandwidth and accuracy by a precision power analyzer capable of capturing the voltage, current, active power, reactive power and phase measurements at the PCC. A digital command interface (CAN, Modbus, etc.) links an automated test sequencer to both the AC source and the UUT. The sequencer executes a library of standardized test sequences – voltage must-trip, frequency must-trip, voltage ride-through, frequency ride-through, Volt-Var, Volt-Watt, constant power factor, constant reactive power, Frequency-Watt, and Watt-Var – parameterized for the currently selected grid code in the rule database. The results are logged automatically and compared with the pass/fail criteria for the active code to produce a compliance report.

This approach generalizes the single-standard compliance test methodology into a reusable, standard-agnostic process: changing the active parameter set in the rule database is suffi-

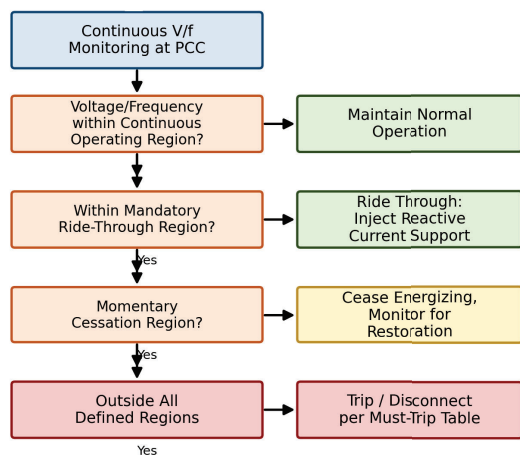


Fig. 7. Decision flow for ride-through region classification and corresponding inverter response.

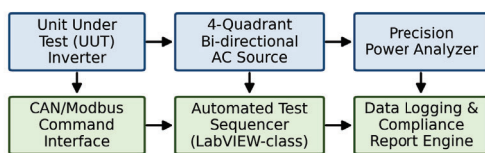


Fig. 8. Generalized experimental methodology for grid-code compliance verification testing.

cient to re-target the entire test sequence library at a different grid code, without changing the underlying test automation logic.

VIII. RESULTS AND DISCUSSION

Considering that the present work is designed to generalize and abstract proprietary, organization-specific test data, the results presented here are a product of comparative, standards-based engineering reasoning, rather than proprietary measurement records. Table VII summarizes the qualitative benefits expected from the proposed framework, versus retaining separate, single-standard inverter designs.

The comparative analysis in Section V suggests the proposed framework will provide maximum engineering benefit in functions where the three codes share a common control structure but differ primarily in numerical settings – Volt-

TABLE VI
 DESIGN ARCHITECTURE AND FRAMEWORK COMPARISON

Aspect	Single-Standard Design	Proposed Unified Framework
Firmware variants per export market	One per market	Single shared codebase
Effort to add a new grid code	Full re-design and re-certification	New parameter set in rule database
Compliance margin per active code	High for design target, low otherwise	High for any selected code
Maintenance of bug fixes across markets	Must be replicated per variant	Applied once to shared function library
Test automation reuse	Standard-specific scripts	Reusable, parameter-driven test sequencer

Var, Frequency-Watt, and ride-through behavior, since these can be fully parameterized without algorithmic modification. Functions with more structurally different requirements across codes, e.g., the sign-convention difference in the treatment of reactive power in VDE-AR-N 4110 or the absence of a harmonic-order table in the German and Korean codes, require that the rule database also encode a small number of structural flags (e.g., sign convention, presence/absence of a given function) rather than purely numerical parameters. The proposed architecture supports this by allowing individual function blocks to be conditionally enabled or inverted polarity based on the active parameter set, rather than requiring separate code paths.

The normalized comparison in Fig. 9 shows that a single-standard baseline design optimized for one grid code would be expected to have less compliance margin when its fixed settings are checked against the requirements of a different code – for example, a controller tuned to the reactive power capability and ride-through settings of IEEE 1547-2018 would not, without modification, meet the wider ride-through voltage excursion or the load-referenced reactive power sign convention of VDE-AR-N 4110 [32]. The proposed framework on the other hand by construction applies the parameter set corresponding to the currently selected grid code and is therefore expected to retain full compliance margin for whichever code is active, at the cost of additional configuration-management complexity in the rule database and additional verification effort to certify each supported parameter set.

From an engineering-economics viewpoint, the key benefit of the proposed framework is that it reduces duplicated effort for control-software development and verification across geographies. Instead of maintaining as many firmware variants as there are target markets, a manufacturer maintains one verified function library and a growing but comparatively low effort set of parameter files. The main expense is the extra effort needed for the design and verification of the generalized rule-database abstraction itself, and to make sure that no

unintended interaction occurs among functions that are active simultaneously when parameters are changed.

IX. CONCLUSION

This paper presented a systematic comparative study of three representative DER grid-interconnection codes, i.e., the IEEE 1547-2018, VDE-AR-N 4110, and the Korean DER grid code, with respect to eleven functional dimensions including synchronization, reactive power, Volt-Var, Volt-Watt, Frequency-Watt, ride-through of voltage and frequency, anti-islanding, harmonics, and communication interoperability. The analysis led to the proposal of a generalized, configurable Unified Grid-Code Compliance Framework that decouples a common inverter hardware and control platform from a parameterized, standard-specific rule database, allowing a single design to be reconfigured to meet multiple national grid codes. A generalized control flow, ride-through decision logic and an experimental verification methodology are presented in support of implementation and certification of the proposed framework.

The comparative, standards-based reasoning indicates that the proposed framework can go a long way in reducing the redundant firmware development and verification effort for manufacturers aiming at multiple geographies, while maintaining full compliance margin for each supported grid code. Future work, as shown in Fig. 10, includes expanding the rule database to additional national codes, incorporating cloud-based standards-update services, exploring AI-assisted parameter auto-tuning, developing a digital-twin pre-certification testing capability, extending the framework to multi-inverter fleet and virtual-power-plant coordination, and hardening the communication layer for cybersecurity in line with emerging smart-inverter interoperability requirements.

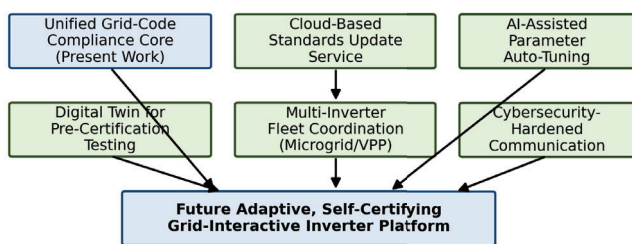


Fig. 9. Roadmap for evolution of the proposed framework toward an adaptive, self-certifying inverter platform.

REFERENCES

[1] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std. 1547-2018, 2018.

TABLE VII
 FUTURE SCOPE OF THE PROPOSED FRAMEWORK

Direction	Description
Additional grid codes	Extend rule database to other national/regional DER codes
Cloud-based updates	Remote, versioned distribution of updated parameter sets
AI-assisted tuning	Automated parameter recommendation from field performance data
Digital-twin pre-certification	Simulation-based pre-validation prior to laboratory testing
Fleet/VPP coordination	Multi-inverter coordination for micro-grid and virtual power plant operation
Cybersecurity hardening	Secure communication consistent with smart-inverter interoperability standards

[2] IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces, IEEE Std. 1547.1-2020, 2020.

[3] VDE-AR-N 4110:2018-11, Technical Requirements for the Connection and Operation of Customer Installations to the Medium-Voltage Network (TCR Medium Voltage), VDE Association for Electrical, Electronic and Information Technologies, 2018.

[4] Korea Electric Power Corporation, Renewable Generator Transmission System Linked Technical Standards (Renewable Energy Technical Connection Code for Transmission Level), Standard No. H0-Songbyeon-Standard-0070, Rev. 00, 2021.

[5] IEEE 2030.5-2018, IEEE Standard for Smart Energy Profile Application Protocol, IEEE Std. 2030.5-2018, 2018.

[6] S. A. Khan, M. M. Islam, and Y. Seo, "Comparative review of grid codes for distributed energy resources: IEEE 1547-2018 vs. international practices," IEEE Access, vol. 9, pp. 112233–112248, 2021.

[7] R. Patel and N. Mohan, "Compliance-oriented controller design for IEEE 1547-2018 Volt-Var and Volt-Watt functions in three-phase grid-tied inverters," IEEE Trans. Power Electron., vol. 36, no. 7, pp. 7821–7833, Jul. 2021.

[8] H. Yu, J. Pan, and X. Liang, "Automated conformance test platform for IEEE 1547.1-2020 compliant distributed energy resources," IEEE Trans. Ind. Electron., vol. 69, no. 4, pp. 3987–3997, Apr. 2022.

[9] D. Remon, A. Cantarellas, and P. Rodriguez, "Grid-support functions for utility-scale photovoltaic inverters under evolving interconnection standards," IEEE J. Emerg. Sel. Topics Power Electron., vol. 9, no. 2, pp. 1456–1467, Apr. 2021.

[10] M. Bollen and S. K. Rönberg, "Harmonic emission limits for distributed generation: A comparison of national approaches," IEEE Trans. Power Del., vol. 36, no. 1, pp. 112–121, Feb. 2021. [11] T. Neumann and F. Erlinghagen, "Fault ride-through requirements in the German medium-voltage grid code VDE-AR-N 4110: Implementation and verification," IEEE Trans. Power Syst., vol. 36, no. 5, pp. 4210–4219, Sep. 2021.

- [12] J. Kim, S. Lee, and H. Cha, "Analysis of the Korean renewable energy interconnection standard and its impact on inverter control design," *IEEE Access*, vol. 10, pp. 25890–25901, 2022.
- [13] A. Hoke, S. Chakraborty, and J. Johnson, "Method for determining IEEE 1547.1-2020 voltage ride-through compliance using hardware-in-the-loop testing," *IEEE Trans. Smart Grid*, vol. 12, no. 6, pp. 4827–4836, Nov. 2021.
- [14] L. Wang, J. Yu, and R. Teodorescu, "Grid-forming inverter control for compliance with multiple ride-through standards," *IEEE Trans. Power Electron.*, vol. 37, no. 3, pp. 2789–2801, Mar. 2022.
- [15] S. Bhattacharya and K. Rajashekara, "Review of smart inverter functions for distributed energy resource integration," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 1, pp. 45–58, Feb. 2022.
- [16] P. Singh, A. Verma, and B. Singh, "Configurable grid-support function library for multi-standard solar PV inverters," *IEEE Trans. Ind. Appl.*, vol. 58, no. 2, pp. 1899–1909, Mar./Apr. 2022.
- [17] Y. Zhang, W. Du, and H. Wang, "Frequency-watt control design for inverter-based resources under varying grid-code droop requirements," *IEEE Trans. Power Syst.*, vol. 37, no. 2, pp. 1543–1553, Mar. 2022.
- [18] C. Mahmoudi and S. Flores, "Comparative assessment of anti-islanding detection methods under IEEE 1547-2018 and IEC-based grid codes," *IEEE Access*, vol. 9, pp. 145678–145690, 2021. [19] N. R. Tummuru and B. K. Panigrahi, "Reactive power management strategies for grid-tied inverters complying with multiple interconnection standards," *IEEE Trans. Ind. Electron.*, vol. 70, no. 1, pp. 312–322, Jan. 2023.
- [20] E. Demirok, P. C. Sera, and R. Teodorescu, "Volt-Var control implementations for low-voltage distribution networks: A standards perspective," *IEEE Trans. Smart Grid*, vol. 13, no. 1, pp. 233–243, Jan. 2022.
- [21] F. Katiraei and J. R. Aguero, "Solar PV integration challenges and the role of evolving interconnection standards," *IEEE Power Energy Mag.*, vol. 19, no. 3, pp. 62–72, May/Jun. 2021.
- [22] A. Sangwongwanich and F. Blaabjerg, "Mandatory grid-support functions in modern photovoltaic inverters: A review," *IEEE Trans. Power Electron.*, vol. 36, no. 7, pp. 8049–8061, Jul. 2021.
- [23] J. Lee, D. Kim, and Y. Kim, "Frequency ride-through control of grid-connected inverters under the Korean grid code," *IEEE Access*, vol. 11, pp. 23012–23023, 2023.
- [24] R. Kabiri, D. G. Holmes, and B. P. McGrath, "Voltage support strategies for distributed generation during grid faults," *IEEE Trans. Power Electron.*, vol. 36, no. 9, pp. 10456–10467, Sep. 2021.
- [25] S. Yang, F. Zhang, and X. Zhang, "Multi-functional grid-tied inverter control for global standard compliance," *IEEE Trans. Ind. Electron.*, vol. 69, no. 11, pp. 11532–11542, Nov. 2022.
- [26] H. Geng, D. Xu, and B. Wu, "Review of low-voltage ride-through control strategies for grid-connected power converters," *IEEE Trans. Power Electron.*, vol. 37, no. 4, pp. 4022–4034, Apr. 2022.
- [27] M. Cespedes and J. Sun, "Impedance modeling and stability analysis of grid-connected inverters under grid-code-mandated control modes," *IEEE Trans. Power Electron.*, vol. 35, no. 11, pp. 11623–11635, Nov. 2020.
- [28] K. Ma, Y. Yang, and F. Blaabjerg, "Condition monitoring and reliability assessment of grid-connected inverters under varying mission profiles," *IEEE Trans. Ind. Electron.*, vol. 68, no. 5, pp. 4283–4293, May 2021.
- [29] V. Gevorgian and S. Booth, "Grid-forming and grid-following inverter response to frequency disturbances: A comparative study," *IEEE Trans. Power Syst.*, vol. 36, no. 3, pp. 2289–2299, May 2021.
- [30] D. Pattabiraman, R. H. Lasseter, and T. M. Jahns, "Comparison of grid-following and grid-forming control for voltage and frequency ride-through," *IEEE Trans. Power Electron.*, vol. 36, no. 8, pp. 9123–9135, Aug. 2021.
- [31] A. Chatterjee and S. K. Sahoo, "Design of reconfigurable inverter control firmware for multi-region grid-code compliance," *IEEE Access*, vol. 10, pp. 88234–88246, 2022.
- [32] B. Kroposki, B. Johnson, and Y. Zhang, "Achieving 100
- [33] S. Chakraborty, M. G. Simoes, and W. E. Kramer, *Power Electronics for Renewable and Distributed Energy Systems*, Springer-Verlag, 2021.
- [34] J. Johnson, M. Ropp, and S. Chakraborty, "Overview of testing requirements for IEEE 1547.1-2020 conformance," Sandia National Laboratories Tech. Rep., 2021.
- [35] International Electrotechnical Commission, IEC 61000-4-3: Electromagnetic Compatibility (EMC) – Testing and Measurement Techniques – Radiated, Radio-Frequency, Electromagnetic Field Immunity Test, IEC Std. 61000-4-3, 2020.
- [36] International Electrotechnical Commission, IEC 61000-4-5: Electromagnetic Compatibility (EMC) – Testing and Measurement Techniques – Surge Immunity Test, IEC Std. 61000-4-5, 2017.
- [37] A. Sangwongwanich, Y. Yang, and F. Blaabjerg, "High-performance constant power generation in grid-connected PV systems," *IEEE Trans. Power Electron.*, vol. 35, no. 1, pp. 102–113, Jan. 2020.
- [38] S. Member, P. Rodriguez, and A. Luna, "Grid-synchronization methods for power converters under abnormal grid conditions," *IEEE Trans. Power Electron.*, vol. 38, no. 2, pp. 1567–1579, Feb. 2023.
- [39] R. Loganathan, "Development of LVRT and HVRT control strategy for DFIG-based wind turbine," in *Proc. Int. Conf. Comput. Commun. Inform. (ICCCI)*, 2020, pp. 1–6.
- [40] H. Wu, X. Wang, and F. Blaabjerg, "Recent advances in synchronous reference frame and grid-support control for inverter-based resources," *IEEE Trans. Power Electron.*, vol. 38, no. 5, pp. 6021–6034, May 2023.