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TOPICAL REVIEW

Virtual Inertia Support in Power Systems for High Penetration of Renewables–Overview of Categorization, Comparison, and Evaluation of Control Techniques

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ABSTRACT By replacing conventional generation units with renewable energy sources (RESs), the power system gains an alternate source of future power generation and a better environmental platform. RESs, on the other hand, are unable to provide the required power demand due to poor inertia responses and low-frequency stability. As a result, multiple inertia augmentation control strategies were developed to increase frequency stability and maximize power usage in the grid-integrated renewable energy systems. Accordingly, this study thoroughly reviews existing virtual inertia control (VIC) strategies for improving inertia response and frequency stability. This study investigates 51 VIC approaches regarding required parameters, configurations, key contributions, sources, controllers, and simulation platforms. Furthermore, to emphasize the most promising ones, the VIC approaches are classified as intelligent, adaptive, derivative, coordinated control, and other VIC techniques. The classification approach is followed by the system configuration and the mode of operation of each control scheme. Integrating intelligent methods, such as fuzzy logic, genetic algorithm, non-convex optimization, and heuristic optimization, signify intelligent control methods. In contrast, adaptive control schemes emphasize the adaptation of control operations. These studies include both the standalone and grid-connected RESs frequency and power control approaches with necessary mathematical modelling and equations, which are rarely available in the recent existing works. The current state of research on improving frequency stability and inertia response in the grid-integrated RESs is discussed. Finally, this literature review reflects the present status of VIC technique research paths, and the categorization and analysis of these approaches demonstrate an extensive insight into the research field.

INDEX TERMS Renewable energy, virtual inertia control techniques, synthetic inertia control, frequency stability, intelligent control, adaptive control, derivative control, coordinated control.

NOMENCLATURE

A. ABBREVIATIONS

ADP	Approximate Dynamic Programming
ASA	Artificial Sheep Algorithm
ASIG	Active-Stall Induction Generator
AVI	Adaptive Virtual Inertia.
BGC	Bi-directional Grid-Connected Converter.
CDM	Coefficient Diagram Method.
CSO	Chicken Swarm Optimization.
CVaR	Conditional Value at Risk.
DAB	Dual Active Bridge.
DCT	Derivative Control Technique.
DE	Differential Evaluation.
DFIG	Doubly-Fed Induction Generator.
DPMSG	Directly-Driven Permanent Magnet Synchronous Generator.
EMTP	Electromagnetic Transient Program.

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ESS	Energy Storage System.
FADE	Fuzzy Adaptive Differential Evaluation.
FDM	Frequency Deviation Margin.
GEC	Generation Emulation Control.
GSC	Grid Side Converter.
GTC	Grid-Tied Converter.
HDP	Heuristic Dynamic Programming.
HVDC	High Voltage Direct Current.
LVDC	Low Voltage Direct Current.
MGP	Motor-Generator Pair.
PV	Photovoltaic.
MMC	Modular Multilevel Converter.
MPC	Model Predictive Control.
NSGA	Non-dominated Sorting Genetic Algorithm.
OFW	Offshore Windfarms.
PD	Proportional-Derivative.
PI	Proportional-Integral.
PID	Proportional-Integral-Derivative.
PLL	Phase-Locked Loop.
PMSG	Permanent Magnet Synchronous Generator.
PSO	Particle Swarm Optimization.
PVA	PV Array.
RESs	Renewable Energy Sources.
ROCOF	Rate of Change of Frequency.
RPWFNN	Recurrent Probabilistic Wavelet Fuzzy Neural Network.
SG	Synchronous Generator.
SIC	Synthetic Inertia Control.
SMES	Super Conducting Magnetic Energy Storage.
SOC	State of Charge.
SOP	Step-Over Production.
VDM	Virtual DC Machine.
VIC	Virtual Inertia Control.
VSC	Voltage Source Converter.
VSG	Virtual Synchronous Generator.
WOS	Web of Science.
WPIS	Wind Power Integrated System.

B. SYMBOLS

A	The interaction matrix.
C_{dc}	The discharge power of the capacitor.
C_v	The virtual capacitance.
C_{vir}	The virtual inertia control coefficient of the controller.
D_b	The droop coefficient.
D_i	The damping factor.
D_m	The damping coefficient of microgrid.
E_K	The rotational energy.
f	Frequency.
f_n	Nominal Frequency.
H	The inertia constant.
H_i	The resultant inertia of the system.
H_{tot}	Total system inertia.
H_{vir}	The virtual inertia.
I_{set}	The dc output current reference of BGC.
J	The moment of inertia.
P_{set}	The active power reference of DC.
S	The rated power of the generator.
T_d	The delay of the telecommunication system.
T_{d_avg}	The average delay of the telecommunication system.
T_e	The electromagnetic torque of the generator.
T_m	The mechanical torque of the turbine.
U_{l_n}	The rated low voltage dc (LVDC) bus voltage.
U_n	The rated dc bus voltage.
δ_i	The coefficient number.
Δf	The frequency deviation.
ΔP_m	The generated power variation of the thermal power plant.
ΔP_{si}	The power generated from the solar power plant.
ΔP_{pv}	The solar power variation.
ΔP_w	The wind power variation.
ΔP_{inr}	The virtual inertia power.
ΔP_L	The load power variation.
$\Delta P_{Hydro,i}$	The power deviation of the hydropower plant.
$\Delta P_{Thermal,i}$	The power deviation of the thermal power plant.
$\Delta P_{Tidal,i}$	The power deviation of the tidal power plant microgrid.
$\Delta P_{inertia,i}$	The virtual inertia power variation.
$\Delta P_{Load,i}$	The load power variation.
Δu_{MPC}	The change of control signal generated by MPC.

I. INTRODUCTION

Power consumption is growing daily [1], [2] due to fast technological advancement worldwide. Additional fossil-fuel-based power plants are being constructed as the demand for power increases. These power plants, however, have significant environmental consequences because they emit toxic elements, such as CO_2, SO_2, NO_2, and other pollutants into the air [3], [4], [5]. These plants also cause acid rain, which is responsible for global warming [6], [7]. According to research [8], fossil fuel-based power plants release around 2.2 billion tons of CO_2. On the other hand, according to the Paris Agreement, greenhouse gas emissions must be reduced by around 40% by 2030 for clean air [9]. When considering environmental consequences and fossil fuel reserves, renewable energy sources (RESs) such as photovoltaic and wind can be considered alternative power sources [10], [11], [12], [13], [14], [15], [16]. RESs are environmentally beneficial, cost-effective, and emit no harmful components. However, the high RESs integration into the existing power grids poses challenging issues due to the low inertia and damping responses, low-frequency stability, and intermittent electricity supply [17], [18], [19], [20], [21]. In this case, many review analyses are conducted to comprehensively investigate different terms to increase frequency stability and inertia response [22], [23], [24], [25], [26], [27]. Reference [1] proposes a complete assessment of several virtual inertia (VI)-based controllers in the grid-integrated renewable energy system. The study investigated current trends in VI applications and their future directions. Different VI-based inverters, such as virtual synchronous generators (VSG), virtual synchronous machines, and synchronverters, are investigated in terms of topology, operation, and system-level stability. The research also highlights the present limits and constraints of using VI-based inverters in industrial and commercial settings. Reference [3] presents a critical analysis of different inertia response and frequency control techniques for integrated power systems for RESs (wind turbine and solar photovoltaic (PV)). The study suggests a significant insight into the field of research by analyzing the deloading techniques for the RESs power reservation and the inertia emulation techniques. Further research should be based on the primary frequency protection and control and the integration of intelligent communication technology. Another body of research [10] covers the present state of several virtual inertia control (VIC) approaches for improving frequency stability. The study gives information on synchronous generator VIC methodologies such as the swing equation, frequency power response, and a droop-based method. As a result, the proposed research project denotes the many words used in VIC approaches to improve frequency stability, inertia responses, and damping responses in grid-integrated RESs. Reference [28] demonstrates a comprehensive study of synthetic inertia control techniques for grid-integrated and standalone micro-hydro power plant-based RESs. A detailed analysis of the inertia response concept, system modelling, problem formulation, and control structures are provided. Reference [29] presents a critical analysis based on integrating RESs into the grid, where the challenges and solutions are discussed. There is a lack of investigation on the effect of RESs integration on the industrial application and the impact of power and frequency fluctuations. Reference [30] discusses different virtual inertia and frequency response control techniques for wind-based RESs connected to the grid. There is a lack of analysis of different intelligent control techniques, dynamic frequency response, and ESS integration to the grid. Table 1. illustrates the contributions of the proposed research work in comparison to existing research works.

Various studies have illustrated various elements of power system stability and optimal performance. For example, the frequency of support for wind turbines (WT) with variable speed and the power reserve is explored in [31]. The WT is an effective tool for controlling frequency regulation in the study. However, the ideal time of kinetic energy discharge and optimal calculation of the power surge is not considered in [31]. In [32], a unique strategy for reducing voltage and frequency variations in microgrids is presented. To handle changes and boost renewables in the microgrid, the procedure adds an algebraic-type VSG. Reference [33] proposes a synchronous motor-generator pair for improving inertia and damping responses. This method for analyzing frequency stability in the microgrid uses a small-signal model. In [34], a control strategy is given that uses both the voltage source converter-based high voltage DC (VSC-HVDC) connection and the kinetic energy of the wind turbine to optimize frequency responses. In addition, [35] proposes an inertia emulation control approach for the VSC-HVDC system that offers inertia support for DC voltage changes within an allowed range. Although the study is essential for HVDC integration in transmission networks, it lacks an investigation of the dynamic stability and economic feasibility of PV grid integration. Reference [36] proposes a VSG-based control system to increase dynamic responsiveness and frequency stability. The electromagnetic transient program (EMTP) validates the efficacy of the suggested approach. The VSG control has limitations regarding fluctuating loads and distributed power supplies. Therefore, [37] shows how to integrate RESs into a microgrid more efficiently using an upgraded grid code reinforcement method. The concept examines virtual wind and synthetic inertia to improve frequency stability and shows how energy storage systems (ESS) might be connected to the microgrid. But this study could not demonstrate a secure integration of RESs and a combined operation of wind and solar PV. Reference [38] proposes a load frequency control method for the microgrid with pumped hydropower ESS, and the artificial sheep algorithm (ASA) is used to assess the method's efficiency. However, though this study proves efficient in controlling frequency stability under various operating conditions, there is a lack of analysis in analyzing the flexibility of intelligent controllers. To address this issue, [39] presents a load frequency management solution based on fuzzy logic control (FLC) that reduces frequency variations in the WT-connected microgrid. In addition, the system employs a particle swarm optimization (PSO) technique to determine the microgrid's optimal functioning. Reference [40] describes a frequency control technique for an isolated microgrid without ESS and communication infrastructure. PSCAD/EMTDC software simulates the control technique, which shows how to regulate frequency stability in a microgrid.

A step-over production (SOP) based modified inertia-emulation control strategy is presented in [41] to assure fast control response and reduce the influence of energy recovery for WT-based microgrids. Moreover, the PSO algorithm was added to the control system to ensure optimal energy sharing across sources. But the technique necessitates the inclusion of a second controller to assist each WT with local circumstances. In [42], a transient stability control scheme is suggested, and its performance is evaluated using the PSCAD program on a standard IEEE 34 bus distribution feeder. Reference [43] presents a method for calculating the appropriate virtual inertia and frequency control settings, which can improve the microgrid's inertia and damping responses. In constructing an ideal operating model for resilient performance, inertia constants, frequency droop coefficients, and load frequencies exist. Reference [44] proposes a control

TABLE 1. The contributions of the proposed research work in comparison to existing research works.

Contributions	This Paper	[1]	[3]	[10]	[22]	[23]	[24]	[25]	[26]	[28]	[29]	[30]	[31]
Classification based on operating characteristics	✓	×	✓	×	×	×	×	×	×	×	×	×	×
Inertia response and frequency stability	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓
RESs in both grid-connected and standalone mode	✓	×	✓	✓	✓	✓	✓	✓	×	✓	✓	×	✓
Relative comparison among control techniques	✓	✓	×	×	×	×	×	✓	✓	✓	✓	×	×
Construction, advantages, and limitations	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Implementation and simulation platforms	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×
Mathematical model and equations	✓	✓	✓	✓	✓	×	×	×	✓	✓	✓	✓	✓

strategy for battery ESS (BESS) that shows how to adjust the speed of a permanent magnet synchronous generator (PMSG)-based WT during load fluctuations and is simulated in the MATLAB/Simulink environment. Reference [45] proposes a network VIC technique for analyzing the impacts of inertia and power fluctuations in a microgrid with high renewable energy penetration. The effect of incorporating different wind turbines into virtual inertia is also discussed in this paper. PMSG has a superior inertia distribution than doubly fed induction generator (DFIG), according to the results of the experiments. A dynamic frequency control scheme using an ESS is proposed in [46] to mitigate the effect of connecting wind and solar PV to the isolated microgrid. However, there are certain limits to this study's analysis of RES fluctuation and prediction accuracy. Reference [47] addresses this issue using a derivative control technique to investigate the dynamic impact of connecting RESs in microgrids. The proposed scheme is implemented in the MATLAB/Simulink environment to demonstrate the system's inertia response improvement. Reference [48] offers a frequency response estimation approach for RESs that considers both voltage and frequency responses. However, this work will require other techniques to enhance and handle WT inertia responses. Thus, to resolve this difficulty, another control scheme is proposed in [49] to analyze the VSG effect when connected to smart grids. The study presents a small-signal model to analyze the sensitivity of intelligent grids. A control scheme is proposed in [50] that considers the SG's dynamic characteristics. A small-signal model is presented to analyze system stability and optimal power-sharing.

A synchronous motor-generator pair (MGP) system is proposed in [51] to enhance grid stability and frequency response. An analysis of damping and inertia responses, efficiency, and rotor angle relationships is presented to ensure the optimal operation of the system. This study investigates stable operation, transient response, and feedback control strategies for RESs. A decoupled frequency and voltage control approach is proposed in [52] that maintains the voltage level in an inertia-free mode and the frequency with a frequency recovery control loop. The feasibility of the proposed scheme is carried out for 3 cases: low diesel generator (DG) penetration rate, high DG penetration rate, and no penetration of DG. A fast power emulation strategy for multi-area power systems is demonstrated in [53], which analyzes WT-based microgrid power fluctuations. The results of simulations show that integrating WTs improves the system's frequency response. Ref. [54] describes a hybrid frequency control approach that examines the microgrid's primary frequency responses for high RES penetration. The study covers four primary frequency controllers (inertia emulation control, droop control, fast power reserve emulation, and de-loading control). However, according to simulation results, the inertia emulation control method is the optimum controller for primary frequency control. To increase power system stability, [55] presents a synchronous resonant control approach for the PMSG. A small-signal model is employed to investigate the proposed method's frequency regulation and power sensitivity. In [56], the authors investigate frequency variations and low inertia responses in the European continental synchronous area. The research suggests that flywheels can be used to improve inertia responsiveness at a cheap cost. Reference [57] demonstrates several smart grid control strategies, attributes, and applications. The article describes the distributed approach for solving microgrids' optimization issue, including distributed model predicted techniques (MPC), consensus-based, agent-based, and decomposition-based techniques. A receding horizon management technique is proposed in [58] to mitigate frequency variations in wind and future load-connected microgrids. In this paper, by combining load forecast inaccuracies, the system decreases the computational overhead and reduces energy losses. With 25% frequency fluctuations, simulation findings indicate that energy efficiency is above 97%. Reference [59] proposes a synchronous power controller for a heavily penetrated microgrid that considers inertia, damping, and the microgrid's droop characteristics. A 10 kW grid-connected converter is used for two tasks: connecting to the weak grid and operating without a grid connection. The simulation results show that the proposed technique can effectively reduce frequency fluctuations. Reference [60] presents a synchronous inertia-constrained economic dispatch method to tackle frequency variations in the microgrid. A Gaussian PSO technique was also introduced in the study to improve frequency and power stability. A frequency control technique based on superconducting magnetic energy storage (SMES) is proposed in [61], which investigates frequency regulation and battery lifetime. The system includes a power-sharing controller that considers the dynamic droop factor in ensuring efficient power management.

The potential effect of incorporating a combined control scheme is demonstrated in [62], which integrates inertial response and primary frequency control to minimize frequency fluctuations in the microgrid. However, the study has limitations in analyzing wind variability and prediction errors during operation. Reference [63] presents an inertia control technique for a DFIG based on the WT torque limit to overcome this constraint. Several case studies, such as changeable wind speed and power penetration levels, are considered in the control strategy. Reference [64] proposes a cost-risk model for deeply penetrated RESs in the microgrid that considers inertia and demand responses to construct a cost-effective platform. The strategy adds conditional value at risk to reduce expenses. Reference [65] examines the inertia response and damping characteristics of a WT-based microgrid and proposes a frequency control scheme. The control approach is evaluated in different cases: DFIG, active-stall induction generator (ASIG), and PMSG, which considers both steady-state and transient responses. The technology ensures power stability by maintaining appropriate power distribution in both AC and DC grids. A hierarchical frequency control strategy that considers a VSG and droop controller is proposed in [66] to provide frequency stability. Under communication delay, the PSCAD/EMTDC software platform is used to investigate the system's stability and impact of frequency regulation, VSG control, and secondary frequency control. An inertia enhancement approach based on frequency derivation is proposed in [67] for enhancing inertia response that utilizes grid frequency and active power reference. The technique includes a frequency-locked loop to ensure frequency stability. The transient and steady-state responses and droop characteristics are analyzed in [68], which compares the VSG and droop control techniques. The transient frequency response is investigated in different scenarios, including standalone mode, SG-connected mode, inertia droop control, and the influence of controller delays. Reference [69] shows a synthetic inertia control (SIC) method that incorporates predictive model control to maintain optimal power-sharing between sources. The project employs virtual capacitance regulation to assure steady-state and dynamic stability while removing the need for a PWM module. A modular multilevel converter (MMC) based SIC system is proposed in [70] to ensure frequency support in the microgrid. The technique considers the inertia coefficient, penetration ratio, and modulation index to control the highly penetrated renewable sources' frequency rate (ROCOF). Another SIC system for improving inertia response in offshore wind farms is proposed in [71], which includes generator emulation control and a coordinated control strategy (OFWs). An aggregate load-frequency management strategy for wind and hydropower-based microgrids is proposed in [72] to ensure frequency stability. Reference [73] presents a hierarchical frequency control strategy that considers demand and dynamic inertia to achieve technical and economic efficacy. The system uses stochastic programming to control frequency variations. A new current control strategy is proposed in [74] for maintaining optimal active and reactive power allocation between sources. The approach employs the Lyapunov method and a repeated spatial controller to manage the current flow to investigate stability. Reference [75] proposes a VSG based on fuzzy logic control to maintain frequency and voltage stability in renewable integrated systems.

Reference [76] proposes a load frequency control strategy for an islanded, interconnected microgrid platform that integrates seagull and balloon effect modulation based on Jaya optimizes as the optimization tool. The approach provides virtual inertia and virtual damping in the proposed microgrid with an inverter-based energy storage system to minimize frequency fluctuations and maintain power in the tie-line. An optimal network planning for the power distribution side considering load demand and renewable resources is proposed in [77], which analyzes the uncertainties caused by component outages and branch congestions. The effectiveness of the proposed model for stochastic-based multiple scenarios is verified by a graph and fictitious load-based theory with numerical solutions that minimize the total cost (investment cost, substation cost, power loss cost, environmental penalty cost, etc.). Reference [78] demonstrates a review analysis of the current state and future trend of renewable energy resources (RERs) in Egypt that discusses the Egyptian energy policy, regulatory framework, and the availability of RERs and ESS. A multi-objective optimization strategy for the congestion of transmission lines is proposed in [79]. The scheme aims to find an optimal location for distributed generators (wind and geothermal power plants) that minimizes the power transmission loss and improves the voltage profile. The optimization is carried out utilizing the hybrid swarm optimization algorithm that ensures better performance than the particle swarm optimization (PSO) algorithm. Reference [80] presents an optimal energy scheduling approach between distributed generation units and EV energy storage units that allows consumers to participate in energy management programs. The approach minimizes the total operational cost by integrating two probabilistic self-adjusted modified PSO algorithms. An automatic voltage regulator (AVR) design based on a proportional-integral-derivative (PID) controller is proposed in [81] that aims to obtain three control operations: optimality, robustness, and resilience. The D-decomposition method is applied to trace PID controllers' control basins (CB) for simulation and validation purposes. Reference [82] proposes a virtual impedance control approach for the electric vehicle-to-grid interface with a 3-phase 4-leg inverter. The approach aims to facilitate optimal power-sharing under load-changing conditions, reactive power compensation, voltage support during fault conditions, and minimize the inverter harmonic for both the grid-connected and the standalone modes. A multi-functional approach is presented in [83] that aims to minimize active and reactive power oscillations, ensure reactive power compensation, and provide overcurrent protection in a microgrid. This approach integrates the parallel operation of 3-phase inverters under asymmetric grid faults conditions simulated in PSCAD/EMDTC software.

Based on the above-mentioned analysis, it is clear that researchers have proposed a lot of research on improving inertia responses for grid-integrated RESs. These studies, however, do not provide any classification or precise comparative analysis of parameters, configurations, and operating procedures for various inertia control techniques. Therefore, this paper has the following contributions:

- Provides an in-depth analysis of the present state of several VIC techniques for improving inertia response and frequency stability.
- Various types of VIC schemes, such as intelligent approaches, adaptive techniques, derivative techniques, coordinated control techniques, and other VIC techniques, are classified in this work.
- It presents a critical analysis of different VIC systems in terms of configurations, fundamental characteristics, simulation platforms, features, and contributions.

The relevant information is necessary to research a specific topic [84]. The authors discussed keywords with each other multiple times to collect related research articles for the research work. The most relevant keywords are VIC techniques, RESs, and low inertia response. Various sites are used for gathering research articles, including Google Scholar, Scopus, and Web of Science (WOS). After a keyword-based paper collection approach, a total of 135 documents were chosen to continue the research, comprising 117 journals (100 articles and 17 review papers), six websites, and 12 conference papers. The authors identify various control strategies in the review process and analyze system configuration, fundamental parameters, simulation platform, and contributions. As illustrated in Figure 1, the post-review process involves a graphical depiction of various parameters and an illustration of keywords, such as considered sources, small-signal modelling, and simulation platforms. Several studies on inertia control strategies for high-penetration renewables have been conducted over the years. Figure 2 shows a graphical depiction of the number of publications on the topic mentioned above per year (2011–2022). The figure also includes a cumulative graphical representation of the significant growth of publications year after year. The majority of the papers, 28 of them, were published in 2019.

This paper is organized into four sections. Section 1 depicts the preliminary study and literature assessment of several existing inertia control systems. This section also highlights the proposed research work's contributions and outlines the workflow of the work from article selection through the post-review procedure. Section 2 offers the classification of various VIC procedures, thoroughly examining these techniques. A review on the relative comparisons among different significant parameters, and simulation platforms are shown in Section 3. Section 4 summarizes the findings and conclusions of the proposed research, as well as the research's future directions.

II. CLASSIFICATION OF VARIOUS VIC TECHNIQUES

The inertia response and frequency stability are reduced because of the high penetration of RESs in the grid. Many inertia control approaches are offered to improve frequency stability and inertia responsiveness. The study will look at various VIC approaches and propose a categorization system for them. The five categories of VIC techniques are intelligent, adaptive, derivative, coordination, and other VIC techniques. The considered control approaches are categorized based on the mode of functioning. Several control approaches utilize different intelligent techniques such as genetic algorithm, non-convex optimization, heuristic optimization, fuzzy logic, particle swarm optimization algorithm, and neural network. Hence these techniques are categorized into the intelligent control technique. The adaptive control scheme includes adaptive virtual inertia and adaptive virtual governor gain to adjust frequency regulation and power oscillations. The derivative approaches integrate the derivative of frequency concept and derivative control loop to regulate inertia and frequency response. The coordinated control scheme combines different aspects, such as virtual inertia, primary frequency control, and control parameter setting method for optimal frequency and power control in grid-integrated RESs. The approaches that cannot be classified are put under the other VIC technique section. The proposed categorization of VIC approaches is depicted in Figure 3.

Figure 4 shows a graphical depiction of the number of research papers for various VIC approaches (intelligent control, adaptive control, derivative control, distributed control, coordination control, and other VIC techniques) over time (2015-2020). In 2019, the illustration depicted the most publications (19 publications).

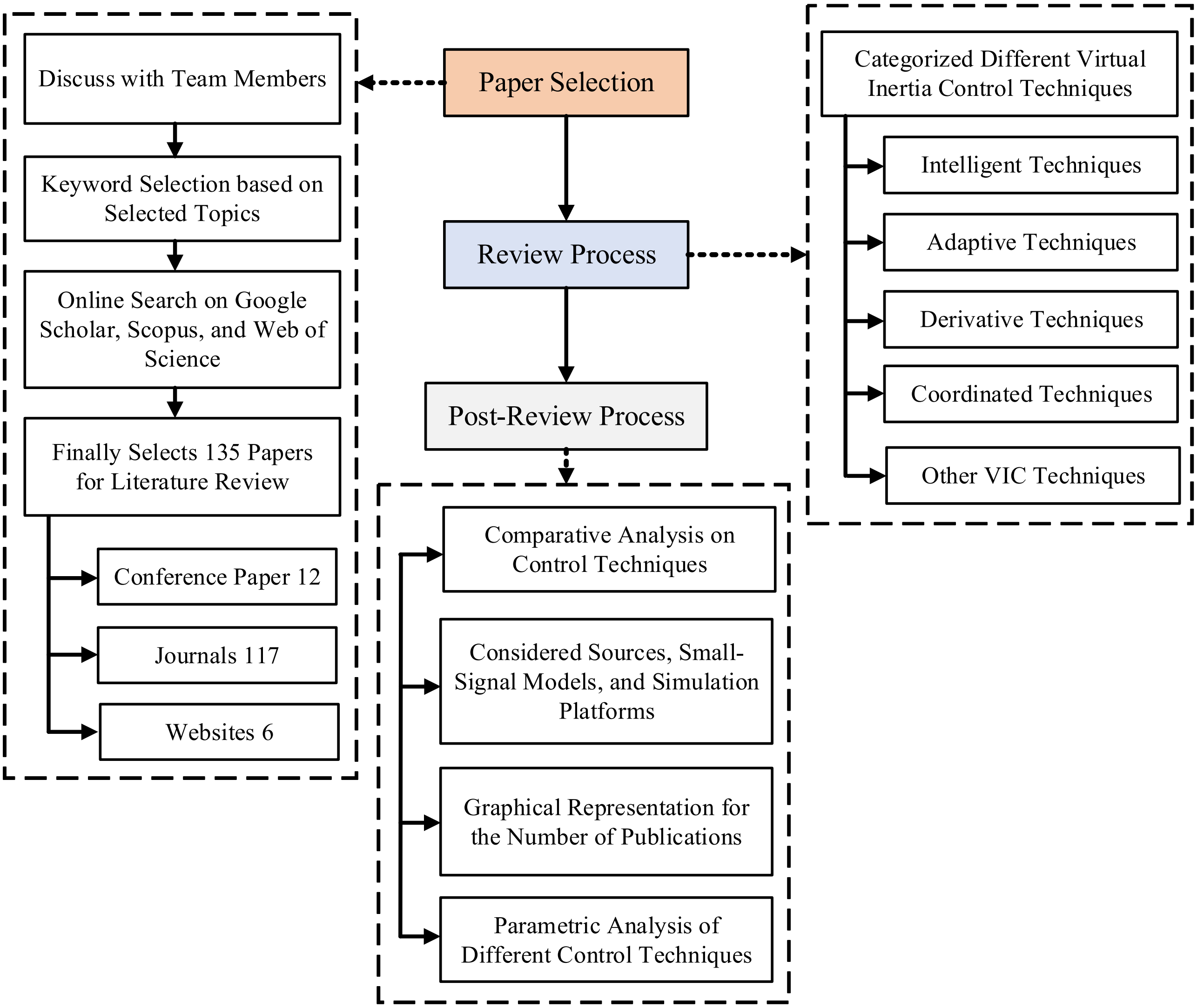


FIGURE 1. An overview of the paper selection, review process, and post-review process of the performed research work.

A. INTELLIGENT VIC TECHNIQUES

This section analyzes four types of intelligent VIC approaches for wind and PV-based, solely wind-based, only PV-based, and SG-based strategies. A non-dominated sorting genetic algorithm (NSGA-II) for lowering operating costs and frequency oscillations is presented in [85]. The communication system delay and ultra-capacitor are included in the proposed algorithm. The system operation is performed in the MATLAB/Simulink platform to evaluate system reliability, and the strategy avoids frequency fluctuations for low-inertia microgrids. Two objective functions of the proposed algorithm can be expressed as

$$IAE = \sum_{i=1}^{N} |\Delta f|_i + |f|_i, \tag{1}$$

$$\text{CostF} = \left(H_{\text{vir\_avg}} - H\right) + \frac{T_{\text{d\_avg}}}{T_d} = H_{vir} + \frac{T_{\text{d\_avg}}}{T_d}, \tag{2}$$

where Δf is the frequency fluctuations, H_{vir} is the virtual inertia, IAE is the frequency fluctuation function, CostF is the cost of operation, T_d is the delay of the telecommunication system, and $T_{\text{d\_avg}}$ presents the average delay of the telecommunication system. A VIC strategy based on the chicken swarm optimization (CSO) is proposed in [86] that incorporates a proportional-integral-derivative (PID) controller to attain a standard frequency regulation in high-penetrated RESs. The strategy maintains an inertia level in a feasible range to meet uncertainties. Researchers evaluate various dynamic responses under MATLAB/Simulink software scenarios and compare them with other optimization techniques. In [87], a reinforcement learning-based VIC strategy is proposed, which introduces an optimization algorithm based on deep deterministic policy gradients to analyze the frequency stability of microgrids. The performance of the proposed strategy is compared with that of H-infinity and proportional-integral (PI) controllers. Figure 5 (a) depicts a typical virtual inertia block diagram that integrates the ESS, a ROCOF, and a power limiter ($P_{\text{i,max}}, P_{\text{i,min}}$) for reliable operation in a microgrid. The concept maintains frequency support for the

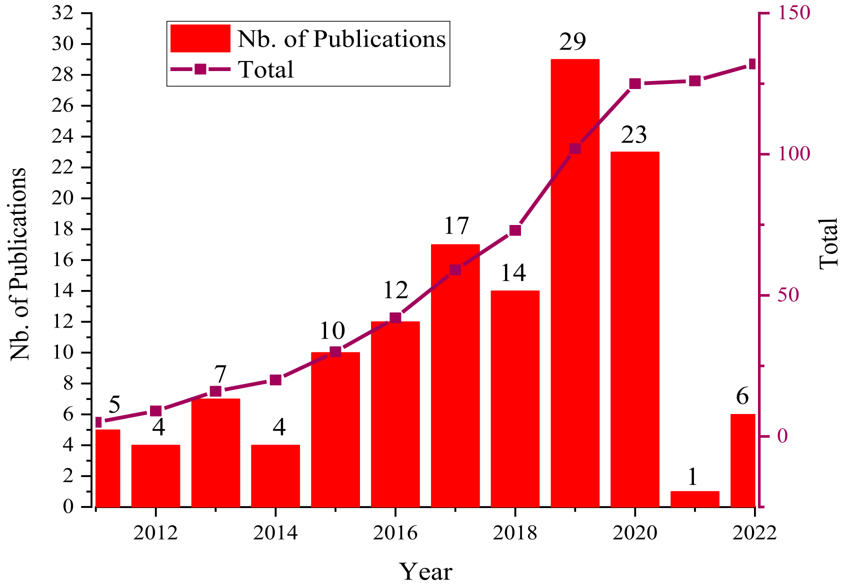


FIGURE 2. A graphical representation of the number of publications in different years (2011-2022).

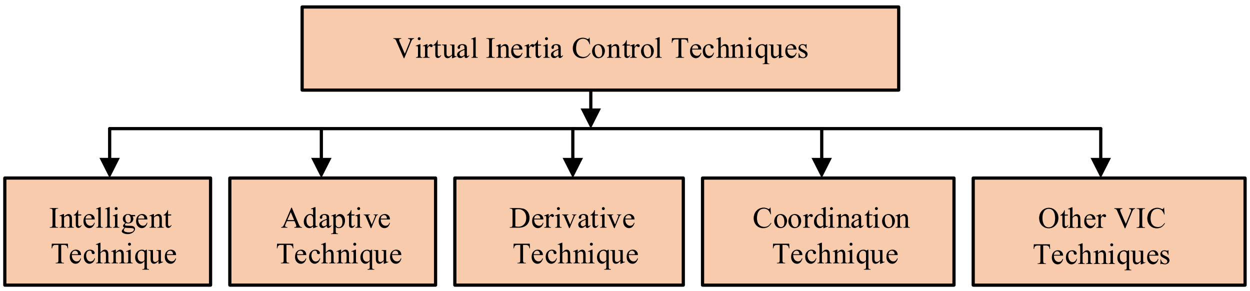


FIGURE 3. A classification of VIC techniques.

renewable energy system with fluctuating power generation. The inertia response, $\Delta P_{inertia}$ is determined by changing the time derivative of the frequency signal with considering the VI-constant (K_{VI}) and the VI-time constant (T_{VI}). The frequency deviation of the proposed microgrid can be expressed as

$$\Delta f = \frac{1}{2Hs + D}\left(\Delta P_m + \Delta P_W + \Delta P_{PV} + \Delta P_{inertia} - \Delta P_L\right), \tag{3}$$

where Δf is the frequency deviation, ΔP_m is the generated power change in the distributed generation unit, ΔP_W is the wind power change, ΔP_{PV} is the PV power change, and ΔP_L is the load power change.

An optimal virtual inertia planning strategy is proposed in [88] that considers the DFIG and frequency deviation margin (FDM) synchronization concept to establish power system stability. The proposed control scheme is primarily concerned with improving inertia response for WT and DFIG penetration in the grid. The IEEE 118-bus system is the testing platform demonstrating the proposed scheme's feasibility. Reference [89] presents an artificial bee colony (ABC) algorithm-based heuristic optimization technique to maintain optimal frequency regulation for WT connected to the microgrid. Figure 5(b) represents the considered model that consists of two areas connected via the AC tie line and the high voltage DC (HVDC) line. Each area has a conventional power plant, wind power plant, and loads (home and industry). The frequency of each area is constant and is monitored by the wide-area frequency measurement system (WAFMS). The fluctuation in frequency for the conventional power plant is compensated by the primary frequency control unit, where the secondary control is used for area frequency control. The inertia control unit is used for frequency control in the wind power plant. Researchers implement the proposed strategy in different scenarios: poolco, bilateral, and contract violations to verify system efficacy. A VIC strategy for DFIG integration with the power system is proposed in [90] that considers WT's stochastic excitation and stochastic parameters for stability analysis. The strategy's reliability is verified in the IEEE four generator, two area system, and the New England 10-machine, 39-bus system.

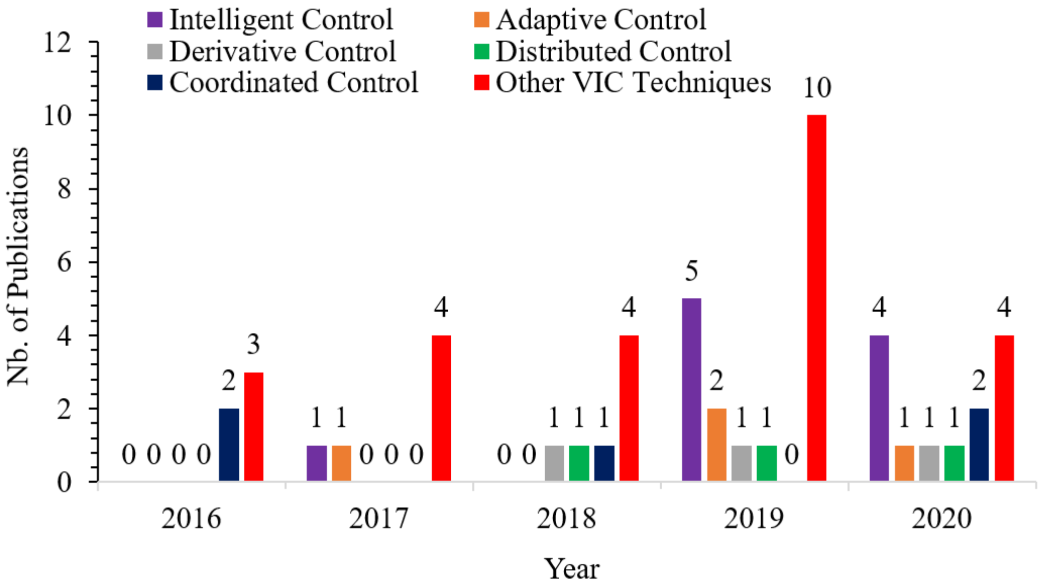


FIGURE 4. A graphical representation of the number of publications of different inertia control schemes in different years (2016-2020).

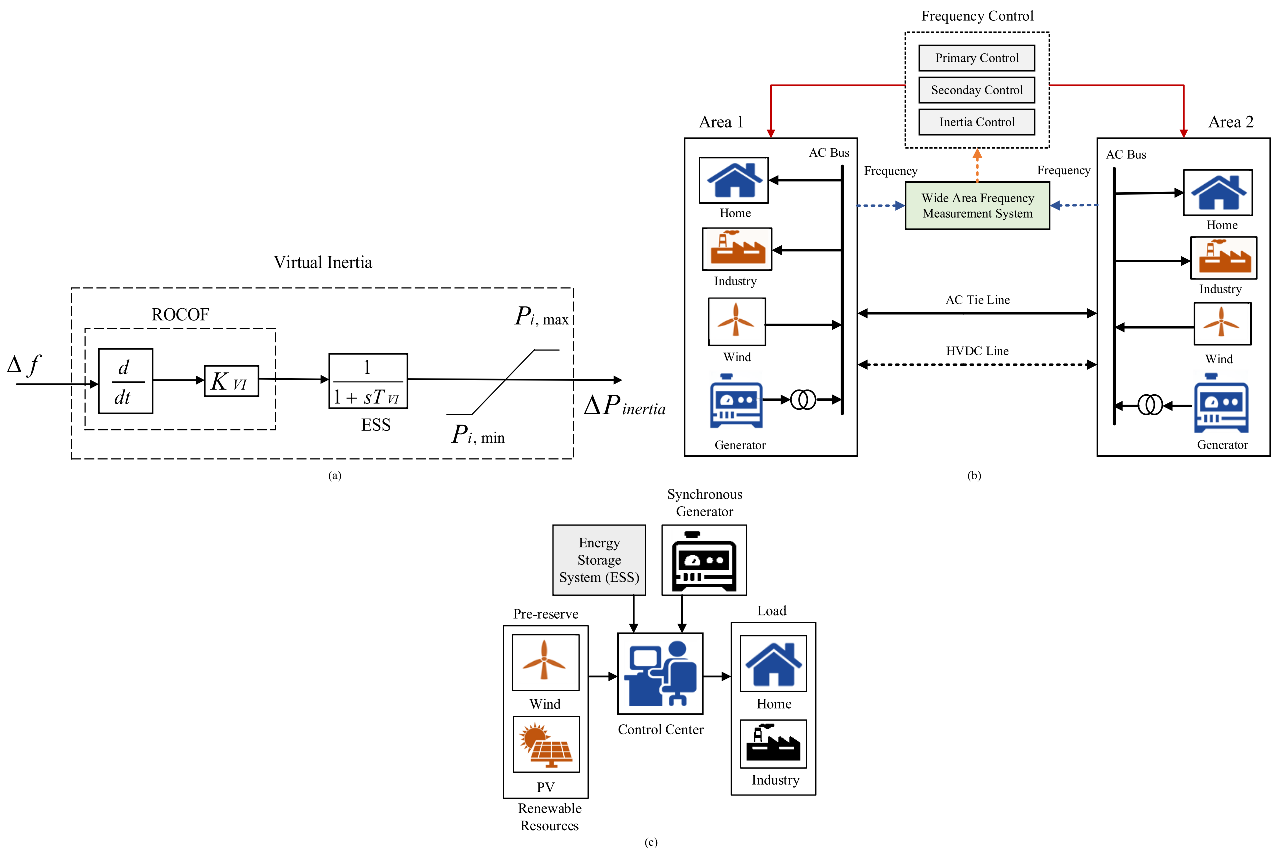


FIGURE 5. A schematic representation of (a) the reinforcement learning-based VIC block diagram [87], (b) the heuristic optimization-based VIC technique [89], and (c) the forecasting-based VIC technique [95].

A novel adaptive VIC strategy for DFIG-based wind microgrids based on fuzzy logic has been introduced [91]. The process enhances inertia response and handles frequency oscillations. An approximate dynamic programming (ADP) approach is demonstrated in [92], which ensures online VIC parameters tuning. The system is designed and implemented in the PSCAD/EMTDC simulation platform.

A VIC based on a master-slave concept is presented in [93], where RES and ESS act as masters and the microgrid acts as a slave. A recurrent probabilistic wavelet fuzzy neural network (RPWFNN) controls the transient and reactive power response instead of using the PI controller. The intelligent control scheme proves itself as an efficient method to control the frequent load changes and transient responses. A fuzzy-based dynamic inertia control strategy is proposed in [94], introducing a supercapacitor for PV-based microgrid. The dynamic inertia response for multiple sub-microgrids is analyzed. Based on the analysis, the fuzzy-based controller influences the system to obtain stability. The proposed strategy is evaluated in the MATLAB/Simulink platform and compared with the traditional droop control scheme. A forecasting-based VIC strategy is introduced in [95] that estimates some results from the PV system to maintain frequency stability without incorporating an ESS. The simulation results prove the proposed scheme is more effective in controlling frequency oscillations than other control strategies. The schematic representation of the proposed strategy is illustrated in Figure 5(c). The figure implies that the control center analyzes the short-term load forecasting information on the consumer's side and utilizes the pre-reserved PV power output. Synchronous generator and energy storage system (ESS) signifies the energy back up for the proposed model's normal operation, which is connected to the control center. A VIC strategy based on the neural network heuristic dynamic programming (HDP) is illustrated in [96]. The proposed method overcomes the system instability for a three-phase grid-connected inverter. Another VIC-based frequency control scheme is proposed in [97] that considers a VSG to analyze inertia responses and enhance frequency stability. The control scheme introduces the PSO algorithm to maintain renewable sources' optimal operation in the microgrid. The controller is designed for both small-scale and large-scale power systems. A comparative analysis of different intelligent VIC techniques is illustrated in Table 2.

B. ADAPTIVE VIC TECHNIQUES

An adaptive VIC-based coordinated power management scheme is proposed in [98] that mainly focuses on enhancing AC's frequency stability to the DC microgrid. The system assures optimal power-sharing, ROCOF, and dynamic responses in the microgrid. A novel adaptive control method based on model predictive control (MPC) is presented in [99] that deals with frequency stability and load fluctuations. The schematic representation of the method is illustrated in Figure 6(a). Load frequency control (LFC) aids the proposed VIC control to keep the frequency level at a normal equilibrium stage with a power balance condition. The system operation is simulated in MATLAB/Simulink software for different cases and compared with other conventional controllers. A block diagram is presented in Figure 6(b) for a VIC model consisting of the first-order derivative transfer function with the MPC controller. The MPC control signals can control VIC power by considering the virtual inertia variable gain. The VIC signal for the change in inertia power, ΔP_{inr} can be expressed as

$$\Delta P_{\text{inr}}(j+1) = \Delta P_{\text{inr}}(j) + A\sum_{i=0}^{n_T} \delta_i \Delta u_{\text{MPC}}(j-1), \quad (4)$$

where A is the interaction matrix, Δu_{MPC} is the change of control signal generated by MPC, and δ_i presents the coefficient number. An adaptive VIC strategy based on an improved bang-bang control strategy is presented in [100] that deals with frequency fluctuations under steady-state conditions. The control scheme determines a virtual inertia range for steady-state conditions at which the frequency level changes. The frequency deviation is analyzed by designing a small signal model. The system's effectiveness is validated by incorporating MATLAB/Simulink software. A comparative analysis of different adaptive VIC techniques is illustrated in Table 3.

C. DERIVATIVE VIC TECHNIQUES

In [101], a VIC method based on the derivative technique is presented for enhanced frequency control and system stability. Unlike previous derivative approaches, the system considers both the microgrid's inertia and damping properties and trajectory sensitivity to examine both. It is built using the MATLAB/Simulink platform to compare the dependability and robustness of the time-domain model with alternative control techniques. Another VIC strategy, depicted in Figure 7(a), is proposed in [102] and includes trajectory sensitivities to analyze inertia and frequency stability for renewables in the microgrid. The control approach generates a feasible foundation for multi-area power systems with highly penetrated RESs. Reference [103] describes a VIC system that uses the derivative control technique (DCT) to enhance the dynamic response of a solar PV and ESS-based microgrid. The method aims to improve inertia response and frequency stability. The block diagram and a dynamic model for the proposed DTC are depicted in Figures 7 (b) and 7 (c), respectively. The VIC block in Figure 7(c) aids inertia supports during the poor dynamic performances for solar PV and ESS integration. The frequency deviation, Δf for the proposed microgrid can be expressed in terms of the power generated at the thermal generator (ΔP_m), the solar active power (ΔP_{solar}), the VI-power (ΔP_{VI}), and the load demand (ΔP_{load}).

$$\Delta f = \frac{K_{ps}}{D + 2Hs}\left(\Delta P_m + \Delta P_{solar} + \Delta P_{VI} - \Delta P_{load}\right), \quad (5)$$

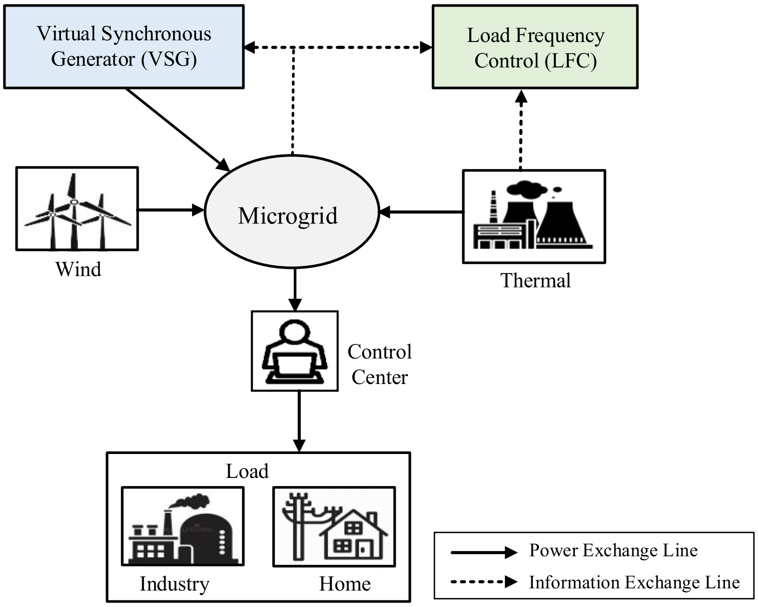
where K_{ps} is the power system gain constant, D is the damping coefficient, and H is the system inertia constant. Table 4 illustrates a comparison of several derivative VIC approaches.

D. COORDINATED VIC TECHNIQUES

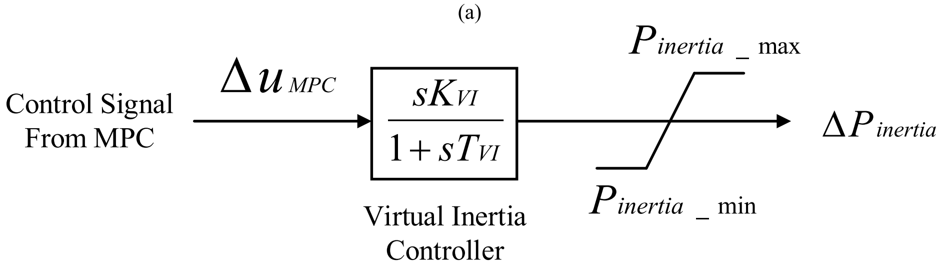
In [104], a coordinated virtual inertia and primary frequency control technique are described for improving the inertia response and frequency regulation for DFIGs. The concept combines a diesel engine with renewables and examines inertia responses at various WT speeds. Moreover, the strategy supports an adjustable method for optimizing WTs

TABLE 2. A comparative analysis of different intelligent VIC techniques.

Ref	Considered Approach	Year	Testing Platform/ Test System	Description
[85]	Non-dominated sorting genetic algorithm (NSGA-II) based VIC	2019	MATLAB/Simulink	• Considers communication system delay and ultra-capacitor size • Two fitness functions: frequency oscillations and cost • Minimizes frequency oscillations and enhances stability
[86]	Adaptive virtual inertia (AVI) and CSO-based control	2020	MATLAB/Simulink	• Introduces CSO technique • Considers PID controller • Improves frequency stability
[87]	Reinforcement learning-based VIC strategy	2020	MATLAB/Simulink	• Based on a deep deterministic policy • Compares with H-infinity and PI controllers • Enhances stability and inertia responses
[88]	Grid-side converter (GSC) controller-based VIC	2018	12-bus system and IEEE 118-bus system	• Introduces non-convex optimization problem • Includes Lyapunov function method • Enhances inertia response with feasible frequency deviation
[89]	Heuristic optimization technique based VIC	2020	MATLAB/Simulink	• Introduces the ABC algorithm • Analyses load-frequency responses for different scenarios • Enhances frequency stability, minimizes frequency deviation
[90]	Reduced-order model and phase-locked loop (PLL) based VIC	2017	IEEE four generator two area system and the New England 10-machine 39-bus system	• Considers the stochastic excitation and stochastic parameters of WT • Introduces a system stability degree index to analyze small-signal stability
[91]	Fuzzy logic-based VIC	2019	MATLAB/Simulink	• Handles frequency oscillations • Three cases for simulation: DFIG without VIC, DGIG with fixed gain VIC, and DFIG with adaptive fuzzy VIC • Improves frequency stability
[92]	Proportional-Derivative (PD) controller-based VIC	2013	PSCAD/EMTDC	• Introduces approximate dynamic programming (ADP) approach • Solves online parameter tuning problem • Enhances frequency stability
[93]	Master-slave concept-based VIC	2019	MATLAB/Simulink and Microgrid with 3 kW varying resistive three-phase load	• Introduces a master-slave controller • PI controller is replaced by a RPWFNN • RPWFNN improves the steady-state and transient responses
[94]	The fuzzy-based dynamic inertia control strategy	2020	MATLAB/Simulink	• Analyzes the SOC level of supercapacitor • Considers multiple area sub-microgrid to develop a small-signal model • Improves the dynamic responses in microgrid
[95]	Forecasting-based VIC strategy	2019	MATLAB/Simulink	• Utilizes the PV to improve inertia response instead of using ESS • Handles frequency oscillations • Enhances dynamic stability
[96]	Neural network-based VIC	2019	Inductive and resistive grids	• Introduces HDP • Two subnetworks: critic network and action network • Better performance in resistive grid
[97]	PSO based VIC	2019	MATLAB/Simulink	• Three virtual models: virtual rotor, virtual primary control, and virtual secondary control • Controls frequency fluctuations and enhances dynamic response



(a)



(b)

FIGURE 6. (a) & (b) A schematic representation and block diagram of the MPC-based VIC technique, respectively [99].

TABLE 3. A comparative analysis of different adaptive VIC techniques.

Ref	Considered Approach	Year	Testing Platform/ Test System	Description
[98]	Synchronverter and virtual dc machine (VDM) based VIC	2020	MATLAB/Simulink	• Optimal power-sharing • Minimum ROCOF • Utilizes dynamic responses
[99]	MPC based VIC	2017	MATLAB/Simulink	• Improves frequency stability and robustness • Compared to fuzzy logic and other conventional techniques
[100]	Improved bang-bang control-based VIC strategy	2019	MATLAB/Simulink	• A small-signal model for stability analysis • Reduces dynamic frequency deviation and improves frequency stability

under various variable coefficients. For a directly-driven PMSG, a coordinated VIC strategy is proposed in [105]. The system contains a proportion-differential VIC approach to investigate frequency stability and pitch angle control for WTs. Another VIC approach based on the coordinated control parameter setting method is demonstrated in [106], where a small-signal model is introduced to analyze the frequency stability, as shown in Figure 8 (a). The model uses the eigenvalue damping ratio as an objective function and an inertia-dependent frequency constraint as a frequency

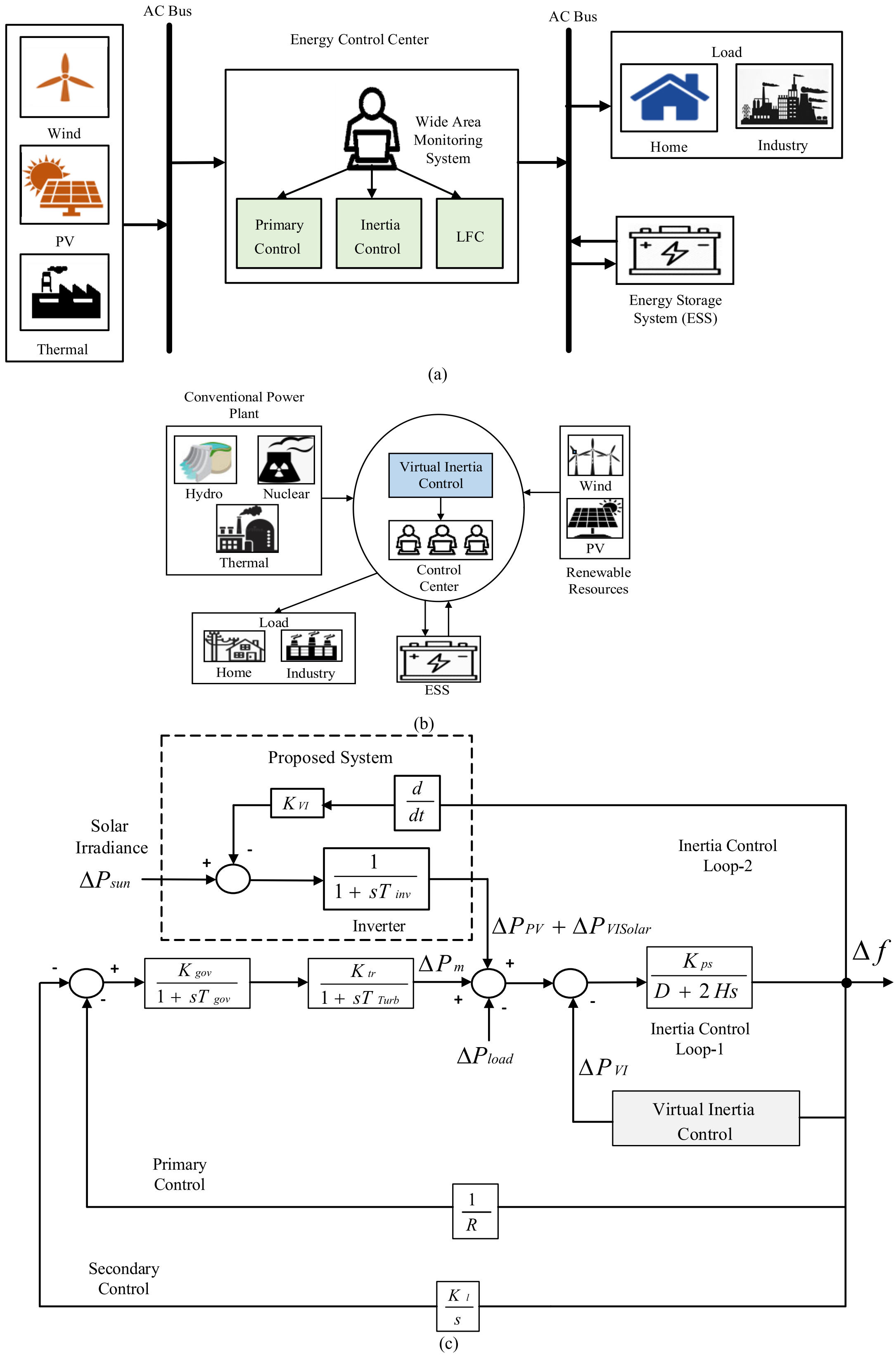


FIGURE 7. A schematic representation of (a) the derivative technique considering the second-order characteristics of microgrid [102], (b) & (c) the model and the block diagram of the derivative technique based VIC for ESS and PV, respectively [103].

TABLE 4. A comparative analysis of different derivative VIC techniques.

Ref	Considered Approach	Year	Testing Platform/ Test System	Description
[101]	Derivative technique-based VIC	2019	MATLAB/Simulink	• Analyzes dynamic response of inertia and damping with trajectory sensitivities • Enhances frequency stability
[102]	Derivative technique considering second-order characteristics of microgrid	2018	MATLAB/Simulink	• Presents a second-order characteristic • Introduces trajectory sensitivities to analyze inertia and damping responses • Enhances frequency stability and inertia responses
[103]	Derivative technique-based VIC for ESS and PV	2020	MATLAB/Simulink	• Considers the abrupt and variable load changes • Analyzes different levels of RES penetration: high, low, medium • Improves frequency stability

regulation factor. Figure 8(b) from [107] depicts a new coordination control strategy for the inertia response and frequency management of microgrid with high RESs penetration. The control strategy includes a PSO-based PI controller for analyzing the microgrid's inertia characteristics. To prove the proposed scheme's validity in the power system, researchers assessed several MATLAB/Simulink software instances. A PV system coordination technique integrating VIC and frequency damping control (FDC) has been described in [108]. Considering the inertia constant and damping constant, the procedure preserves frequency stability. According to MATLAB/Simulink software simulation findings, the coordination technique is more successful and cost-effective than other traditional methods. Figure 8(c) depicts the block diagram of the proposed control strategy, which integrates both the switching signal of FDC and VIC for the PV system. The pulse width modulation (PWM) signal is generated by comparing the power output of both the VIC and the FDC segment and by introducing a PI controller. The PWM signal is then applied to the boost controller for full-range frequency regulation. A comparative analysis of different coordinated VIC techniques is illustrated in Table 5.

E. OTHER VIC TECHNIQUES

In [109], a resilient H-infinity VIC scheme with a linear fractional transformation approach is developed for maintaining frequency stability and resilience in an islanded microgrid. The control system incorporates inertia as an uncertainty factor and the number of renewables and loads as a microgrid disturbance factor to design an optimal platform. The MATLAB/Simulink platform was used to run the time-domain simulation. When comparing the robust controller to the optimal PI controller, the robust controller appears to be more dependable and frequency stable. As depicted in Figure 9 (a), [110] proposes a VIC method based on superconducting magnetic energy storage (SMES). The approach addresses frequency instability and inertia reduction to increase renewable energy penetration in the microgrid. The SMES-based approach takes into account the system's dynamic properties and assesses its efficacy using time-domain simulations. The concept considers the frequency regulation of the system that imitates the inertia power to enhance inertia response. The major advantage of integrating SMES the fast inertia response with high efficiency and high power output. The transient response is significantly enhanced with favorable peak deviation and settling time range. The solid lines in figure 9 (a) imply the power exchange line, whereas dashed lines imply the communication and information exchange line. Two measurement signals from SMES and the thermal power plant provide the control center's system status and control information. Reference [111] proposes a grid-forming and grid-following VIC method that incorporates a system norm-based optimization technique to ensure microgrid stability. The proposed technology is tested on the electricity grid in South-East Australia. Reference [112] presents an effective frequency control strategy for integrating renewables into an islanded microgrid based on VIC. The microgrid consists of different electrical loads, the ESS and distributed generators (thermal, wind, solar PV power plant) that form a nonlinear model to control. A coefficient diagram method (CDM) is used in the control methodology to smooth the microgrid's frequency management and inertia augmentation. The technical operation is simulated in the MATLAB/Simulink platform to compare control strategies like the H-infinity technique. Figure 9 (b) depicts the block diagram for the proposed CDM controller and the non-linear model for highly penetrated renewables in the microgrid. The load variation (ΔP_{Load}), wind power variation (ΔP_{Wind}), and solar power variation (ΔP_{Solar}) are considered disturbances for the proposed microgrid that causes frequency fluctuations. The generation rate constant (GRC) and the governor dead band (GDB) are integrated into the system to maintain optimal

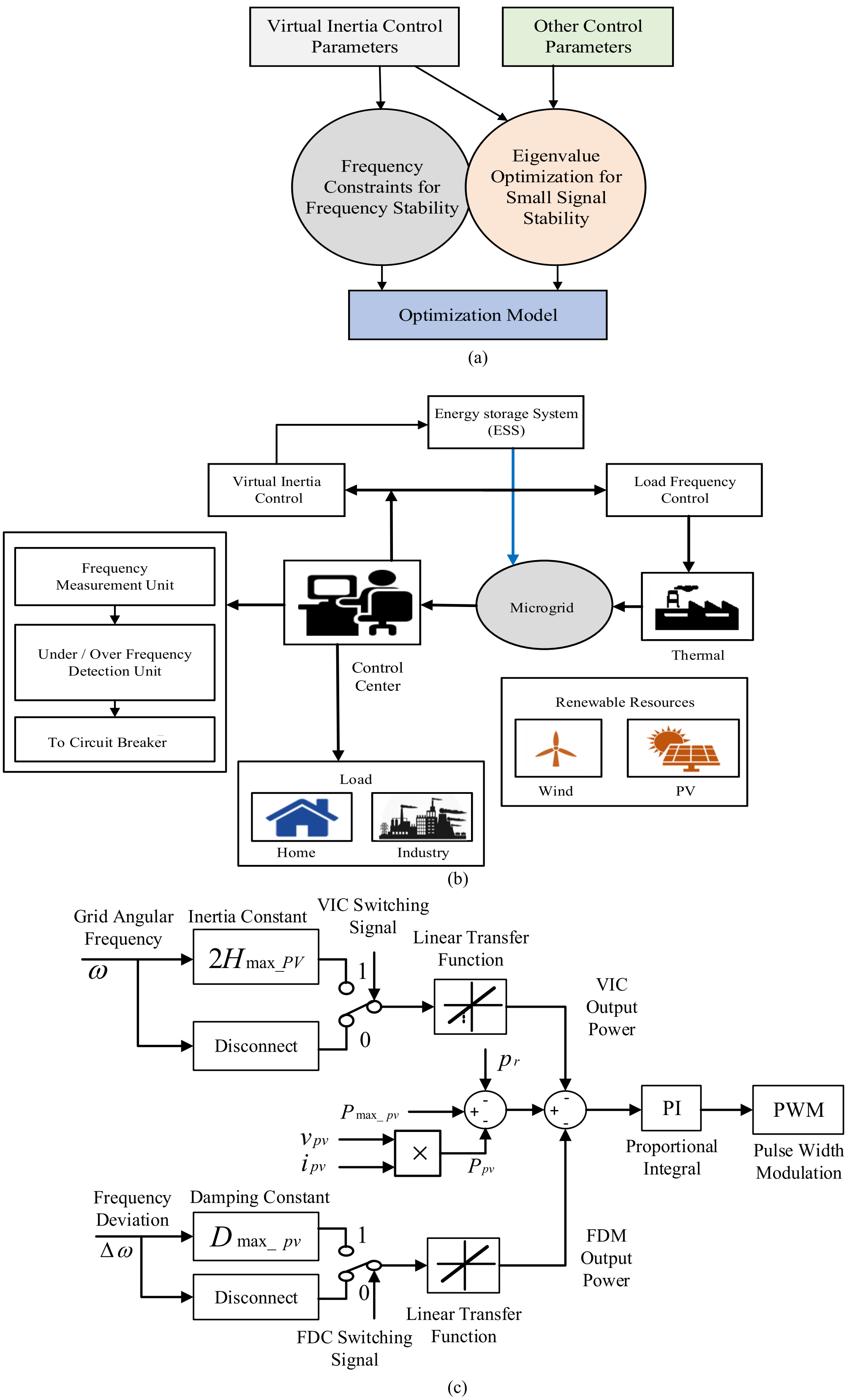


FIGURE 8. A schematic representation of (a) the coordinated control parameter setting method-based VIC scheme [106], (b) the optimal PI controller-based VIC [107], and (c) the coordination control strategy [108].

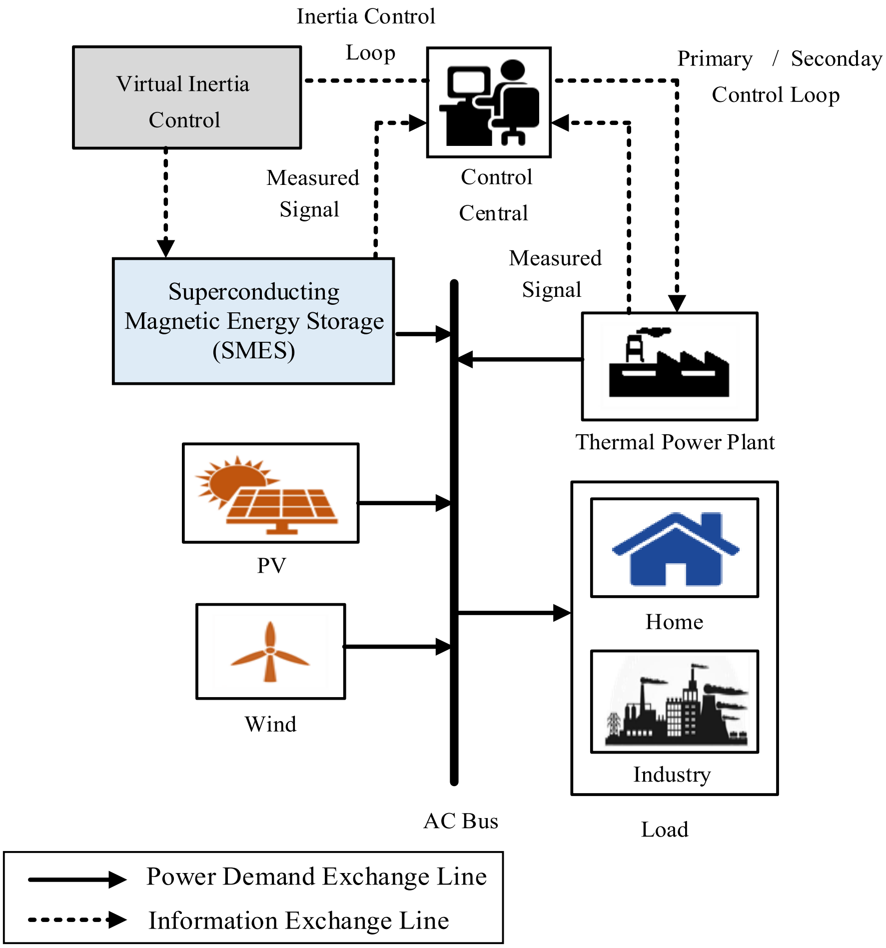
TABLE 5. A comparative analysis of different coordinated VIC techniques.

Ref	Considered Approach	Year	Testing Platform/ Test System	Description
[104]	A variable coefficient method based on virtual inertia and primary frequency control strategy	2016	DIgSILENT PowerFactory	• Introduces a variable coefficient method to illustrate the relationship between controller gain and wind speed • Analyzes frequency response for different wind speeds • Considers the droop control gain • Improves frequency stability
[105]	The proportional-differential controller-based VIC scheme	2016	MATLAB/Simulink	• Considers frequency regulation capability for D-PMSG • Considers pitch angle control for the WT • Two cases: a sudden increase in load and a sudden decrease in load
[106]	Coordinated control parameter setting method based VIC scheme	2020	IEEE four-generation two-area system and the 39-bus New England test system, DIgSILENT PowerFactory	• Applied to DFIG wind farm • Introduces the Newton-based eigenvalue optimization algorithm • Small signal model for frequency stability
[107]	Optimal PI controller-based virtual inertial control	2018	MATLAB/Simulink	• Minimizes frequency deviation • Enhances inertia responses and frequency stability
[108]	Coordination control strategy	2020	MATLAB/Simulink	• Considers inertia constant and damping constant • Reduces ROCOF • Minimizes frequency regulation and enhances stability

frequency regulation. Reference [113] demonstrates a novel inertia control scheme that improves the frequency stability for renewables, and the transient response is considered for different swing periods. The reliability of the proposed method is tested in the hardware-in-the-loop platform for WT penetration in the microgrid. As shown in Figure 9(c), [114] proposes a linear feedback configuration-based VIC scheme that incorporates virtual impedance and virtual capacitance for virtual inertia injection and damping operations. The scheme focuses on determining the output voltage and inductor current that maintains dynamic responses to decrease the rate of change of voltage (RoCoV). The system can stabilize the DC microgrid in numerical simulations during frequency oscillations, transient responses, and inertia responses. A distributed VIC strategy is demonstrated in [115] that emphasizes increasing inertia and decreasing the DC grid's voltage rate. The approach considers the virtual inertia coefficient and designs a small-signal model to verify system stability. The system operation is implemented in the MATLAB/Simulink platform to demonstrate system efficacy. The power output, ΔP_{out} of the DC-bus can be expressed as

$$\Delta P_{\text{out}} = (C_{\text{dc}} + C_{\text{vir}}) \times u_{\text{dc}} \times \frac{du_{\text{dc}}}{dt}, \qquad (6)$$

where C_{dc} is the discharge power of the capacitor, C_{vir} presents the VIC coefficient of the controller, u_{dc} is the DC bus voltage. The virtual inertia control (C_{vir}) is provided in addition to DC control (C_{dc}) that reduces the pressure on DC microgrid capacitance. Figure 9(d) depicts a block diagram of the proposed control scheme, which combines VIC and droop control. A reference current is generated by combining the VIC and the droop control scheme, which effectively reduces the voltage fluctuations on the proposed DC microgrid. WT's active power-sharing based on the VIC approach is used in [116]. The proposed controller is simulated on the MATLAB/Simulink platform and regulates inertia enhancement and optimum power-sharing. Reference [117] described another VIC strategy for achieving system stability and increased inertia response in wind power integrated systems (WPIS). The control technique used a state-space averaging model to investigate the transient response and load-changing impact. Reference [118] shows a VIC-based DFIG-integrated system that handles frequency oscillations and low inertia response. The oscillation response for multiple operational modes was handled by a PLL and VIC, which was evaluated in the IEEE 10-machine 39-bus system. Reference [119] proposes a VIC-based frequency control system that combines primary frequency control and



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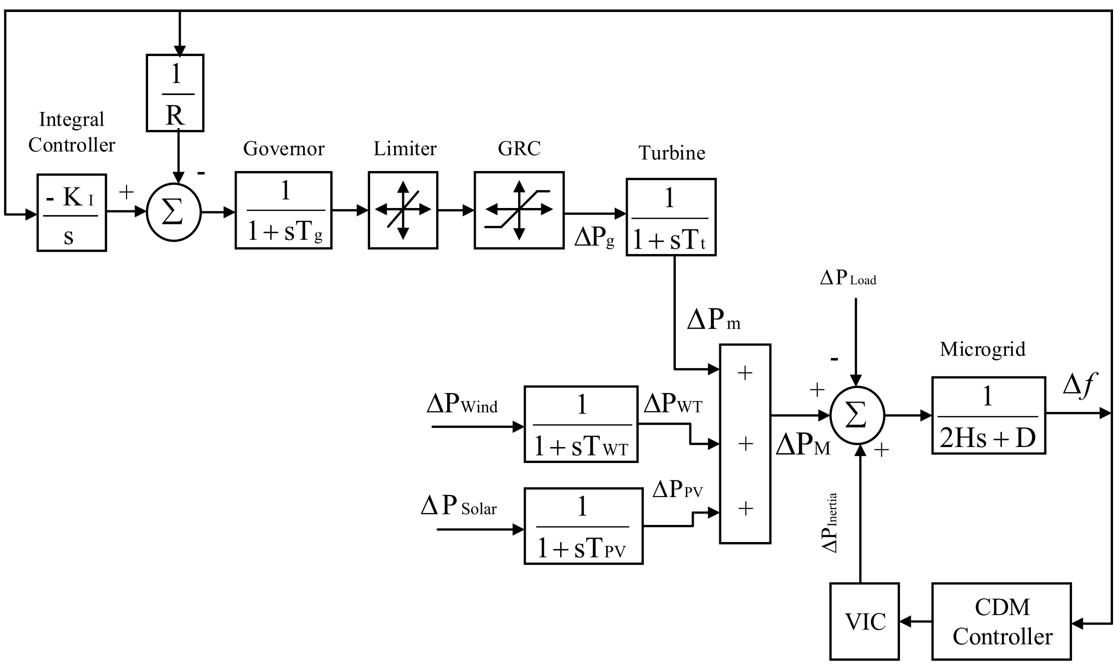

(b)

FIGURE 9. A schematic representation of (a) the dynamic frequency support based on VIC [110] (b) the CDM controller based VIC [112] (c) the virtual inductance and virtual capacitance approach-based VIC [114] (d) the block diagram of the Distributed VIC scheme for PMSG based wind turbine [115].

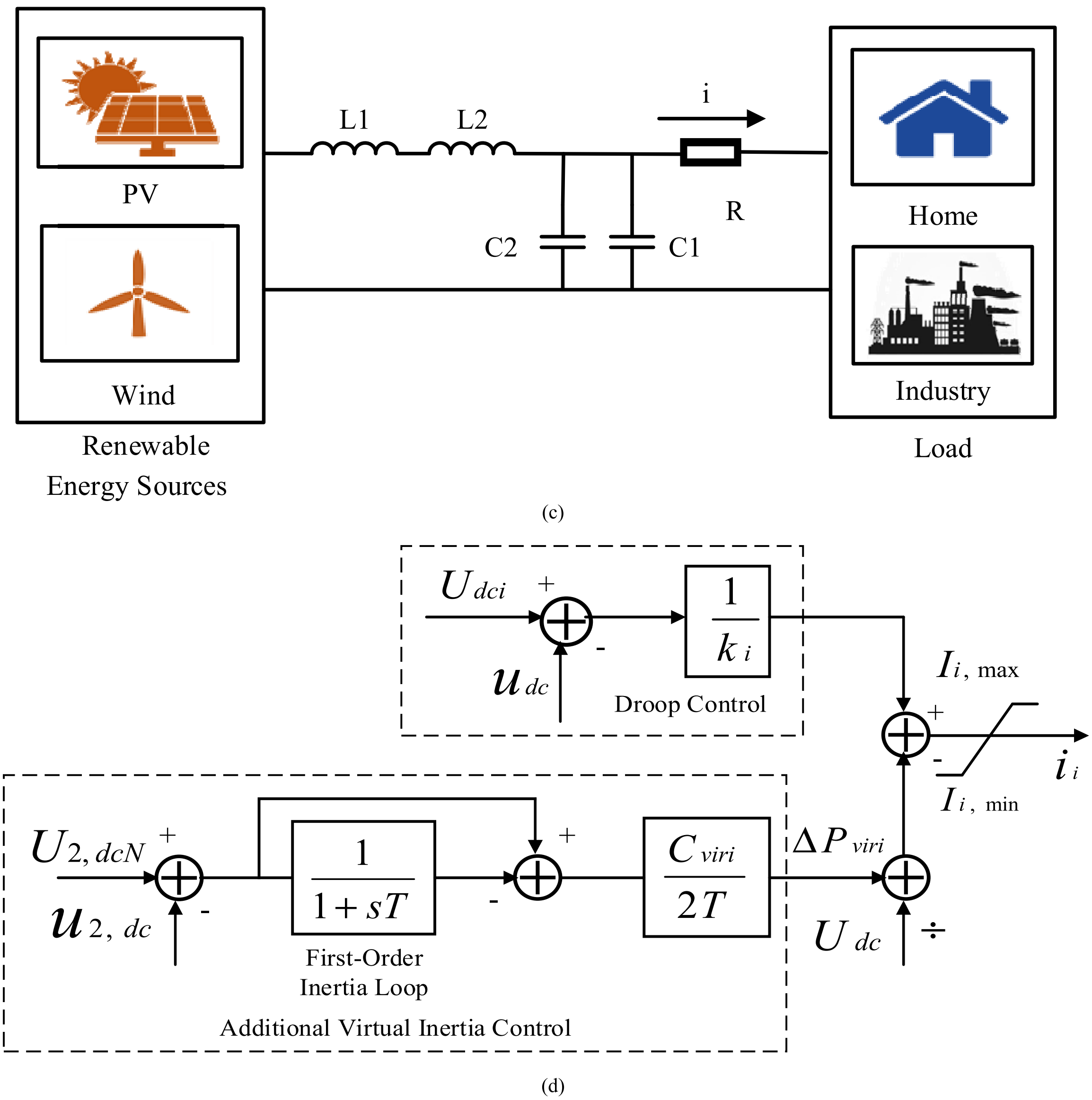

FIGURE 9. ***(Continued.)*** **A schematic representation of (a) the dynamic frequency support based on VIC [110] (b) the CDM controller based VIC [112] (c) the virtual inductance and virtual capacitance approach-based VIC [114] (d) the block diagram of the Distributed VIC scheme for PMSG based wind turbine [115].**

enhanced pitch control algorithms. The suggested technique considers multiple frequency coefficients to maintain the frequency level under varied load scenarios. Reference [120] proposes another VIC approach for DFIG-based WTs to provide frequency stability in the microgrid. The results of simulations for various operating circumstances offer a more reliable approach than other approaches. Reference [121] proposes a VIC system for the wind-connected microgrid that considers frequency regulation and rotor angle stability. The transient responses in distinct WT instances are investigated. The suggested strategy is implemented in the hardware-in-the-loop experimental platform and is a practical method for various applications. A VIC method for PV arrays (PVAs) is developed in [122] to evaluate frequency regulation and dynamic responses. Using the method's active power controller, researchers can adjust ROCOF by adjusting the inertia gain at an appropriate moment. Simulation results demonstrate the efficiency of the proposed strategy under various operating situations. Reference [123] presents a power feedforward control approach for DC microgrid based on VIC. Instead of using a dual active bridge (DAB), the suggested controller mitigates the low inertia response and voltage fluctuation. The virtual inertia of a DC microgrid can be described as follows:

$$P_{\text{set}} - P_{\text{dcm}} - D_m \left(U_l - U_{l_n} \right) = C_{c_l} U_{l\_n} \frac{dU_l}{dt}, \tag{7}$$

where P_{set} is the active power reference of the dc microgrid, U_{l_n} is the rated low voltage dc (LVDC) bus voltage, and D_m presents the damping coefficient of the microgrid.

TABLE 6. A comparative analysis of other VIC techniques.

Ref	Considered Approach	Year	Testing Platform/ Test System	Description
[109]	Robust H∞ controller-based VIC	2017	MATLAB/Simulink	• Considers inertia for uncertainties • Considers the number of RESs and loads for disturbances • Minimizes frequency deviations • Enhances frequency stability
[110]	SMES-based VIC	2019	MATLAB/Simulink	• Analyzes dynamic effects of inertia responses • Enhances frequency stability • Improves inertia responses
[111]	Grid-forming and grid-following VIC	2019	South-East Australian power system	• Introduces a system norm-based optimization approach • Improves inertia and frequency responses
[112]	CDM controller-based VIC	2019	MATLAB/Simulink	• Considers the uncertainties and disturbances of microgrid • Improves frequency stability • Compared to the H-infinity controller
[113]	Transient stability in microgrid based on VIC	2019	Hardware-in-the-loop platform	• Considers transient responses for different swing conditions • Improves frequency stability
[114]	Virtual inductance and virtual capacitance approach based VIC	2020	MATLAB/Simulink	• Considers linear configuration feedback to improve dynamic responses • Two components: a virtual inductance and a virtual capacitance • Proposes a small-signal model to analyze frequency stability
[115]	Distributed VIC scheme for PMSG-based wind turbine	2018	MATLAB/Simulink	• A first-order inertia loop • Considers virtual inertia coefficient • A small-signal model for frequency stability
[116]	Active power-sharing controller between stator and rotor for wind power plant	2017	MATLAB/Simulink	• Ensures optimal power-sharing • Enhances frequency stability
[117]	PI Controller-based VIC	2013	MATLAB/Simulink	• Proposes a state-space averaging model for WT • Analyzes the transient responses and the effect of load changing • Establishes frequency stability
[118]	Dynamic energy function-based VIC	2019	IEEE 10-machine 39-bus system	• Introduces PLL to control inertia responses at different conditions • Minimizes frequency oscillations
[119]	De-loading control-based VIC	2016	MATLAB/Simulink	• Introduces the primary frequency control and the improved pitch control techniques • A de-loading control method to handle inertia and frequency response • The ROCOF is reduced, and frequency stability is improved
[120]	Dynamic frequency support based on VIC	2020	EMPT restructured version	• DFIG-based WT generator • Simulation for three cases: wind speed =10 m/s, wind speed = 8 m/s, and wind speed = 13 m/s • Improves frequency stability

TABLE 6. ***(Continued.)*** **A comparative analysis of other VIC techniques.**

[121]	The VIC scheme for rotor angle stability for wind turbine	2019	Hardware-in-the-loop experimental platform	• Analyzes transient characteristics for WT • Handles frequency regulation and rotor angle stability for WT
[122]	PI Current Controller-based VIC	2017	MATLAB/Simulink	• Introduces the active power controller for PV arrays • Frequency stability and inertia responses are analyzed using an impedance-based stability analyzer • Enhances dynamic performances and stability margin
[123]	DAB converter and power feedforward control based VIC	2019	Micro-network test prototype with DSP_TMS320F28335+ FPGA_XC6SLX9	• A power feedforward control scheme • Minimizes voltage fluctuations in dc grids • Improves inertia in microgrid
[124]	Dynamic stability in ac microgrid based on VIC	2019	MATLAB/Simulink	• Analyzes the dynamic changes of SOC level of supercapacitor for PV microgrid • Enhances inertia and damping level • Simulation for two cases: inertia response for sudden load changes and PV irradiation variations
[125]	Distributed VIC for PV-based microgrid	2016	6-bus renewable microgrid	• Monitors transient responses to stabilize system frequency • Inertia response of PV is controlled by adjusting the charging/discharging of the dc-link capacitor
[127]	Three-phase power converter-based VIC	2018	dSPACE control platform	• Analyzes the instability issues for three-phase power converters • Minimizes instabilities in microgrid
[128]	BGC based VIC	2016	PSIM	• Proposes a small-signal model to analyze the dynamic responses in dc microgrid • Improves frequency stability
[129]	VIC based on frequency deadband	2019	dSPACE control platform, MATLAB/Simulink	• Introduces grid-connected power converters to improve frequency response • Improves frequency stability and enhances inertia responses
[130]	VIC for steady-state and dynamic response in microgrid	2019	MATLAB/Simulink	• Considers damping coefficient effects • Enhances dynamic characteristics and frequency stability • Analyzes the steady-state characteristics
[131]	Grid-connected inverter-based VIC	2018	MATLAB/Simulink	• Considers the frequency response characteristic of ac grids • Analyzes wind speed and ac load mutation
[132]	Voltage outer-loop and voltage inner-loop-based VIC	2020	Star-Sim hardware-in-the-loop experimental platform	• Considers the negative feedback of the system • Enhances frequency regulations and damping responses • Improves frequency stability in dc microgrid
[133]	Energy router microgrid-operation model-based VIC	2018	PSCAD/EMTDC	• Includes three strategies: virtual synchronous-motor control strategy, virtual DC-motor control strategy, and virtual synchronous-generator control strategy • Improves frequency and inertia stability in both ac and dc interface

TABLE 6. ***(Continued.)*** **A comparative analysis of other VIC techniques.**

[134]	VIC for variable speed heat pump	2020	Hardware-in-the-loop experimental platform	• Develops a small-signal model to analyze inertia and frequency responses • Minimizes ROCOF and droop gain
[135]	MMC based VIC	2017	PSCAD/EMTDC	• Comparative analysis of different converter • Discusses frequency deviation • Analyzes the effect of MMC on the transient period • Improves transient stability

TABLE 7. **A numerical representation of different parametric values.**

Types of Wind Turbines	Reference	Year	WT Rated Power	Rated Wind Speed (m/s)	Inertia Time Constant (s)
DFIG	[88]	2018	4MW	Not indicated	Not indicated
DFIG	[90]	2017	1.5MW	Not indicated	5.29
DFIG	[91]	2019	400MW	Not indicated	Not indicated
PMSG	[105]	2016	2MW	11.36 m/s	6.5
PMSG	[115]	2018	60kW	12 m/s	Not indicated
DFIG	[116]	2017	250kW	12 m/s	Not indicated
PMSG	[117]	2013	2MW	11.36 m/s	Not indicated
DFIG	[118]	2019	1.45MW	Not indicated	Not indicated
DFIG	[119]	2016	900MW WPP	10 m/s	Not indicated
DFIG	[120]	2020	5MW	11 m/s	5
DFIG	[121]	2019	720MW WPP	10 m/s	Not indicated

Reference [124] proposes a VIC method for supercapacitors in standalone PV-connected microgrid. For two-area PV microgrid clusters, the system evaluates the dynamic change in state of charge (SOC) level and keeps the frequency and inertia response within a defined range. The suggested scheme's stability is tested using MATLAB and Simulink software. Reference [125] proposes a distributed VIC scheme that improves the inertia response of RESs, particularly PVs, to contribute to the microgrid. The technique evaluates the transient characteristics of renewables to modify frequency stability. Reference [126] proposes a modified VIC for VSG. This lowers power oscillations while also providing additional power assistance. The suggested approach examines transient characteristics to ensure frequency and power stability. An improved VIC scheme is proposed in [127] to analyze the instability characteristics of weak grids connected to three-phase voltage source converters. The dSPACE control platform verifies the system's effectiveness. A VIC technique for DC microgrid is proposed in [128], incorporating a bi-directional grid-connected converter (BGC). A small-signal model for BGC analyzes the dynamic responses of the DC bus. The control strategy concerns maintaining the system stability and standard frequency regulation. The virtual inertia expression can be illustrated as

$$I_{\text{set}} - I_0 - D_b\left(u_{\text{dc}} - U_n\right) = C_v u_{\text{dc}} \frac{du_{\text{dc}}}{dt} \approx C_v U_n \frac{du_{\text{dc}}}{dt}, \quad (8)$$

where I_{set} is the dc output current reference of BGC, D_b is the droop coefficient, U_n is the rated dc bus voltage, and C_v presents the virtual capacitance.

A frequency deadband-based VIC method for microgrid is proposed in [129]. The control method increases inertia and improves frequency regulation within a short time. Reference [130] proposes an improved VI-method for VSG, which examines the link between the steady-state active power deviation and the dynamic response. The method takes into account the damping coefficient to control frequency stability. In [131], a VIC technique that evaluates both the virtual inertia principle and the energy storage algorithm to assure frequency stability is presented. The ac transmission system's frequency characteristics are investigated. A cascaded VIC method is proposed in [132] to investigate the impact of linking the voltage outer loop and current inner loop. The stability of the DC bus is considered in a feedback analytical manner. The suggested approach improves frequency control and inertia responses, according to simulation findings. An energy router microgrid-operation model for VIC in both ac and dc interfaces is illustrated in [133]. The model increases the microgrid's inertia and frequency stability. The PSCAD/EMTDC simulation platform assesses the model's efficacy. Reference [134] presents a VIC technique for a variable-speed heat pump. The system develops a small-signal model to examine inertia and frequency responses.

TABLE 8. A representation of different VIC techniques that covers multiple terms.

Ref.	Source Considered			VSG	Small Signal Model	Controller			Simulation Platform		
	Wind	PV	SG			Robust H-Infinity Controller	Intelligent Control	PI Controller	PSCAD/EMTDC	DIgSILENT PowerFactory	MATLAB/Simulink
[85]	✓	✓	✓	×	×	×	✓	×	×	×	✓
[86]	✓	✓	×	×	×	×	✓	×	×	×	✓
[87]	✓	✓	×	×	×	×	✓	✓	×	×	✓
[88]	✓	×	×	×	✓	×	×	×	×	×	×
[89]	✓	×	×	×	✓	×	✓	×	×	×	✓
[90]	✓	×	✓	×	✓	×	×	✓	×	×	×
[91]	✓	×	×	×	×	×	✓	×	×	×	✓
[92]	✓	×	×	×	×	×	✓	×	✓	×	✓
[93]	×	✓	×	×	×	×	✓	✓	×	×	✓
[94]	×	✓	✓	×	✓	×	✓	×	×	×	✓
[95]	×	✓	×	✓	×	×	✓	×	×	×	✓
[96]	×	×	×	✓	×	×	✓	✓	×	×	×
[97]	×	×	×	✓	✓	×	✓	×	×	×	✓
[98]	✓	✓	×	×	✓	×	×	×	×	×	✓
[99]	✓	×	✓	×	×	×	×	×	×	×	✓
[100]	×	×	×	✓	✓	×	×	×	×	×	✓
[101]	✓	✓	×	×	✓	×	×	×	×	×	✓
[102]	✓	✓	✓	×	×	×	×	×	×	×	✓
[103]	×	✓	×	×	×	×	×	×	×	×	✓
[104]	✓	✓	✓	×	×	×	×	×	×	✓	✓
[105]	✓	×	✓	×	×	×	×	×	×	×	✓
[106]	✓	×	×	×	✓	×	×	×	×	✓	×
[107]	×	✓	✓	×	×	×	✓	✓	×	×	✓
[108]	×	✓	✓	×	×	×	×	×	×	×	✓
[109]	✓	✓	×	×	×	✓	×	✓	×	×	✓
[110]	✓	✓	✓	×	×	×	×	×	×	×	✓
[111]	✓	✓	×	×	×	×	×	×	×	×	×
[112]	✓	✓	×	×	×	×	×	×	×	×	✓
[113]	✓	✓	×	×	×	×	×	×	×	×	×
[114]	✓	✓	×	×	✓	×	×	×	×	×	✓
[115]	✓	✓	×	×	✓	×	×	×	×	×	✓
[116]	✓	×	×	×	×	×	×	×	×	×	✓
[117]	✓	×	×	×	✓	×	×	✓	×	×	✓
[118]	✓	×	✓	×	×	×	×	×	×	×	×
[119]	✓	×	×	×	×	×	×	×	×	×	✓
[120]	✓	×	×	×	✓	×	×	×	✓	×	×
[121]	✓	×	✓	×	×	×	×	×	×	×	×
[122]	×	✓	×	×	✓	×	×	✓	×	×	✓
[123]	×	✓	×	×	×	×	×	×	×	×	×
[124]	×	✓	✓	×	×	×	×	×	×	×	✓
[125]	×	✓	×	×	×	×	×	×	×	×	×
[126]	×	×	×	✓	×	×	×	×	×	×	×
[127]	×	×	×	✓	×	×	×	×	×	×	×
[128]	×	×	×	✓	✓	×	×	×	×	×	×
[129]	×	×	×	✓	✓	×	×	×	×	×	✓
[130]	×	×	×	✓	×	×	×	×	×	×	✓
[131]	×	×	×	✓	×	×	×	×	×	×	✓
[132]	×	×	×	✓	×	×	×	×	×	×	×
[133]	×	×	×	✓	×	×	×	×	✓	×	×
[134]	×	×	✓	×	✓	×	×	×	×	×	×
[135]	×	×	✓	×	×	×	×	×	✓	×	×

✓ means the term is included and × means the term is not included in the research work

The suggested system is tested in a hardware-in-the-loop simulation platform to confirm its efficacy. Reference [135] proposes another VIC technique for DC microgrid that looks at frequency variation and the MMC impact during the transient phase. The proposed approach uses PSCAD/EMPDC software to implement the system. Table 6 depicts a comparative analysis of several other VIC approaches.

III. DISCUSSIONS

The existing VIC plans consider several sources, including wind, PV, and SG. Again, distinct types of wind turbines are used in these schemes: DFIG and PMSG. An overview of technical parameters is necessary to perceive the system's operation. The numerical representation of several wind turbine parametric values: rated power, rated wind speed, and inertia time constant can be found in Table 7. According to the presentation, the majority of wind turbines are DFIG models.

The fundamental characteristics of several VIC approaches are compared in this study. Table 8 depicts an overview of several VIC approaches using various terminology. A relative comparison of relative terms depicts the current status of research motivation for inertia implementation strategies. The graph demonstrates the increasing use of intelligent approaches in inertia control schemes (PSO, fuzzy logic, CSO, and MPC). Only one of the 51 control schemes uses the H-infinity controller to improve frequency and inertia responses. Several strategies use small-signal models to investigate inertia and frequency responses. The table indicates whether or not a control technique produces a small signal model. Most control methods use MATLAB/Simulink software as a simulation or testing platform. That means that the MATLAB/Simulink platform is used in most frequency and inertia control studies. Though just a few people use PSCAD/EMPDC and DIgSILENT PowerFactory, these simulation platforms are projected to become more widespread soon because they are more focused.

IV. CONCLUSION AND FUTURE DIRECTIONS

The article proposes several VIC approaches to improving inertia response and frequency stability in RESs-integrated power systems. The authors look into 51 different VIC approaches. The existing VIC methods are classified according to their features in the literature. The literature review thoroughly examines various key keywords associated with each of the existing VIC approaches, such as system design, sources, considered controllers, simulation platforms, and working methodology. The representation of wind turbines' technical parameters based on the system's operating characteristics and parametric values (rated power, rated wind speed, and inertia time constant) can be significant in the field of inertia responses. The overview of the inertia implementation with different intelligent control schemes in different simulation platforms motivates researchers to perform activities to improve frequency and inertia responses. The following are the key conclusions of the performed study:

- The resilient H-infinity technique incorporates inertia as an uncertainty factor and loads as a disturbance component to obtain an ideal microgrid platform. The CDM is used in another VIC approach for inertia and frequency stability. Operators can achieve power system stability by maintaining synchronization between DFIG and FDM.
- The SMES-based VIC considers the microgrid's dynamic features to preserve frequency stability. Operators can also use a BGC to make a small model that reduces frequency control.
- A traditional VIC approach uses a voltage outer loop and a current inner loop to evaluate frequency regulation. Another VIC technique includes an MMC to maintain frequency stability.
- CSO-MPC can be used with a PID controller to ensure frequency stability. The frequency enhancement can be influenced by the ABC algorithm, the PSO algorithm, and the fuzzy logic controller.
- The derivative VIC approach introduces trajectory sensitivities to assess the steady-state and transient features in the high renewable penetrated microgrids. The derivative control techniques considered the frequency derivative to regulate inertia and frequency response.
- A distributed VIC approach focuses on enhancing PV performance in the microgrid to ensure optimal power generation. An adaptive VIC control technique utilizes adaptive virtual inertia and adaptive governor gain to improve frequency responses for system stability. The adaptive bang-bang control technique focuses on building a small-signal model to improve frequency responsiveness. The ABC algorithm-based intelligent control technique integrates a derivative control loop for enhancing frequency response. Operators can include MPC and the fuzzy logic controller as other adaptive VIC techniques.

Future research might investigate the adaptability of renewables in the power system and enhance the virtual inertia and frequency responses under the fluctuating power output. A comprehensive review of damping inertia control approaches, synthetic inertia control techniques, and VIC techniques can be adopted to enhance RESs power utilization. The authors aim to perform technical research by integrating intelligent techniques to optimally maintain frequency and inertia responses. The adaptation of power electronic converters to control the inertia responses of RESs-connected microgrids can significantly contribute to this field of research.

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