Majlesi Journal of Electrical Engineering **Vol. 17, No. 1, March 2023**

A Comprehensive Review on Grid-forming Inverter: Potential and Future Trends

Samuel S. Yusuf[1*], Adamu S. Abubakar[2]
1- Department of Electrical Engineering, Ahmadu Bello University Zaria, Zaria, Nigeria.
Email: yusufssamuel@gmail.com (Corresponding author)
2- Department of Electrical Engineering, Ahmadu Bello University Zaria, Zaria, Nigeria.
Email: abubakaras@abu.edu.ng

Received: 12 October 2022 Revised: 8 December 2022 Accepted: 23 January 2023

ABSTRACT:
There is growing commitment to phase-out the conventional fossil-fuel based power stations to decentralized power generation with high share of renewable energy sources that is based on low-emission to meet the various techno-economic, environmental and secure energy requirements. This paradigm shift from conventional generators to the inverter-dominated DGs/RESs, has come with some technical challenges of low inertia, frequency instability, harmonic distortion etc. The challenges require effective and efficient inverter-based power system control for a reliable and stable grid interface. Based on the way inverters functions, it is grouped into three categories: grid-feeding, grid-supporting, and grid-forming. Several control schemes have been proposed for grid-forming inverter; these control schemes are based on the concept of Virtual synchronous machine, Power synchronization control, and Direct power control. This paper presents a comprehensive review on the recent advancements in grid-forming inverter control technologies. This review covers different control techniques that have been successfully implemented for the inverter-based power system to grid interface, benefits and challenges of attaining the estimated 100% non-synchronous power generation. The cornerstone of the survey is to also establish state-of-the-art on the grid-forming inverter and identify future research areas for improving the existing techniques and developing novel ones.

KEYWORDS: Distributed Generation, Grid-forming, Power Synchronization Control, Renewable Energy Sources, Virtual Inertia.

1. INTRODUCTION

The modern electric power system is confronted with unsustainable energy as a result of high energy demand globally, due to population growth, technological advancement, and rising standards of living. The rising concerns of climate change resulting from anthropogenic emission of environmental pollutants into the ecosystem from thermal plants, have make huge investment into the traditional power system architecture that utilizes fossil-fuel undesirable [1-5]. These have become major global concerns, which have necessitated the economic evaluation of the fossil-fuel usage, availability, and the way to curb the undesirable environmental impacts [6-8]. There is need for a transition and decommissioning of the central conventional fossil-fuel-based power stations that uses electromechanical synchronous generators to decentralized power generation with high share of renewable energy sources that is based on low-emission to meet the various techno-economic, environmental and secure energy requirements.

Renewable energy sources (RESs) are those sources of energy generation that replenish themselves over a short-period of time and do not dwindling. These sources include; wind, solar, biomass, geothermal, hydropower energies, etc. and are often regarded as the alternative sources of energy [9-11]. The most promising among the RESs are the hydroelectric power (HEP), wind energy and solar PV technology with large deployment as a result of their huge potential and abundance across the nations of the world [12-15]. RESs are the primary, environmental-friendly, widely distributed, and inexhaustible green energy resources [16]. In the near future, the total energy generation from these RESs is projected to grow exponentially across the globe, because the technology provides an excellent platform for mitigation and decarbonization of global emission and reduction of global warming through a large deployment of RESs and phase-out of

Paper type: Review paper
DOI: 10.30486/mjee.2023.1970278.0
How to cite this paper: S. S. Yusuf, A. S. Abubakar, **“A Comprehensive Review on Grid-forming Inverter: Potential and Future Trends”**, *Majlesi Journal of Electrical Engineering*, Vol. 17, No. 1, pp. 1-27, 2023.

the traditional energy sources [16-18]. An improved RESs technology that can harness these sources for a distributed or decentralized generation will solve some lingering issues involving power instability and insecurity [19, 20].

More recently, Distributed Generation (DG) has become a research hotspot for modern power system engineers, since its integration with existing utility provides enormous advantages such as; energy efficiency, promotion of massive use of locally accessible RESs, voltage support, deferment of transmission and distribution upgrade, improvement of power quality, relieve network congestion, reduction in environmental impact, smarter distribution system etc. DG technologies can broadly be classified into two categories: non-renewable and renewable energy resources [21, 22]. The former consist of reciprocating and internal combustion engines, gas-turbines, micro-turbines, fuel cells, and micro-Combined Heat and Power (CHP) plants, while the latter includes; small hydro, wind, biomass, solar photovoltaic (PV), ocean-based power plants etc. [23, 24]. These inverter-based DGs technology is devoid of rotating part for the inertia response, but can contribute frequency support through addition of synthetic inertia via the power electronics inverters, while the synchronous generator (SG) provides frequency support during network disturbance through its rotating mass (source of inertia) [25, 26]. Implementation of a single DG or improper DG units installation in a distributed system can result in negative impacts that can lead to several problems as it may solve [27, 28]. The most efficient way of utilizing the emerging potential, diversity and salient prospects of a DG is to view the generation and associated loads as a small clusters, microsources or microgrids [1, 27, 29].

Microgrids (MGs) are integrated energy systems consisting of interconnected domestic loads and distributed energy resources such as; fuel-cells, small hydro-turbines, solar PV and wind turbines, storage systems, like; flywheels, battery energy storage and capacitors, and controllable and uncontrollable loads which can be operated in parallel with the grid (grid-connected mode) or in an intentional islanded-autonomous mode [30]. MGs are classified into ac MGs and dc MGs, the dc MGs offer huge benefits of power quality, reliability, low cost, simple control mechanism and high efficiency when compared to the ac MGs [31]. These small grids (MGs) are expected to offer black-start operation, active and reactive power flow control, frequency and voltage stability, management of storage energy and active power filter capabilities [32]. MGs functionality is similar to the main grid, it uses the following three main control levels hierarchy: primary control level (voltage and frequency stability maintenance), secondary control level (ensure voltage and frequency deviations compensation), and tertiary control level (manage power exchange between the MGs and the utility grid) [32, 33]. Moreover, for a better reliability and superior performance of MGs operation, they are best operated as a networked (multiple) known as networked microgrid (NMGs). A networked microgrids is an energy control coordinated management process of interconnecting multiple MGs in a spatial proximity to provide a reliable, resilient, efficient and cross-border energy exchange between different areas [34-36]. The most important interface through which MGs are customarily connected to the electric power grid is via actively-controlled power electronics inverters (converters) at the point of common coupling (PCC) to provide fast switch, high efficiency and full controllability.

The RESs cannot deliver the electricity needed directly at a nominal voltage magnitude and frequency and therefore requires inverters to convert and also act as an interface between the microgrids and the energized grid. Conventionally, traditional power inverter only extracts/draws maximum power from its sources and delivers it to the grid or end-users. However, in this modern day grid with massive penetration of RESs in the bulk power system on the pathway towards achieving a climate sustainability and deep decarbonization trends, inverter-based power system (IBPS) are anticipated to perform more roles (such as control of voltage, frequency and power, self-healing, service restoration, autonomous operation etc.) in order to ensure a robust RESs to grid interface, which will enhance system reliability, security, and sustainability [35, 37-40]. These applications have increased the use of power electronics devices on the network (grid) with corresponding reduction in the number of synchronous generators (SGs). Based upon the way inverters functions, it can be categorized into three groups: (i) grid-feeding, (ii) grid-supporting, and (iii) grid-forming [41-44]. Grid-feeding (GFI) is a traditional inverter that exploits or draws maximum energy from the DG unit to the loads or grid [45-47]. Grid-supporting extracts maximum energy from DGs and also provides other ancillary services such as transient support to the grid during instability of frequency, reactive power support during voltage sag and harmonic compensation. Grid-forming (GFM) inverter functions by forming a self-governed grid with stable voltage and frequency [48]. Since GFM maintains stable voltage and frequency, the grid-forming inverters can operate as a standalone/islanded and grid-connected modes [49]. This inverter technology (GFM) is an innovative and evolving concept with a large deployment of inverter-interfaced generation and application of RESs.

The continuous progression and rising demand for RESs power generation (exceeding 65% of non-synchronous generation sources), harm the overall grid dynamics and subject the network to frequency instability, harmonic resonance and decrease the amount of rotational inertia in the grid [50-54]. These contrasting dynamical behaviour that massive penetration of renewable power generation introduced into the grid, have beaconed for more sophisticated, robust and promising grid-control mechanism (schemes) that can enhance the efficiency of grid-tied power converter to behave identically to the output/response of electromechanical synchronous machines with capability of maintaining system stability that is utmost importance. Several state-of-the-art GFM topologies have been extensively researched for the control and regulation of GFM inverter output. These control schemes are mostly based on the concept of Virtual synchronous machine (VSM), Power synchronization control (PSC), and Direct power control (DPC). Recently, the inertia-based emulated control techniques for grid-forming inverter have gain world-reaching recognition in the effective capability to enhance frequency response in a weak and low-inertia grids [55, 56].

This paper reviews state-of-the-art grid-forming inverter and various GFM control schemes. In Section 2, the power converters, grid-feeding, grid-supporting and grid forming are presented. Control mechanism of grid-forming is attained in Section 3. Section 4 explained the benefits and challenges of grid-forming inverters. In Section 5, the future trend in grid forming is discussed. Finally conclusions are drawn in Section 6.

2. POWER ELECTRONICS CONVERTERS

Power electronic converters is a technology that comprises effective and efficient conversion, control and conditioning of electric power by statics devices from the available input into a desired output and efficiency [57]. Power electronics converters are mostly compose of semiconductor switches and energy storage elements [58]. Recently, power electronics have experienced a rapid evolution, which is largely caused by two factors. The first factor is the introduction of fast switches from semiconductors with ability to switch rapidly and handle high power applications. The second one is the development of high speed real-time computer controllers that can use advanced and complex control algorithms [59, 60]. These two factors have resulted in the advent and innovation of massive variants of cost-effective and grid-friendly converters for connecting renewable energy to the grid. The flow of energy between two sources is processed by a converter, that is, a source called the generator (input source) or a load called output source. These two sources are; voltage and current sources, which can be a generator or a load [61]. Power electronics converter can be grouped into four categories according to their applications [61]:

a) AC-DC (rectifiers): It converts AC voltage to a stable DC output voltage.
b) DC-AC (inverters): It is a device that produces an AC output of a definite phase (single or polyphase), frequency and magnitude from a DC source.
c) DC-DC (choppers): It changes the DC input voltage to a higher or lower DC output voltage.
d) AC-AC (cycloconverters): It converts AC source and deliver it to an AC load with desired voltage/current of different frequency, amplitude and phase.

These categories of converters have a wide-spectrum of applications in power generation and transmission, transportation, industrial, consumer products applications etc. Based on the inverters control capability and functions, it can be categorized into three groups: (i) grid-feeding, (ii) grid-supporting, and (iii) grid-forming [41, 42, 62].

2.1 Conventional Inverter/GFI

GFI controllers are the traditional, most prevalent and widespread type of control technique for grid-tied RESs (PV and wind) inverters [63]. This inverter operates as grid-following (GFL) by “following” or “tracking” the voltage angle at the terminal of the grid using a phase-locked loops (synchronization unit) in order to regulate and match the power output [63-66]. PLL is an essential asset in GFI for extracting information of the phase angle and voltage magnitude at the point of common coupling of a grid-connected power generation systems [67-69]. In this inverter control technique, PLL is utilized to synchronize inverter-based resources to the grid and the output current is regulated via a predetermined power to the grid [70-72]. The inverter harvests maximum power from DG units (irrespective of the voltage magnitude or power flow) and supply to an energized grid without reducing the harmonic voltage contents [73-75]. This grid-connected current-controlled GFI operates by maintaining a unity power factor [45, 46]. It usually feeds the grid as an ideal sinusoidal current source [45]. This current-controlled GFI can efficiently control current and operate during grid fault, but cannot perform efficiently when in standalone or/with weak grid, because the control is fixed on current [76]. Moreover, GFI is also not designed with adequate (large) BESS to emulate constant supply of committed power to the grid during fault, inertia response, fault current behaviour and low switching device in comparison to the SGs working principles. Consequently, diverse alternative concepts and approaches for controlling the operation of GFI inverter to imitate the electromechanical behaviours of SGs have emerged.

A current-controlled virtual synchronous machine (VSM) for a grid-feeding inverter was presented in [51, 77], the concept of a VSM control approach is basically derived from the replication of behavioural characteristics of a SGs. VSM demonstrates the tendency for seamless integration of the decentralized RESs (wind, PV and fuel cell system) to a weak grids, as a result of virtual inertia injection to the power system (PS). In [78], a variant form of VSM model of algebraic type was presented. Ref. [46], reported a simplified virtual synchronous compensator (S-VSC) for grid support services. The S-VSC features synchronous generator mechanical properties by providing current limiter to control overcurrent during faults and mimic swing equation of the synchronous generator to reduce the risk of loss of synchronization. H-infinity method of PI controller for GFI was reported in [79], the PI controller was tuned using *hinfstruct* optimization function in order to regulate the active and reactive power exchange of the inverter to grid. A collaborative voltage unbalance elimination technique was adopted for AC MGs with grid-feeding inverter to eliminate voltage unbalance at any node of the AC grid where sensitive loads are attached [80]. Refs [81, 82], developed a novel synchronverter, a controller that uses mathematical model to mimic the working principle of synchronous generator, with a prime function of controlling power (active and reactive), voltage, and frequency of the MGs to grid.

The demand from IBPS is growing rapidly in this present era and is beyond only harvesting maximum energy from the RESs to the grid, but an inverter that is capable of supporting the grid with or without SGs. This has made the conventional GFI not to be technically feasible in these contemporary and future power systems, because inverter will need to lead the grid behaviour and not to follow the grid, during steady-state and transient conditions. To this end, next-generation inverter-based infrastructure that can operate autonomously, capable of supporting weak grid to stronger grid, and provides ancillary support services to the grid is indispensable. This has brought a new concept of a grid-connected inverter known as grid-supporting.

2.2 Grid-Supporting Inverter

Grid-supporting inverter (GSI) draws maximum energy form DGs and also offers other grid ancillary services such as transient support during instability of the grid frequency, reactive compensation during voltage dip, harmonic compensation and islanding/standalone capabilities [73, 83]. This voltage-controlled inverter (VCI) is designed based on the model or idea of droop behaviour and it is inspired on the basis of the working principles of synchronous generators (SGs) to solve some of the inadequacies of the current-controlled inverters (GFI). The GSI provides a direct voltage support to the grid and can be operated in standalone and grid-connected modes. This inverter has in addition logic such as virtual impedance and self-synchronizing concept to ensure current transient and magnitude of the voltage are within acceptable tolerance [84, 85]. It provides grid stability by regulating the voltage level via active power curtailment and compensation of reactive power regardless of the RESs connected. It performs several functions for different grid disturbances and is capable of functioning as a static synchronous compensators (STATCOM), active filter, and unified power quality conditioner [42]. For this inverter to efficiently provide the required support to the grid, a robust control scheme that can mimic the stability behaviour and dynamic performance of electromechanical SGs is desirable.

Recently, there have been rapid interests in developing an inverter control techniques with high performance for secure grid-support inverter integration. Virtual synchronous machine (VSM) was developed to emulate synchronous machine in [86], the distribution power controller (VSM) was implemented for a smooth changeover between grid-connected or standalone converters. In this case, VSM monitors and controls the controllable units as well as providing ancillary services such as load voltage compensation, reactive power compensation, and supports the frequency regulation of the system. In-depth studies on several models of VSM for GSI control have been extensively researched with diverse nomenclatures and various practical implementations in [74, 87, 88]. Ref. [84], presented an enhanced virtual synchronous machine (eVSM) with physical existing of inertia using dc-link element for inertia response rather than depending on dedicated battery storage. The developed control model has a similar performance of synchronous machine with ability to improve transient and stability of a weak grid. Author [42], reported a review that provided details opportunities and challenges of grid-connected inverter, utility-scaled BESS, and vehicle-to-grid (V2G) technology. Various architectures, topologies and technology for BESS and V2G interface to the distribution level were highlighted. Utility-scaled BESS implementations at different distribution levels for grid-supporting functions were also tabulated. A novel voltage control algorithm, Jacobi-Proximal Alternating Direction Method of Multipliers (JP-ADMM) was presented in

[89], for grid-support PV inverter. The algorithm was applied to locally optimize the reactive power compensation and active power curtailment of each participating inverter in the voltage control. Author [90], proposed grid-supporting inverter that offers multiple grid support services such as harmonic compensation, negative sequence and power exchange. A dynamic grid-support in a low voltage grid was investigated in [91], different requirements for a dynamic grid support in medium and high voltage grids were discussed. Parameters for under voltage protection and the inverter reactive current controller were suggested.

It is envisioned that the RESs share is estimated to reach a nearly 100% of non-synchronous generation [92], in order to achieve this ambitious goals, advanced control functionality that can provide stable frequency and voltage at PCC in resemblance to SGS output pattern is desirable. To this end, grid-forming inverter technology is the ideal for these functionalities.

2.3 Grid-Forming Inverter

The paradigm shift from the conventional power generation with synchronous generators (SGs) to the inverter-dominated DGs/RESs, has come with challenges of low inertia and damping effect on the dynamic stability performance of the grid. The aforementioned issues is also accompanied by voltage rise as a result of reverse power from PV source, power fluctuations as a consequence of the intermittent nature of RESs, disproportionate amount of power supply due to full generation of participating DGs, and degradation of frequency stability, thereby raising the level of rate-of-change-of-frequency (RoCoF) particularly in a stand-alone MGs [93-96]. The power generated from RESs is variable, intermittent, stochastic, non-dispatchable and cannot provide the grid with the necessary ancillary support services required [97, 98]. Therefore, in order to explore maximally the emerging potential and salient prospects of RESs into the main grid, a robust technology that will improve the behavioural output pattern and dynamic response of the RESs is quintessential. The essential asset through which RESs are interface to the grid at the PCC is via power electronic converters [63, 99, 100]. The conventional power electronic converters (RESs-to-grid connector) have proved not to provide adequate in-built system synchronization inertia response and suitable high short-circuit current to the grid. This future sustainable energy system can be a viable and feasible solution that will cause a paradigm shift from the conventional generators (SGs) to RESs.

Far-reaching innovative techniques and methods are on the pathway towards developing an efficient control and operation of grid-connected inverters to imitate the kinetic energy and the self-synchronization characteristic of SGs at controlling voltage, blackstart, load-sharing, and frequency during normal and fault conditions. A GFM unit can work autonomously of grid strength and can also be grid-connected (self-synchronizing capabilities) to an energize ac grid [101]. GFM inverters do not require PLL for successful grid interface, because it shares comparable fundamental principle with SGs, by regulating the voltage amplitudes and frequency to ensure self-synchronization, grid stability and better dynamic performances [38, 102]. The followings are the potential functionalities expected from a grid-forming inverter: (i) ability to work under normal (small signal) condition; (ii) work autonomously after isolation from main grid; (iii) capability of working under transient conditions; (iv) provision of black start services (having a sufficient energy buffer) to initiate system restoration after a blackout. It is also imperative for GFM controller to effectively and swiftly limit the output current of the inverter during grid faults condition to protect all the power electronics components [103-106].

2.3. Recent developments in GFM

This section presents reviews of previous studies on grid-forming inverter control schemes. The cornerstone is to review recent developments and establishes future research areas for improving the existing techniques. **Singh, Lopes [107]** presented a grid control scheme for grid-forming inverter using per-phase dq control scheme (cascaded inner current and outer voltage loops) with fictive axis emulation (FAE) for regulating voltage and frequency under a highly unbalanced hybrid mini-grid. Battery energy storage system as a vital asset for enabling diesel-less operation of diesel-hybrid mini-grids with massive RESs penetration was established. The proposed model was evaluated on a number of conditions such as unbalanced resistive loads, motor loads, non-linear loads and with high penetration of single phase RESs to evaluate the effectiveness of the proposed control scheme. The battery management system was employed which focused on state-of-charge of the battery and synchronization to the diesel engine generator for the BESSs interface control. In **Miveh, Rahmat [108],** an advanced multi-loop control technique for a three-phase, four-leg voltage source inverter operating under unbalanced loads in a standalone distribution system was presented. The control method consists of nested-loop proportional-integral (PI) voltage controller loop and a proportional current loop. The instantaneous output voltage was regulated and pulse width modulation voltage of the inverter was generated using the voltage controller and current loop respectively. The proposed controller was able to balance the inverter output voltage under ultraunbalanced loading conditions. Due to the weakness of PI controller at increasing the proportional gain to high level in order to eliminate the steady-state error, a voltage decoupling feedforward path was used to improve the PI inner loop performance. The fine-tuned PI with voltage decoupling feedforward path was compared with conventional PI, the former out-performed the latter in the system stability during the unbalanced loads analysis.

Li, Zang [109] reported a nested-loop control approach for an autonomous grid-forming inverter containing an LC output filter and loads devoid of passive and active damping mechanism. The control technique comprises of a sliding mode control (SMC) in the inner current loop and a mixed H_2/H_∞ optimal control in the outer voltage loop. The inner and outer loops offers the advantages like constant switching frequency, low-total harmonic distortion and robustness against variations of parameters, external disturbances and fast transient response. The proposed model was compared with the traditional PI-based nested-loop control techniques in terms of transient stability response. A microgrid control technique based on a GFM inverter operating as a virtual synchronous generator in combination with supercapacitor (SC)-based energy storage system for dynamic response stability was conducted by **Serban and Ion [110]**. The GFM inverter was designed to respond only in transitory regimes, the steady-state load was shared among the participating MG-support inverter, so that the GFM VSG can preserve its full power reserve capacity for dynamic stability response. Frequency control response was evaluated based on four scenarios associated with load dynamic, GFM frequency response, and different operational conditions (malfunctioning) of one of the GFM inverters. The proposed control scheme along with a higher overloading capacity during transitory regimes was recommended for future studies.

Arghir, Jouini [111] considered a grid-forming control strategy of power system centred on synchronous machine model that dwell on the main features of SGs in a low inertia power system. In order to match the dynamic of SGs, a feedback was enabled between the critical coupling DC-side voltage and its counterpart AC-side frequency while preserving the passivity properties of the inverter. The converter was augmented by virtual oscillator whose frequency is driven by DC side voltage measurement and which regulates the inverter PWM signal, thus enabling the converter to behave identical to the SGs dynamics. The model enhances incremental droop, passivity and power-sharing properties that are compatible with the operational requirements of the conventional grid. The viability of the model was tested based on two scenarios; voltage and frequency regulation with single converter and voltage and frequency regulation with multi-converters scenario. The control scheme yields a favourable transient response to the disturbances that the system was subjected to, but a trade-off between the power load and AC voltage amplitude was identified. In **Markovic, Stanojev [112]**, a partial grid-forming concept for 100% inverter-based transmission systems was investigated. A type-2 phase locked loop in a SRF was applied for the synchronization unit in order to provide a suitable frequency reference to the outer control loop which is based on dq transformation. The concept of this partial grid-forming was brought forth to show that a power system with zero rotational inertia can operate without a dedicated GFM voltage source converter unit. The partial grid-forming was achieved using the combination of the four converter operation modes (GFM, frequency-forming, voltage-forming and GFI) distributed across different VSC units. The voltage magnitude and frequency are independently formed by the individual participating VSC at different locations in the grid.

Qoria, Li [113] proposed a direct AC voltage control based on state-feedback control to enhance power inverter bandwidth for fast and smooth RESs to high voltage grid integration. The paper presents a technique to protect the power converter against the extreme events of short-circuits and overcurrent that can occur as a result of phase shift and sudden increase in network loads. A linear quadratic regulator was utilized for the control of the inverter gains. The unrestricted nature of the direct AC voltage control to the inverter current was solved by adding threshold virtual impedance to the state-feedback control in order to protect the inverter against overcurrent. In **Yu, Awal [114]**, a passivity-oriented discreet-time voltage controller for reference tracking performance, load-rejection capability and passive output impedance under a weak condition for grid-forming was presented. To offer more degrees of freedom in terms of gains control, the complex vector methods were adopted for the modelling and control of the GFM. Discreet-time complex variable resonant controller (DCVRC) was implemented to remove the steady-state error under $\alpha\beta$-frame in order to enhance the passivity of the output impedance.

In **Yazdani, Ferdowsi [101]**, a photovoltaic synchronous generator (PVSG) hierarchical control technique based on modified virtual synchronous machines for high penetration PV-based inverter was investigated. In the study, PVSG as a grid-forming inverter was designed to emulate SGs mechanical properties by injecting inertia to the system to counteract the frequency deviation during unbalance conditions. The internal voltage controller with nonlinear current control loop adjusts the PCC voltage and limits the network current during an unbalanced condition. The proposed model performance was verified during islanded mode operation, islanded and unbalanced-grid connected mode, unbalanced grid-connected mode, and islanded and unbalanced grid-connected and irradiation variation mode. The model was also compared with conventional synchronverter equipped with current-limiting loop, PVSG outperforms synchronverter in the PCC overcurrent and voltage regulation. The application of a coherency-based aggregation technique for a large-scale power systems analysis of a grid-forming, droop-controlled inverter was presented in **Hart, Lasseter [115]**. The work used a generalized eigenvalue perturbation (GEP) algorithm for coherency identification in the GFM droop-controlled inverter. The GEP algorithm was also used to construct a reduced-order dynamic model that mimics the dynamic response of the outcome of the network during large disturbances. **Huang, Wang [116]** proposed a decentralized control strategy for multiple three-phase parallel GFM DG units in a standalone microgrid. Fixed system frequency that is independent of large or rapid load variation was imposed on grid-forming DG units for the MGs stability. Filtered tracking error was developed based on the reformulated system model; it helps to manoeuvre the output bus voltage components in stationary reference frame to track their desired trajectory voltage parameters through their control laws. The technique was used to tune the controller in order to achieve superior PCC voltage regulation and power sharing performance among the participating DGs. Voltage control and power sharing at the point of common coupling were evaluated using Lyapunov method. The proposed model and conventional droop-based hierarchical control methods were compared.

A novel controller based on linear quadratic regulator (LQR) for a three-phase two-level GFM inverter for the regulation of voltage and system stability was presented by **Oue, Sano [117]**. The study used LQR comprising of a state-feedback and an integral compensator replacing the commonly used conventional cascaded voltage and current loop controllers. The integral compensators are capable of controlling the voltage across capacitor without steady-state error in the synchronous rotating frame (SRF). Impedance-method and eigenvalue analyses were utilized in the *dq* reference frame to analyse the grid-forming inverter stability performance with both the LQR and the cascaded PI controller. The results revealed that LQR has more stability margins and potential to be used in GFM inverter than the cascaded PI controller. When the proposed model was compared with cascaded PI control, LQR shows faster voltage response with lower steady-state error and a very small transient coupling effect between the active and reactive powers. The proposed LQR based controller and the cascade PI controller were compared in terms of their stability performance during disturbances. In **Watson, Ojo [118]**, the stability of power system with GFM converters in a common reference frame by applying passivity-based techniques was examined. In this work, frequency droop, angle droop, current loop gain and matching control passivity properties were highlighted and the way to improve their stability performances in a network. This control technique provides a decentralized condition which when satisfied at all the buses, the stability of the interconnected power grid is guaranteed. The GFM passivity properties were improved by merging the concept of virtual resistance with angle droop to form a controller. **Quan, Yu [119]** proposed a Photovoltaic Synchronous Generator to effectively transform an existing PV system from a grid-following to grid-forming. The PVSG transformation technique was achieved by AC couple supercapacitor-based energy storage system (SB-ESS). The novelty control scheme of PVSG was implemented on the SB-ESS side which includes a fast and slow instantaneous power control. The fast-instantaneous power flow control is fulfilled by the DC-link voltage control and AC voltage control. The DC-link voltage control and AC voltage control provide the fast power response function of the propose model. The *df/dt*-based power control was utilized to resists grid frequency deviation.

Khefifi, Houari [120] presented a control scheme for an isolated GFM inverter based on a robust interconnection and damping assignment passivity-based controller (IDA-PBC) with an addition of integral action to robustly step-down the undesired disturbances and uncertainties. The control scheme was based on Hamiltonian modelling; here the objective is to minimize energy function that promises a stable and robust control of the system in a closed-loop. The power export to the local loads was managed via an inverter and LC filter. IDA-PBC model was compared with that of the classical PI controller and conventional IDA-PBC under linear, nonlinear, balanced and unbalanced loading conditions. **Du, et al. [49]** investigated GFL and GFM inverters on a 3-phase, electromechanical model and interconnected them into an open source, 3-phase distribution network solver for easy dynamic simulation under large-scale unbalanced network with high penetration of inverter-based RESs. CERT Droop controller was used to control the voltage magnitude and frequency of the inverter internal voltage, according to the Q-V droop and P-f droop controllers. The study compared the traditional grid-following inverters with high RESs penetration of grid-forming inverters. In **Tayyebi, Anta [121]**, an hybrid angle control (HAC) for grid-forming inverter that guarantees almost global closed-loop for transient stability performance was proposed. The HAC was developed based on the complementary advantages of (dc-matching order and nonlinear angle feedback) droop control and dispatchable virtual oscillator control. The HAC was implemented on high-fidelity nonlinear converter model that was connected to a grid through a dynamic inductive line.

Rosso, Engelken [122] investigated fault-ride through (FRT) strategy for overcurrent limitation of GFM converters under symmetrical and asymmetrical grid faults. The vital parts of this proposed control scheme are the inner loop (virtual admittance) that allows direct control of the converter currents and the outer loop represented by VSM. The FRT approach imitates voltage source behind impedance characteristics under fault conditions reported in **Antunes, Silva [123]**, the FRT gives better quality solution in instantaneous injection of reactive current without the need for tracking first the grid voltage. **Qoria, Gruson [124]** implemented an hybrid current limiting control (HCLC) technique for a transient stability of a grid-forming converter based on the droop control. The current limiting controller was developed by hybridising the advantages of virtual impedance (better quality transient stability) and current saturation algorithm (improved current limitation) into one single control strategy (HCLC). The developed algorithm was simulated on EPMlab and validated on a 3-phase bolted fault. The performance of the model was analysed based on three scenarios; current saturation algorithm (CSA) comparison and virtual impedance (VI) comparison, impact of CSA and VI on transient stability and HCLC for network transient stability. The effect of incorporating phase-locked loop in a grid-forming controlled inverter was presented in **Rokrok, Qoria [125]**. The control scheme composes of three control levels; Level A composes of active power control, Level B as inertial effect and Level C provides active control, inertia effect and frequency support for various short-circuit ratios and phase-locked loop response times. This control technique was implemented in synchronous reference frame (SRF) using park's transformation. **Awal, Yu [99]** proposed a nonlinear grid forming inverter using virtual oscillator control (VOC) for harmonic current mitigation during harmonic distortion in the grid-side voltage. Virtual oscillator control is a time-domain control that can ensure almost global asymptotic synchronization. The harmonic current rejection was achieved by using the converter-side current feedback and inductive virtual impedance based on selective harmonic suppression method to emulate the system required harmonic frequencies. Grid-side current feedback offers a better quality performance with minimal non-passive regions around the resonant frequencies. VOC control methods enable simpler implementation and high harmonic current suppression power than other GFM control methods.

The ancillary services that is expected from a grid-connected inverters includes: load voltage compensation, reactive power compensation, voltage and frequency compensation, harmonic compensation, voltage-based power quality problem mitigation, and current based power quality problem mitigation.

3. GFM CONTROL MECHANISM

Nowadays, urbanization and industrialization development have increased the demand for secure electrical energy, and as a result of these, it has received extensive attention among power engineers on the overall power system quality, stability and security. DGs technology is devoid of rotating part for the inertia response, but can contribute frequency support by the addition of virtual inertia through power electronics inverters, while the synchronous generator (SG) provides the frequency support during network disturbance through its rotating mass [25, 26]. DG units which are electronically regulated and interfaced with the grid cannot provide the needed network inertia and damping to the stability of the power system. These have beaconed for a more sophisticated and robust control technique of the grid-connected inverter and efficient control of the inverter switching pattern, so that the output/response will be identical to the output pattern of SGs [25]. Some of the developed grid-tied power converter control schemes are based on the concepts of Virtual synchronous machine (VSM), Power synchronization control (PSC), and Direct power control (DPC). In Fig. 5, the grid-forming control scheme is presented. The commonly used grid-connected inverter control schemes is the inertia-based emulated control techniques, because of its ability to effectively enhance frequency response in a weak and low-inertia grids [55, 56, 126, 127].

3.1 Virtual Synchronous Machine(Generator)

The fundamental idea of VSM control technique is basically derived from the emulation of inertia strategy, steady-state behaviour and the mechanical characteristics of a real synchronous generator [25, 74, 128]. It comprises of control algorithms, RESs, battery energy storage system (BESS), and power electronics converter that reproduce the dynamic inertia properties identical to a conventional synchronous generators [129-131]. It is usually connected between DG units and the upstream grid as shown in Fig. 1. The control technique is a cornerstone of obtaining and realizing virtual inertial from inverted based sources [132]. In-depth studies have shown that VSM implementations and applications is based on emulating the swing equation of a traditional SGs which is equivalent to the power-frequency droop controllers normally used in most MGs [133-137]. VSM uses standard cascaded voltage–current control in the synchronous rotating dq reference frame for voltage regulation and over-current limitation [8, 138]. The three major functions performed by VSM are: frequency control, oscillation damping, and voltage control. It also adds virtual inertia to the distributed electricity generators to stabilize frequency during disturbances [139-141]. The virtual inertia injection is an essential aspect of the VSM that allows a seamless interface with upstream grid as well as autonomous/standalone operation, and also ensures power sharing among the participating DGs [142, 143]. The virtual inertia is created by VSM from the bank of BESS during a short operation time by means of an advance control system [144]. As the future power system begins its slow evolution, several Authors [19, 144-147], have suggested VSM grid interface converters as the future power system grid-tied connector for high efficient RESs penetration.

Over the recent years, VSM has evolved with diverse innovative approaches and dynamics control as reported in [51, 74, 78, 148-152], which makes the grid-connected inverter to imitate the operating characteristics of SGs, in order to explore the advantages of the SGs in the enhancement of system stability. There are current-controlled (current source) VSM and voltage-controlled (voltage source) VSM, in current-controlled VSM, provision of necessary voltage and frequency support to the system is quite challenging. This deficiency is overcome by a voltage-source VSM. The voltage-controlled VSM technique enables easy simulation of synthetic rotor inertia and system frequency modulation behaviour of SGs for the system frequency and voltage controls [153-155]. A number of VSM topologies have been proposed by different authors, some topologies use mathematical equations to fully mimic SGs behaviour while others use swing equation to imitate the asymmetrical performance of the SGs. A swing equation based VSM inertia response control was proposed in [156-158] to provide synthetic inertia to the upstream grid. Among the well-known existing VSM topologies are; Synchronverters topology [159-162], ISE laboratory developed topology [87, 163, 164], Kawasaki Heavy Industries (KHI) topology [78], Virtual synchronous machine (VISMA) and Institute of electrical power engineering (IEPE) topology [165-167]. Table 1 provides a summary of previous control schemes of grid-connected inverters reviews.

VSM-based control method has been widely used in different studies such as in the grid stability and dynamic control of wind-turbine [168-171], high voltage direct current (HVDC) transmission systems [172-174], grid-side integration of photovoltaic plant [175-179] etc.

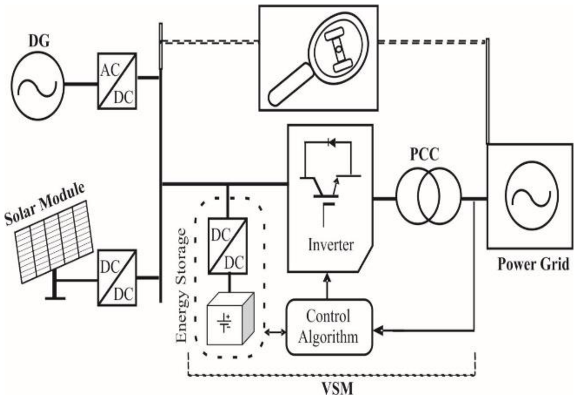


Fig. 1. Virtual Synchronous Machine structure and concept

3.1.1. Modelling of virtual synchronous machine (Generator)

VSM/VSG consists of control algorithms, RESs, battery energy storage system, and power electronics converter that reproduce the dynamic inertia properties of traditional SGs. A three-phase voltage-source converter with a VSM-based control strategy is the fundamental part of the virtual synchronous machine. VSM is coupled to the grid at a PCC with a static switch, marked S as depicted in Fig 2. The output side of the inverter is attached to LCL filter to remove the harmonics contents from RESs before injecting it to the utility grid. The DC source (battery energy storage system) is connected to the DC side of the voltage source converter via a DC bus. The VSM controller measures the phase angle and voltage magnitude at the PCC as a feedback (reference voltage to VSC) and generates equivalent switching pulses. The swing-equation of a synchronous machine is mathematical modelled in Eq. (1):

$$J\frac{d\omega}{dt} = \tau_m - \tau_e \tag{1}$$

Where J, τ_m, τ_e, and ω are the rotor inertia, mechanical power, electrical power, and the angular frequency respectively. To appropriately express the swing-equation in terms of power, equation (1) is multiplied by ω and the power balance equation is formulated as expressed in (2):

$$J\omega\frac{d\omega}{dt} = P_m - P_e \tag{2}$$

Where P_m and P_e are the mechanical and electrical power, respectively, the angular momentum of the SG is denoted by $J\omega$. At synchronous speed, $J\omega$ can be taken as a constant and is referred to as inertia constant and it is represented by Ta. Swing-equation can be rewritten as in (3), after taken into consideration the damping effect of the SG resulting from friction.

$$Ta\frac{d\omega}{dt} = P_m - P_e - K_d(w - w_s) \qquad (3)$$

Where, K_d and w_s are the damping coefficient and synchronous frequency of the generator, respectively. The damping effects produced as a result of friction help in damping the oscillations generated owing to sudden power imbalances. Detailed modelling and mathematical equations of the power–frequency droop behaviour of the governor is presented in [55]. The block diagram of VSM implementation in a utility power grid is depicted by Fig. 2.

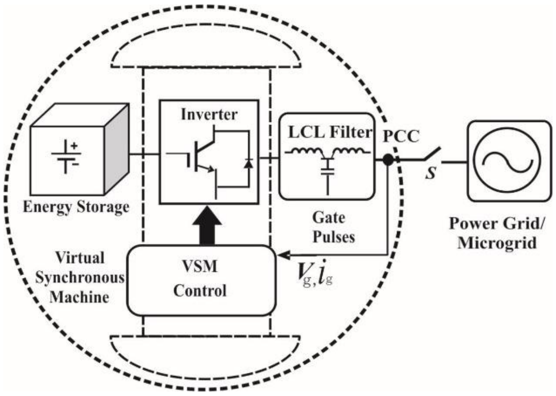


Fig. 2. Block diagram VSM implementation in power grid [55].

3.2. Power Synchronization Control

Another control technique to realize efficient RESs (grid-forming) to energize ac grid interface is through the power synchronization control (PSC). The PSC grid-forming control technique synchronizes voltage source converters with ac energize grid via an active-power synchronization loop instead of using PLL with unstable performance especially in a weak grid or during faults [180]. The PSC control concept is developed from emulation of conventional synchronous generators (i.e the power-angle control) principle, which is viewed as combination of voltage-angle and vector-current controls with the elimination of phase-locked loop. PSC gives a weak ac grid strong voltage support through synchronization mechanism of the swing equation and effective damping capability of GFM inverter terminal [181-183]. PSC is not only limited to SGs behaviour emulation, but it can also improves the inverter output responses as a result of the tunable damping coefficient of the active-power loop which is a second order system [184]. In more recent time, PSC voltage source converters have gained considerable attention for tackling stability challenges [185], there have been in-depth studies on small-signal stability of the PSC grid-connected VSC using Jacobian transfer matrix or impedance matrix [180, 186, 187], and transient stability of PSC voltage source converters [188, 189]. PSC control techniques has been widely implemented in diverse applications such as high voltage direct current (HVDC) transmission systems [190-192], grid-side interface of photovoltaic [183, 193], and wind turbine grid-connected inverter [192].

PSC has demonstrated better response with ultra-weak ac grid stabilization and robust small-signal dynamic [181, 194]. The overview control of PSC is shown in Fig. 3. The phase angle controlled the active power and the alternating voltage, while the magnitude of the voltage source converter is controlled by the multivariable controller [183]. In PSC, a single integration of the power difference is used to obtain the phase angle directly using PSC loop, instead of the double integration for $p - \theta$ transfer function in VSM, this makes PSC to be more robust with higher stability margin for GFM inverter. As a result of the limited number of integrator, PSC has a higher stability margin even in the presence of a very weak grid [8, 195]. Virtual inertia can be added by emulating the swing equation of a SG depicted by Eq. (4) and the power synchronization control law for voltage source converters is obtained using Eq. (5):

$$P_m - P_e = J\omega_0\frac{d\Delta\omega}{dt} + D\omega_0\Delta\omega, \qquad \frac{d\Delta\theta}{dt} = \Delta\omega \qquad (4)$$

$$\frac{d\Delta\theta}{dt} = k_p\left(P_{ref} - P\right) \qquad (5)$$

$$P = P_{ref} + \frac{1}{K_p}\left(\omega_1 - \omega_g\right) \qquad (6)$$

Where ω_1 is considered as the nominal angular synchronous frequency, $\omega_g = \frac{d\Delta\theta}{dt}$ is local instantaneous angular frequency (during faults or disturbances ω_g may differ from ω_1). PSC inherently adds a frequency drop, with droop gain$\left(\frac{1}{K_p}\right)$ to the active-control reference (P_{ref}), P denotes VSC measured active power output, $\Delta\theta$ is the output of the controller and the active-power controller gain is denoted by k_p.

The power transmitted is increased or decreased by adjusting the output voltage phasor of the voltage source converters forward or backward [185]:

$$v_C^* = (V_0 + \Delta V) - H_{HP}(s)i_C \qquad (7)$$

$$H_{HP}(s) = \frac{k_v s}{s + \alpha_v} \qquad (8)$$

$$i_C^* = \frac{1}{\alpha L_f}\left[(V_0 + \Delta V) - v_f - j\omega_0 L_f i_C - H_{HP}(s)i_C\right] + i_C \qquad (9)$$

$$v_C^* = \alpha L_f(i_C^* - i_C) + j\omega_0 L_f i_C + v_f \qquad (10)$$

Voltage is regulated by Eq. (7), here AC voltage-controller (AVC) is utilized which corresponds to the exciter of SGs, except for the integral control in alternative of the typical PI controller to quash high-frequency disturbances, as depicted by Fig. 3. High-pass filter ($H_{HP}(s)$) is given by Eq. 8, for active damping of the GFM frequency resonant poles in the current reference-generating block, modelled in Eq. (9). The current reference-generated in (9) is used to limit overcurrent in the current limitation controller (CLC) during faults condition. A standard dq current controller as given in Eq. (10) is used to tune a set of bandwidth of $\alpha\, rads^{-1}$. PSC demonstrates strong and excellent performance in an ultra-weak grid.

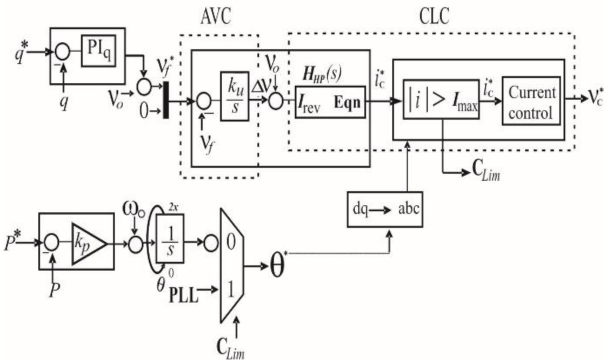


Fig.3. Block structure of Power-synchronization control [8].

3.3 Direct Power Controller

Direct power controller (DPC) technique was first proposed and implemented on three-phase pulse width modulation (PWM) rectifiers based on the change in desired power and the angular position of the grid-voltage [196-199]. The concept of this control technique is based on the principles of direct torque control approach in electrical machines [200-203]. DPC regulates VSC unit during normal operation by controlling its internal angle and amplitude. A current controller is used in DPC to limit overcurrent during fault conditions by shifting its operation to current limiting mode.

In recent decades, DPC has experienced diverse improvement and has been transformed to enhance the capability and efficiency through the use of advanced non-linear controllers [204]. Among these predominant non-linear controllers are; space vector modulation (SPM) for constant switching frequency, synthetic switching pulses, harmonic and voltage dip compensations [205-210], model predictive control for the multivariable [211-214], fuzzy logic controller [215-217], backstepping control [218-220], deadbeat controller [221-224], and sliding mode controller for robustness [225, 226]. It has been extensively researched and applied on two-level inverters [196, 227], multilevel converters [228-230], control of DFIG-based wind turbine[231-235] and grid-side interface of photovoltaic [236-238]. The major drawback confronting the conventional DPC is the variable switching frequency resulting from hysteresis comparator and can be adequately compensated by the aforementioned non-linear controllers. DPC control active and reactive power in a grid-connected inverter, in the same manner, is adopted on induction machine for the control of torque and flux. The controller's instantaneous active and reactive power errors (ΔP and ΔQ) are controlled without any need for ac voltage sensor, PLLs or an inner current controller, but by means of a look-up table and hysteresis comparators for optimal selection of inverter switching state [8]. Fig. 4. shows principle of operation of DPC for two-level inverters. The comparators output with grid voltage angle serves as the input for the optimal switching table where one among the six possible inverter voltage vectors is chosen without applying zero voltage vectors. The inverter switching patterns stays until the algorithm calculate the next time step of the inverter voltage vector as shown in Fig. 5.

DPC is implemented for grid-forming inverter where voltage reference is given instead of the voltage magnitude of the grid, and a virtual phase angle is utilized instead of phase-locked loop-generated voltage phase angle. The powers (active and reactive) proportional to d-axis and q-axis components of the DPC control inverter output current (i_d, i_q) are obtained using equations (11) and (12):

$$P_s = v_d i_d \tag{11}$$

$$Q_s = -v_d i_q \tag{12}$$

The current variation $\Delta\bar{\imath}$ is obtained from the system voltage equation (inverter, RL filter and grid) expressed as:

$$L\frac{\bar{d}_i}{dt} + R\bar{\imath} = \bar{v}_{inv} - \bar{v}_g \tag{13}$$

Where $\bar{v}_{inv}$,$\bar{v}_g$ and $\bar{v}_{inv}$ are the inverter voltage-vector, grid voltage, and switching states (S_a, $S_b, and\ S_c$) of the inverter (2^3- resulting in eight possible application vectors, six active vectors and two zero vectors).

$$\Delta\bar{\imath} \approx \frac{1}{L}\int_0^{T_s}\left(\bar{v}_{inv}(S_a, S_b, S_c) - \bar{v}_g\right)dt \tag{14}$$

Where T_s is the time step of the DPC algorithm. The detailed mathematical modelling of DPC VSC grid-connected control technique is presented in [239]. Although DPC control technique is a robust and powerful approach for pulse width modulation rectifier, it is confronted with high power ripples and variable switching frequency, which needs to be improved for more efficiency by using the advanced non-linear controllers. Other forms of GFM control schemes are: droop-based control (angle and frequency-based) [240-247], virtual oscillator-based control [248-254], H_∞/H_2 based control [109, 255, 256], and distributed phase-locked-loop (dPLL) controls [257]. Fig. 6 shows the Grid-forming control schemes.

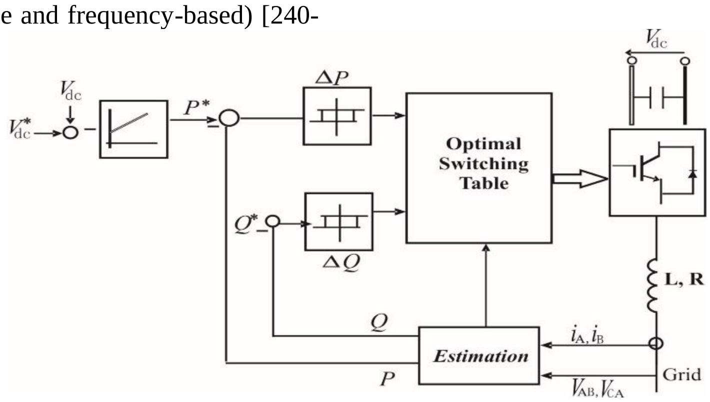


Fig. 4. Principle of operation of DPC for two-level inverters [239].

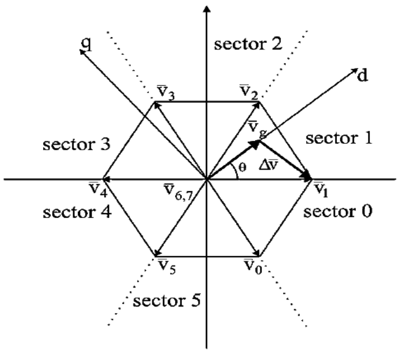
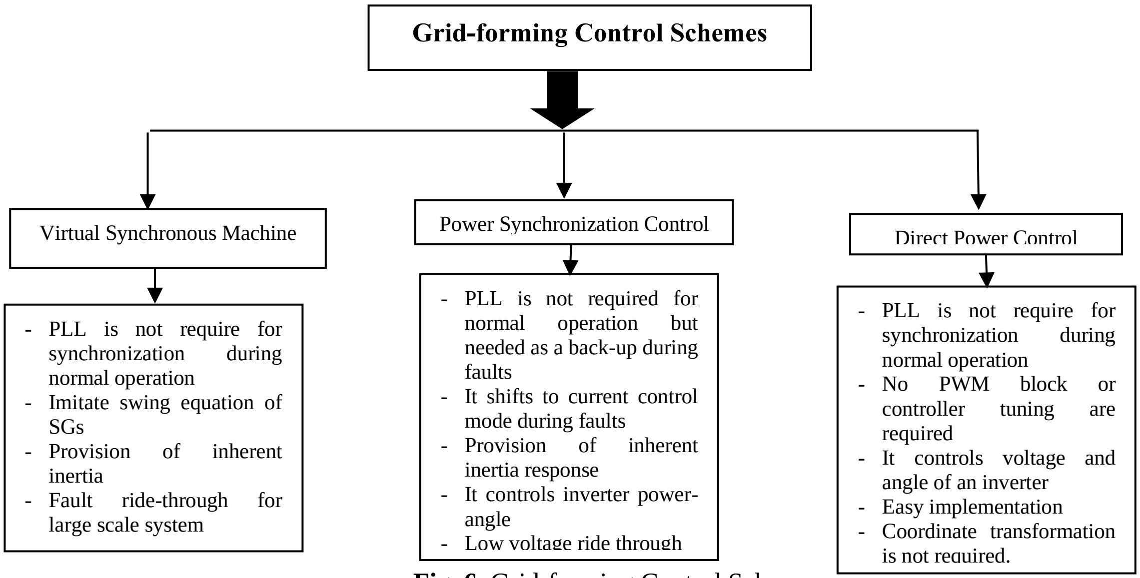


Fig. 5. Two-level inverter voltage vectors [239].



Grid-forming Control Schemes

Virtual Synchronous Machine

- PLL is not require for synchronization during normal operation
- Imitate swing equation of SGs
- Provision of inherent inertia
- Fault ride-through for large scale system

Power Synchronization Control

- PLL is not required for normal operation but needed as a back-up during faults
- It shifts to current control mode during faults
- Provision of inherent inertia response
- It controls inverter power-angle
- Low voltage ride through

Direct Power Control

- PLL is not require for synchronization during normal operation
- No PWM block or controller tuning are required
- It controls voltage and angle of an inverter
- Easy implementation
- Coordinate transformation is not required.

Fig. 6. Grid-forming Control Schemes.

Table 1. Summary of Previous Control Schemes of Grid-connected Inverters Reviews.

Author	Year	Main consideration	Implementation	Control Mechanism	Remarks
[258]	2022	- Fault ride through capability - Transient phase angle response	Three-phase symmetric faults on a grid-connected wind turbine	VSM, PSC and Distributed PLLs	The VSM, PSC and Distributed PLLs GFM control scheme were compared on a 3-phase grid-connected wind turbine during symmetric faults
[259]	2021	- Elimination of third-order harmonic - Grid-synchronization	Simulation on a 3-kW/3-phase /120V	Virtual oscillator control (VOC)	The proposed VOC was realized by remodelling the traditional VOC non-linear current source cubic function.
[260]	2021	- Adaptive grid-forming - Active power filter - Total harmonic distortion	Experimental simulation of grid-connected PV system	Fuzzy gain tuning PI-derivative (FTPID) controller	FTPID-IFONF control scheme was used for GFM to produce an equivalent pulses for seamless PV to grid interface
[46]	2020	- Ancillary services like reactive grid support, virtual inertia and current harmonic compensation system	15kVA grid-connected inverter	Simplified virtual synchronous compensator (S-VSC)	Provision of ancillary services such as current harmonic compensation, reactive grid support and virtual inertia injection.
[261]	2020	- Stabilization of weak grid - Lyapunov stability criterion to adaptively change cross-coupling current - Dynamic response of the inverter to weak grid scenarios	Simulation of 90V rms 3-phas source for grid and 240V idea DC source from inverter	Direct Model reference adaptive control	DMRAC was used to tune the gain cross-coupling current when the inverter is operating non-unit power factor
[121]	2020	- Current limiting control - Power system stability - Nonlinear damping assignment	PV simulation	Hybrid angle control (HAC)	The HAC was developed based on the complementary advantages of droop control and dispatchable virtual oscillator control
[99]	2020	- Harmonic current suppression - Impedance shaping - Small signal model	Laboratory inverter prototype	Virtual oscillator control (VOC)	VOC is a time-domain controller that allows VSC to imitate the dynamic of limit-layer oscillators
[262]	2020	- Voltage/current *dq*-frame cross decoupling - Frequency domain spectrum - Power system stability	Simulation and hardware experiments	Virtual impedance	The proposed tools visualize control loops of power converts and thereof provide intuitive impedance modelling framework
[55]	2019	- Frequency stability - Rate of change of frequency - Battery life management	Kundur two-area system	Swing equation-based VSM	VSM is used to reduce ROCOF
[114]	2019	- Reference tracking performance - Load-rejection capability - Passive output performance	Simulated on 3-phase, three wire inverter with nonlinear load and also validated with hardware-in-the-loop (HIL)	Passivity-oriented discreet-time voltage controller	Discreet-time complex variable resonant controller (DCVRC) was implemented to remove steady-state errors

[101]	2019	- System stability - Current limiting capability - Power sharing ability of GFM - Unbalanced grid condition	Experimental simulation of PV to grid-connected and HIL	Photovoltaic synchronous generator (PVSG)	This grid-forming inverter inject inertia to the system based on the mechanical properties of SGs
[115]	2019	- Reduced-order modelling - Coherency-based aggregation - Droop control	Controller hardware-in-the loop (C-HiL) testbed and a 30-inverter network	Generalized Eigenvalue Perturbation (GEP)	GEP algorithm can accurately replicate grid's response in the aftermath of large fault condition.
[116]	2019	- Multi-parallel GFM - Islanded microgrid - Power sharing - Network stability	NI-PXI-based real-time simulation Platform and 4-parallel connected DG	Filtered tracking error technique	The technique achieved a superior point of common coupling voltage regulation and power sharing performance.
[119]	2019	- Photovoltaic Synchronous Generator (PVSG) - Supercapacitor ESS - AC system stability	Experimentally simulated on a 480V PVSG prototype with TMS320F28379D DSP controller	Photovoltaic Synchronous Generator (PVSG)	Transformation of existing of existing PV system from a GFL to GFM without additional modification to the PV inverter
[120]	2019	- Stand-alone microgrid - System stability - Uncertainties in RESs - PV, wind turbine and ESS	Experimental test using a dSPACE 107 rapid prototyping system	Interconnection and damping assignment passivity-based controller (IDA-PBC)	IDA-PBC was based on Hamiltonian modelling for energy function minimization that ensures a stable and robust control of the system in a closed-loop
[263]	2018	- VSM controller using Linear-quadratic regulator - Adaptive control - Swing equation.	3-area test system	Linear-quadratic regulator	LQR adaptively regulates inertia and damping constants according to the disturbance frequency while preserving the critical frequency limits
[43]	2018	- Reactive power control for grid-feeding, grid-support and grid forming - Harmonic distortion - Frequency stability	Three DG; grid-feeding, grid-support and grid forming	Differential evolution algorithm (DEA)	The MGs is made up of three DG; grid-feeding, grid-support and grid forming
[84]	2018	- Transient stability - Resiliency enhancement through Grid-support	Two-stage PV system	Enhance Virtual synchronous machine (eVSM)	This model used physical dc-link capacitor dynamics for inertia response instead of depending on battery storage
[111]	2018	- Incremental passivity - Droop control - Power-sharing capability	Numerical case study	VSM	Additional control loop; disturbance-decoupling and droop techniques were adopted to control the inverter voltage and frequency amplitude.
[264]	2017	- Frequency control - Dynamic grid support	IEEE 39-bus with embedded hybrid energy storage system and PV unit	A novel voltage-frequency control (*v-f*)	Simultaneous primary frequency and dynamic grip support are achieved
[117]	2017	- Unbalanced load - Synchronous rotating frame - Network stability	Numerical simulation	Linear quadratic regulator (LQR)	LQR comprises of a state-feedback and integral compensator replacing the traditional cascaded

					voltage and current loop controllers
[110]	2017	- Frequency control - Supercapacitor energy storage system - Dynamic response stability	Simulation and experimental on a laboratory scale MG based on 3-parallel inverter	VSG along with supercapacitor (SC)-based energy storage system (ESS).	This VSG control concept provides support only in transitory regime
[108]	2016	- Voltage decoupling feedforward path - Pulse with modulation - Voltage feedforward decoupling path	Three-phase four-leg grid-forming unit	PI tuned with voltage decoupling feedforward path	When compared PI tuned with feedforward path with conventional PI, the former outperforms the latter
[109]	2016	- Damping mechanism - Nested loop control - Sliding mode control	The simulation and hardware experiments	The inner current and outer voltage controllers are the Sliding mode control (SMC) and a mixed H_2/H_∞ optimal control	The results demonstrated that the proposed model performs satisfactorily well in terms of transient stability over PI-based nested-loop control scheme
[265]	2015	- Grid fault scenario - Mathematical modelling of synchronous generators - Hybrid grid and MGs	Real-time simulation of wind-turbine and back-to-back converter with grid	Synchronverter technology	Synchronverter mimics a synchronous generators by using mathematical equivalent
[78]	2013	- Energy management - Harmonic reduction - MGs grid-connected and Islanded mode - Voltage stability	Experimental simulation of two-inverter with operation in grid-connected and islanded mode	VSG model of Algebraic type	This inverter controller technique controls current in *d-q* coordinate.
[51]	2007	- Interconnection of RESs (Wind and PV) to weak grid - Network stability issues	Experimental setup comprise wind turbine, PV integrated with grid	Virtual synchronous machine (VISMA)	VISMA supports the weak grid by behaving similar to the electromechanical synchronous machine

4. BENEFITS AND CHALLENGES OF GFM

4.1 Benefits

In recent years, the benefits of RESs have gained considerable attention of academia and the industry, because of the environmental and socio-economic benefits it offers. The continuous growth of RESs is indeed creating a balance between environmental, economic and innovative technologies [266-271]. The novel GFM approach has come with manifold of benefits such as environmental sustainability (reducing the greenhouse gas emission), increase in fuel diversity (reduce over dependence on oil demand), reduction of grid losses, wildlife preservation (biodiversity conservation), aesthetics impact (offers tourism) and national economic security (increase of economic productivity, since manufacturing output is elastic to changes in electricity supply) [272-274].

Additionally, GFM offers developmental benefits such as rural electrification, seamless RESs to grid interface, provision of local job, decrease in cost of energy production, development of a considerable technological innovation and stability of economy [275-281]. It can standalone and/or grid-connected in actual power system containing conventional synchronous machines to provide a secure electricity. Thus, it has been identified that stable and quality energy is the exchangeable currency of a cutting-edge technology, because without it the whole fabric of society and economy will crumble, so the benefits it offers cannot be overemphasized.

4.2. Challenges

The increase in the popularity of IBPS penetration close to 100% of non-synchronous generation sources adds some technical challenges to the grid. The challenges related to massive integration of inverter-based power system are:

(i) Rising RoCoF (Rate of Change of Frequency).

(ii) Loss of synchronising (torque/power and reference voltage) during severe faults condition.

(iii) Power system integrity, quality and reliability could be compromised.

(iv) High sensitivity to load imbalances and harmonics.

(v) Voltage instability may arise during or post fault conditions.
(vi) Degradation of frequency stability reflects change in voltage angle as a result of changes in power flow.
(vii) There is likelihood of sub-synchronous oscillations and interference with conventional machines and overcurrent protection devices.
(viii) Challenges in modelling of electricity system and RMS.
(ix) Exhibit limited overloading capability (due to the resources intermittency).
(x) Stability issues in case of a low short circuit ratio (SCR).

5. FUTURE TRENDS IN GFM

With the growing popularity of Inverter Based Power Systems such as wind and solar, shows that the future power grid will be dominated by power electronics converters, thereby reducing the share of conventional fossil-fuel-based power generation, and, unavoidably decreasing the amount of rotational inertia and short-circuit contribution of the system. In the event of this occurrence in the system, the grid become more vulnerable to large power swing, frequency instability, harmonic resonance and raising the rate-of-change-of-frequency (RoCoF) level in case of grid disturbances. Also, VSC GFM working in a voltage control mode is vulnerable during overload condition. For this singular reason, the output currents of a VSC are usually limited to 125% of its nominal value in order to protect power electronic switches of the inverter under overload condition. A typical VSC generates distorted voltage and current under asymmetrical and symmetrical short-circuit faults. This behaviour along with other related power quality standards such as IEEE standard 1547 and E.ON grid Code require disconnection of the VSC when a short-circuit occurs in the system. This is an undesirable characteristic in the VSC-IBPS, which are exposed to many asymmetrical short circuit faults. A robust converter control scheme to solve this upstream grid instability is required.

Additional features are also required to the efficient GFM performance:

- reinforce VSC-GFM fault ride-through capability and power quality at the Point of common coupling
- black-start capability
- Power system impedance estimation and islanding detection technique
- management and control of energy storage system.

These new features will enable a more sustainable, intelligence and flexible GFM integration to DG and RESs into the future smart grid.

6. CONCLUSION

A state-of-the-art review on advance control techniques for grid to inverter-based power system interface is discussed in this paper. Diverse of formulation, criteria and models for grid-forming control schemes have been presented. The structural and functional differences between grid-feeding, grid-supporting, and grid-forming are also highlighted. Conventional power inverter extracts/draws maximum power from its sources and delivers it irrespective of the voltage magnitude or power flow to the upstream grid. Conversely, in this contemporary grid with massive penetration of RESs leading towards a climate sustainability and decarbonization, inverter-based power system are expected to perform more ancillary services in order to ensure a robust RESs to grid interface. Attaining 100% non-synchronous power generation and huge transmission system, requires incorporation of new features to the control schemes for a more robust and seamless integration of GFM into the future smart grid. The traditional inverters which are presently controlled in a grid-following mode cannot offer the needed control in this current era. Thus, it is essential to develop the next-generation inverter-based infrastructure that can operate autonomously, capable of grid control from weak grid to stronger grid and provides ancillary support services to the grid. These have brought a new concept of a grid-connected inverter known as grid-forming. Various in-depth studies on GFM control schemes with diverse nomenclatures and practical implementation that is based on the concept of virtual synchronous machine, power synchronization control, and direct power control have been discussed. The paper identifies inertia-based emulated control techniques as the most widely used GFM control method in ultra-weak and low-inertia grids. The review covers grid-forming control schemes, benefits and challenges of attaining 100% non-synchronous power generation. The survey establishes state-of-the-art in the grid to RESs interface and identified future research gaps.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGEMENTS

The authors thank the School of Postgraduate Studies, Ahmadu Bello University Zaria, Nigeria and the Lecturers of the Department of Electrical & Electronics Engineering for their advice and support.

NOMENCLATURE

ADMM	Alternating direction method of multipliers
BESS	Battery Energy Storage System
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DPC	Direct Power Control
EVSM	Enhanced Virtual Synchronous Machine
GFI	Grid Feeding Inverter
GFL	Grid-Following Inverter
GFM	Grid-Forming Inverter
GHG	Greenhouse Gas
GSI	Grid Supporting Inverter
HAC	Hybrid Angle Control
HEP	Hydroelectric Power
HVDC	High Voltage Direct Current
IBPS	Inverter-Based Power System
IFONF	Improved Fractional Order Notch Filter
LQR	Linear Quadratic Regulator
MG	Microgrid
MPC	Model Predictive Control
NMG	Networked Microgrid
PBC	Passivity-Based Controller
PCC	Point of Common Coupling
PI	Proportional Integral
PLL	Phase Locked Loop
PSC	Power Synchronization Controller
PV	Photovoltaic
PWM	Pulse Width Modulation
RESs	Renewable Energy Sources
RoCoF	Rate of Change of Frequency
SRF	Synchronous Reference Frame
SVM	Space Vector Modulation.
VCI	Voltage-Controlled Inverter
VOC	Virtual Oscillator Control
VSC	Voltage Source Inverter
VSM	Virtual Synchronous Machine

REFERENCES

[1] Yoldaş, Y., et al., *Enhancing smart grid with microgrids: Challenges and opportunities.* Renewable and Sustainable Energy Reviews, 2017. **72**: p. 205-214.

[2] Yusuf, S.S., et al., *Transmission Line Capacity Enhancement with Unified Power Flow Controller Considering Loadability Analysis.* ELEKTRIKA-Journal of Electrical Engineering, 2019. **18**(3): p. 8-12.

[3] Sampaio, P.G.V. and M.O.A. González, *Photovoltaic solar energy: Conceptual framework.* Renewable and Sustainable Energy Reviews, 2017. **74**: p. 590-601.

[4] Anand, S., S.K. Gundlapalli, and B. Fernandes, *Transformer-less grid feeding current source inverter for solar photovoltaic system.* IEEE Transactions on Industrial Electronics, 2014. **61**(10): p. 5334-5344.

[5] Yusuf, S.S., et al., *Load-ability Analysis during Contingency with Unified Power Flow Controller Using Grey Wolf Optimization Technique.* Covenant Journal of Engineering Technology (CJET), 2020. **4**(2).

[6] Al-Shetwi, A.Q., et al., *Grid-connected renewable energy sources: Review of the recent integration requirements and control methods.* Journal of Cleaner Production, 2020. **253**: p. 119831.

[7] Şahin, A.D., *Progress and recent trends in wind energy.* Progress in energy and combustion science, 2004. **30**(5): p. 501-543.

[8] Jain, A., J.N. Sakamuri, and N.A. Cutululis, *Grid-forming control strategies for black start by offshore wind power plants.* Wind Energy Science, 2020. **5**(4): p. 1297-1313.

[9] Rathore, N.S. and N. Panwar, *Renewable energy sources for sustainable development*. 2007: New India Publishing.

[10] Østergaard, P.A., et al., *Sustainable development using renewable energy technology*. 2020, Elsevier.

[11] Malek, A.B.M.A., M. Hasanuzzaman, and N. Abd Rahim, *Prospects, progress, challenges and policies for clean power generation from biomass resources.* Clean Technologies and Environmental Policy, 2020. **22**(6): p. 1229-1253.

[12] Blaabjerg, F., et al., *Overview of control and grid synchronization for distributed power generation systems.* IEEE Transactions on industrial electronics, 2006. **53**(5): p. 1398-1409.

[13] Benedek, J., T.-T. Sebestyén, and B. Bartók, *Evaluation of renewable energy sources in peripheral areas and renewable energy-based rural development.* Renewable and Sustainable Energy Reviews, 2018. **90**: p. 516-535.

[14] Sinsel, S.R., R.L. Riemke, and V.H. Hoffmann, *Challenges and solution technologies for the integration of variable renewable energy sources—a review.* renewable energy, 2020. **145**: p. 2271-2285.

[15] Caduff, I., et al., *Reduced-order modeling of inverter-based generation using hybrid singular perturbation.* Electric Power Systems Research, 2021. **190**: p. 106773.

[16] Sansaniwal, S.K., V. Sharma, and J. Mathur, *Energy and exergy analyses of various typical solar energy applications: A comprehensive review.* Renewable and Sustainable Energy Reviews, 2018. **82**: p. 1576-1601.

[17] Markovic, U., et al., *Impact of inverter-based generation on islanding detection schemes in distribution networks.* Electric Power Systems Research, 2021. **190**: p. 106610.

[18] Hassaine, L., et al., *Overview of power inverter topologies and control structures for grid connected photovoltaic systems.* Renewable and

Sustainable Energy Reviews, 2014. **30**: p. 796-807.

[19] Hirsch, A., Y. Parag, and J. Guerrero, *Microgrids: A review of technologies, key drivers, and outstanding issues.* Renewable and Sustainable Energy Reviews, 2018. **90**: p. 402-411.

[20] Qazi, A., et al., *Towards sustainable energy: a systematic review of renewable energy sources, technologies, and public opinions.* IEEE Access, 2019. **7**: p. 63837-63851.

[21] El-Khattam, W., et al., *Optimal investment planning for distributed generation in a competitive electricity market.* IEEE Transactions on power systems, 2004. **19**(3): p. 1674-1684.

[22] Hatziargyriou, N., et al., *Microgrids.* IEEE power and energy magazine, 2007. **5**(4): p. 78-94.

[23] Ameli, A., et al., *A multiobjective particle swarm optimization for sizing and placement of DGs from DG owner's and distribution company's viewpoints.* IEEE Transactions on power delivery, 2014. **29**(4): p. 1831-1840.

[24] Parihar, S.S. and N. Malik, *Optimal integration of multi-type DG in RDS based on novel voltage stability index with future load growth.* Evolving Systems, 2020: p. 1-15.

[25] Cheema, K.M., *A comprehensive review of virtual synchronous generator.* International Journal of Electrical Power & Energy Systems, 2020. **120**: p. 106006.

[26] Hartmann, B., I. Vokony, and I. Táczi, *Effects of decreasing synchronous inertia on power system dynamics—Overview of recent experiences and marketisation of services.* International Transactions on Electrical Energy Systems, 2019. **29**(12): p. e12128.

[27] Lasseter, R.H., *Smart distribution: Coupled microgrids.* Proceedings of the IEEE, 2011. **99**(6): p. 1074-1082.

[28] HassanzadehFard, H. and A. Jalilian, *Optimization of DG units in distribution systems for voltage sag minimization considering various load types.* Iranian Journal of Science and Technology, Transactions of Electrical Engineering, 2021. **45**(2): p. 685-699.

[29] Lasseter, R.H. *Microgrids*. in *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 02CH37309)*. 2002. IEEE.

[30] Ren, L., et al., *Enabling resilient distributed power sharing in networked microgrids through software defined networking.* Applied Energy, 2018. **210**: p. 1251-1265.

[31] Han, Y., et al., *Review of power sharing, voltage restoration and stabilization techniques in hierarchical controlled DC microgrids.* IEEE Access, 2019. **7**: p. 149202-149223.

[32] Vasquez, J.C., et al., *Hierarchical control of intelligent microgrids.* IEEE Industrial Electronics Magazine, 2010. **4**(4): p. 23-29.

[33] Bidram, A. and A. Davoudi, *Hierarchical structure of microgrids control system.* IEEE Transactions on Smart Grid, 2012. **3**(4): p. 1963-1976.

[34] Alam, M.N., S. Chakrabarti, and A. Ghosh, *Networked microgrids: State-of-the-art and future perspectives.* IEEE Transactions on Industrial Informatics, 2018. **15**(3): p. 1238-1250.

[35] Li, Z., et al., *Networked microgrids for enhancing the power system resilience.* Proceedings of the IEEE, 2017. **105**(7): p. 1289-1310.

[36] Shahidehpour, M., et al., *Networked microgrids: Exploring the possibilities of the IIT-Bronzeville grid.* IEEE Power and Energy Magazine, 2017. **15**(4): p. 63-71.

[37] Lissandron, S., et al., *Experimental validation for impedance-based small-signal stability analysis of single-phase interconnected power systems with grid-feeding inverters.* IEEE Journal of Emerging and Selected Topics in Power Electronics, 2015. **4**(1): p. 103-115.

[38] Groß, D. and F. Dörfler. *Projected grid-forming control for current-limiting of power converters*. in *2019 57th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*. 2019. IEEE.

[39] Lliuyacc, R., et al., *Grid-forming VSC control in four-wire systems with unbalanced nonlinear loads.* Electric Power Systems Research, 2017. **152**: p. 249-256.

[40] Ramasubramanian, D., et al., *Operation paradigm of an all converter interfaced generation bulk power system.* IET Generation, Transmission & Distribution, 2018. **12**(19): p. 4240-4248.

[41] Castilla, M., L.G. de Vicuña, and J. Miret, *Control of power converters in AC microgrids*, in *Microgrids design and implementation*. 2019, Springer. p. 139-170.

[42] Choi, W., et al. *Reviews on grid-connected inverter, utility-scaled battery energy storage system, and vehicle-to-grid application-challenges and opportunities*. in *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*. 2017. IEEE.

[43] Zhang, D. and J. Fletcher. *Operation of autonomous AC microgrid at constant frequency and with reactive power generation from grid-forming, grid-supporting and grid-feeding generators*. in *TENCON 2018-2018 IEEE Region 10 Conference*. 2018. IEEE.

[44] Zarei, S.F., et al., *Reinforcing fault ride through capability of grid forming voltage source converters using an enhanced voltage control scheme.* IEEE Transactions on Power Delivery, 2018. **34**(5): p. 1827-1842.

[45] Reichert, S., G. Griepentrog, and B. Stickan. *Comparison between grid-feeding and grid-supporting inverters regarding power quality*. in *2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*. 2017. IEEE.

[46] Mandrile, F., E. Carpaneto, and R. Bojoi, *Grid-Feeding Inverter With Simplified Virtual Synchronous Compensator Providing Grid Services and Grid Support.* IEEE Transactions on Industry Applications, 2020. **57**(1): p. 559-569.

[47] Liu, Q., T. Caldognetto, and S. Buso, *Review and comparison of grid-tied inverter controllers in microgrids.* IEEE Transactions on Power Electronics, 2019. **35**(7): p. 7624-7639.

[48] Denis, G., et al., *The Migrate project: the challenges of operating a transmission grid with only inverter-based generation. A grid-forming control improvement with transient current-limiting control.* IET Renewable Power Generation, 2018. **12**(5): p. 523-529.

[49] Du, W., et al., *Modeling of Grid-Forming and Grid-Following Inverters for Dynamic Simulation of Large-Scale Distribution Systems.* IEEE Transactions on Power Delivery, 2020.

[50] Matevosyan, J., et al., *Grid-forming inverters: Are they the key for high renewable penetration?* IEEE Power and Energy magazine, 2019. **17**(6): p. 89-98.

[51] Beck, H.-P. and R. Hesse. *Virtual synchronous machine*. in *2007 9th International Conference on Electrical Power Quality and Utilisation*. 2007. IEEE.

[52] Ierna, R., et al. *Effects of VSM convertor control on penetration limits of non-synchronous generation in the GB power system*. in *15th Wind Integration Workshop*. 2016.

[53] Colombino, M., et al., *Global phase and magnitude synchronization of coupled oscillators with application to the control of grid-forming power inverters.* IEEE Transactions on Automatic Control, 2019. **64**(11): p. 4496-4511.

[54] Crivellaro, A., et al. *Beyond low-inertia systems: Massive integration of grid-forming power converters in transmission grids*. in *2020 IEEE Power & Energy Society General Meeting (PESGM)*. 2020. IEEE.

[55] Sundaramoorthy, K., et al., *Virtual synchronous machine-controlled grid-connected power electronic converter as a ROCOF control device for power system applications.* Electrical Engineering, 2019. **101**(3): p. 983-993.

[56] Pertl, M., et al., *Transient stability improvement: a review and comparison of conventional and renewable-based techniques for preventive and emergency control.* Electrical Engineering, 2018. **100**(3): p. 1701-1718.

[57] Strzelecki, R. and G.S. Zinoviev, *Overview of power electronics converters and controls*, in *Power Electronics in Smart Electrical Energy Networks*. 2008, Springer. p. 55-105.

[58] Mohan, N., T.M. Undeland, and W.P. Robbins, *Power electronics: converters, applications, and design*. 2003: John wiley & sons.

[59] Zhu, Z. and J. Hu, *Electrical machines and power‐electronic systems for high‐power wind energy generation applications: Part II–power electronics and control systems.* COMPEL-The international journal for computation and mathematics in electrical and electronic engineering, 2013.

[60] Kenyon, R.W., et al., *Stability and control of power systems with high penetrations of inverter-based resources: An accessible review of current knowledge and open questions.* Solar Energy, 2020. **210**: p. 149-168.

[61] Zhang, G., et al., *Power electronics converters: Past, present and future.* Renewable and Sustainable Energy Reviews, 2018. **81**: p. 2028-2044.

[62] Viinamäki, J., A. Kuperman, and T. Suntio, *Grid-forming-mode operation of boost-power-stage converter in PV-generator-interfacing applications.* Energies, 2017. **10**(7): p. 1033.

[63] Kroposki, B., et al., *Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy.* IEEE Power and energy magazine, 2017. **15**(2): p. 61-73.

[64] Pattabiraman, D., R. Lasseter, and T. Jahns. *Comparison of grid following and grid forming control for a high inverter penetration power system*. in *2018 IEEE Power & Energy Society General Meeting (PESGM)*. 2018. IEEE.

[65] Denis, G., et al. *Improving robustness against grid stiffness, with internal control of an AC voltage-controlled VSC*. in *2016 IEEE Power and Energy Society General Meeting (PESGM)*. 2016. IEEE.

[66] Lasseter, R.H., Z. Chen, and D. Pattabiraman, *Grid-forming inverters: A critical asset for the power grid.* IEEE Journal of Emerging and Selected Topics in Power Electronics, 2019. **8**(2): p. 925-935.

[67] Hsieh, G.-C. and J.C. Hung, *Phase-locked loop techniques. A survey.* IEEE Transactions on industrial electronics, 1996. **43**(6): p. 609-615.

[68] Chung, S.-K., *Phase-locked loop for grid-connected three-phase power conversion systems.* IEE Proceedings-Electric Power Applications, 2000. **147**(3): p. 213-219.

[69] Perera B.K., P. Ciufo, and S. Perera. *Point of common coupling (PCC) voltage control of a grid-connected solar photovoltaic (PV) system*. in *IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society*. 2013. IEEE.

[70] Liu, J., Y. Miura, and T. Ise, *Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators.* IEEE Transactions on Power Electronics, 2015. **31**(5): p. 3600-3611.

[71] Pan, D., et al., *Transient stability of voltage-source converters with grid-forming control: A design-oriented study.* IEEE Journal of Emerging and Selected Topics in Power Electronics, 2019. **8**(2): p. 1019-1033.

[72] Rosso, R., S. Engelken, and M. Liserre, *Robust stability investigation of the interactions among grid-forming and grid-following converters.* IEEE Journal of Emerging and Selected Topics in Power Electronics, 2019. **8**(2): p. 991-1003.

[73] Adib, A., F. Fateh, and B. Mirafzal. *A stabilizer for inverters operating in grid-feeding, grid-supporting and grid-forming modes*. in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*. 2019. IEEE.

[74] Driesen, J. and K. Visscher. *Virtual synchronous generators*. in *2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century*. 2008. IEEE.

[75] Elkhatib, M.E., W. Du, and R.H. Lasseter. *Evaluation of inverter-based grid frequency support using frequency-watt and grid-forming PV inverters*. in *2018 IEEE Power & Energy Society General Meeting (PESGM)*. 2018. IEEE.

[76] Sao, C.K. and P.W. Lehn, *Control and power management of converter fed microgrids.* IEEE Transactions on Power Systems, 2008. **23**(3): p. 1088-1098.

[77] Chen, Y., et al., *Dynamic properties of the virtual synchronous machine (VISMA).* Proc. ICREPQ, 2011. **11**.

[78] Hirase, Y., et al., *A grid‐connected inverter with virtual synchronous generator model of algebraic type.* Electrical Engineering in Japan, 2013. **184**(4): p. 10-21.

[79] Bouzid, A.M., et al. *Structured H∞ design method of PI controller for grid feeding connected voltage source inverter*. in *2015 3rd International Conference on Control, Engineering & Information Technology (CEIT)*. 2015. IEEE.

[80] Borrell, A., et al., *Collaborative Voltage Unbalance Elimination in Grid-Connected AC Microgrids with Grid-Feeding Inverters.* IEEE Transactions on Power Electronics, 2020.

[81] Zhong, Q.-C. and G. Weiss, *Synchronverters: Inverters that mimic synchronous generators.* IEEE transactions on industrial electronics, 2010. **58**(4): p. 1259-1267.

[82] Zhong, Q.-C., et al., *Self-synchronized synchronverters: Inverters without a dedicated synchronization unit.* IEEE Transactions on power electronics, 2013. **29**(2): p. 617-630.

[83] Rocabert, J., et al., *Control of power converters in AC microgrids.* IEEE transactions on power electronics, 2012. **27**(11): p. 4734-4749.

[84] Khajehoddin, S.A., M. Karimi-Ghartemani, and M. Ebrahimi, *Grid-supporting inverters with improved dynamics.* IEEE Transactions on Industrial Electronics, 2018. **66**(5): p. 3655-3667.

[85] Qoria, T., et al. *Tuning of cascaded controllers for robust grid-forming voltage source converter*. in *2018 Power Systems Computation Conference (PSCC)*. 2018. IEEE.

[86] 86. D’Arco, S., J.A. Suul, and O.B. Fosso, *A Virtual Synchronous Machine implementation for distributed control of power converters in SmartGrids.* Electric Power Systems Research, 2015. **122**: p. 180-197.

[87] Sakimoto, K., Y. Miura, and T. Ise. *Stabilization of a power system with a distributed generator by a Virtual Synchronous Generator function*. in *8th International Conference on Power Electronics - ECCE Asia*. 2011.

[88] Arco, S.D. and J.A. Suul. *Virtual synchronous machines — Classification of implementations and analysis of equivalence to droop controllers for microgrids*. in *2013 IEEE Grenoble Conference*. 2013.

[89] Almasalma, H., S. Claeys, and G. Deconinck, *Peer-to-peer-based integrated grid voltage support function for smart photovoltaic inverters.* Applied Energy, 2019. **239**: p. 1037-1048.

[90] Zubiaga, M., et al., *Power Capability Boundaries for an Inverter Providing Multiple Grid Support Services.* Energies, 2020. **13**(17): p. 4314.

[91] Lammert, G., et al. *Dynamic grid support in low voltage grids—fault ride-through and reactive power/voltage support during grid disturbances*. in *2014 Power Systems Computation Conference*. 2014. IEEE.

[92] European Center for Power Electronics, E., European Power Electronics and Drives Association, EPE, *Position Paper on Energy Efficiency – The Role of Power Electronics.* Available at: http://www.ecpe.org/securedl/0/1391290694/35ad20b5395221115c886f006df4d0f595ed7174/fileadmin/user upload/Public Relations/ECPEPublications/ECPEPosition Paper Energy Efficiency.pdf, 2017.

[93] Bevrani, H. and T. Hiyama, *Intelligent automatic generation control*. 2011: CRC press New York.

[94] Poolla, B.K., D. Groß, and F. Dörfler, *Placement and implementation of grid-forming and grid-following virtual inertia and fast frequency response.* IEEE Transactions on Power Systems, 2019. **34**(4): p. 3035-3046.

[95] Unruh, P., et al., *Overview on grid-forming inverter control methods.* Energies, 2020. **13**(10): p. 2589.

[96] Serban, I., *A control strategy for microgrids: Seamless transfer based on a leading inverter with supercapacitor energy storage system.* Applied Energy, 2018. **221**: p. 490-507.

[97] Jurasz, J., et al., *A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions.* Solar Energy, 2020. **195**: p. 703-724.

[98] Adaramola, M.S., *Viability of grid-connected solar PV energy system in Jos, Nigeria.* International Journal of Electrical Power & Energy Systems, 2014. **61**: p. 64-69.

[99] Awal, M., et al., *Selective harmonic current rejection for virtual oscillator controlled grid-forming voltage source converters.* IEEE Transactions on Power Electronics, 2020. **35**(8): p. 8805-8818.

[100] Rokrok, E., et al. *Effect of using PLL-based grid-forming control on active power dynamics under various SCR*. in *IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society*. 2019. IEEE.

[101] Yazdani, S., et al., *Advanced current-limiting and power-sharing control in a PV-based grid-forming inverter under unbalanced grid conditions.* IEEE Journal of Emerging and Selected Topics in Power Electronics, 2019. **8**(2): p. 1084-1096.

[102] Fang, J., H. Deng, and S.M. Goetz, *Grid impedance estimation through grid-forming power converters.* IEEE Transactions on Power Electronics, 2020. **36**(2): p. 2094-2104.

[103] Gkountaras, A., S. Dieckerhoff, and T. Sezi. *Evaluation of current limiting methods for grid forming inverters in medium voltage microgrids*. in *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*. 2015. IEEE.

[104] Mahamedi, B. and J.E. Fletcher, *The equivalent models of grid-forming inverters in the sequence domain for the steady-state analysis of power systems.* IEEE Transactions on Power Systems, 2020. **35**(4): p. 2876-2887.

[105] Jiang, Y., et al. *Grid-forming frequency shaping control for low-inertia power systems*. in *2021 American Control Conference (ACC)*. 2021. IEEE.

[106] Korai, A.W., et al., *Modelling and Simulation of Wind Turbines with Grid Forming Direct Voltage Control and Black-Start Capability*, in *Modelling and Simulation of Power Electronic Converter Dominated Power Systems in PowerFactory*. 2021, Springer. p. 245-268.

[107] Singh, M., L.A. Lopes, and N.A. Ninad, *Grid forming Battery Energy Storage System (BESS) for a highly unbalanced hybrid mini-grid.* Electric Power Systems Research, 2015. **127**: p. 126-133.

[108] Miveh, M.R., et al., *An Improved Control Strategy for a Four-Leg Grid-Forming Power Converter under Unbalanced Load Conditions.* Advances in Power Electronics, 2016.

[109] Li, Z., et al., *Control of a Grid-Forming Inverter Based on Sliding-Mode and Mixed ${H_2}/{H_\infty}$ Control.* IEEE Transactions on Industrial Electronics, 2016. **64**(5): p. 3862-3872.

[110] Serban, I. and C.P. Ion, *Microgrid control based on a grid-forming inverter operating as virtual synchronous generator with enhanced dynamic response capability.* International Journal of Electrical Power & Energy Systems, 2017. **89**: p. 94-105.

[111] Arghir, C., T. Jouini, and F. Dörfler, *Grid-forming control for power converters based on matching of synchronous machines.* Automatica, 2018. **95**: p. 273-282.

[112] Markovic, U., et al. *Partial grid forming concept for 100% inverter-based transmission systems*. in *2018 IEEE Power & Energy Society General Meeting (PESGM)*. 2018. IEEE.

[113] Qoria, T., et al., *Direct AC voltage control for grid-forming inverters.* Journal of Power Electronics, 2019. **20**(1): p. 198-211.

[114] Yu, H., et al. *Passivity-oriented discrete-time voltage controller design for grid-forming inverters*. in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*. 2019. IEEE.

[115] Hart, P.J., R.H. Lasseter, and T.M. Jahns, *Coherency identification and aggregation in grid-forming droop-controlled inverter networks.* IEEE Transactions on Industry Applications, 2019. **55**(3): p. 2219-2231.

[116] Huang, X., et al., *Decentralized control of multi-parallel grid-forming DGs in islanded microgrids for enhanced transient performance.* IEEE Access, 2019. **7**: p. 17958-17968.

[117] Oue, K., et al. *Stability Analysis of Grid-Forming Inverter in DQ Frequency Domain*. in *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*. 2019. IEEE.

[118] Watson, J., et al. *Stability of power networks with grid-forming converters*. in *2019 IEEE Milan PowerTech*. 2019. IEEE.

[119] Quan, X., et al., *Photovoltaic synchronous generator: Architecture and control strategy for a grid-forming PV energy system.* IEEE Journal of Emerging and Selected Topics in Power Electronics, 2019. **8**(2): p. 936-948.

[120] Khefifi, N., et al., *Control of grid forming inverter based on robust IDA-PBC for power quality enhancement.* Sustainable Energy, Grids and Networks, 2019. **20**: p. 100276.

[121] Tayyebi, A., A. Anta, and F. Dörfler, *Hybrid angle control and almost global stability of grid-forming power converters.* arXiv preprint arXiv:2008.07661, 2020.

[122] Rosso, R., S. Engelken, and M. Liserre. *Current limitation strategy for grid-forming converters under symmetrical and asymmetrical grid faults*. in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*. 2020. IEEE.

[123] Antunes, H.M.A., et al., *A fault-tolerant grid-forming converter applied to AC microgrids.* International Journal of Electrical Power & Energy Systems, 2020. **121**: p. 106072.

[124] Qoria, T., et al., *Current limiting algorithms and transient stability analysis of grid-forming VSCs.* Electric Power Systems Research, 2020. **189**: p. 106726.

[125] Rokrok, E., et al., *Classification and dynamic assessment of droop-based grid-forming control schemes: Application in HVDC systems.* Electric Power Systems Research, 2020. **189**: p. 106765.

[126] Singh, A.K., et al., *A Comprehensive Review on Active and Reactive Power Control of Grid Connected Converters.* Innovations in Cyber Physical Systems, 2021: p. 659-666.

[127] Sangwongwanich, A., J. He, and Y. Pan, *Advanced power control of photovoltaic systems*, in *Control of Power Electronic Converters and Systems*. 2021, Elsevier. p. 447-469.

[128] Mohammed, O., et al., *Virtual synchronous generator: an overview.* Nigerian Journal of Technology, 2019. **38**(1): p. 153-164.

[129] Tamrakar, U., et al. *Improving transient stability of photovoltaic-hydro microgrids using virtual synchronous machines*. in *2015 IEEE Eindhoven PowerTech*. 2015.

[130] Bevrani, H., T. Ise, and Y. Miura, *Virtual synchronous generators: A survey and new perspectives.* International Journal of Electrical Power & Energy Systems, 2014. **54**: p. 244-254.

[131] Chen, Y., et al. *Investigation of the virtual synchronous machine in the island mode*. in *2012*

3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe). 2012. IEEE.

[132] Manaz, M.M. and C.-N. Lu, *Optimal Switched Mode Control to Synthesize Dynamic Frequency Response from Virtual Synchronous Machine in Islanded Microgrid Operation.* IFAC-PapersOnLine, 2018. **51**(28): p. 610-615.

[133] D'Arco, S. and J.A. Suul, *Equivalence of virtual synchronous machines and frequency-droops for converter-based microgrids.* IEEE Transactions on Smart Grid, 2013. **5**(1): p. 394-395.

[134] Li, D., et al., *A self-adaptive inertia and damping combination control of VSG to support frequency stability.* IEEE Transactions on Energy Conversion, 2016. **32**(1): p. 397-398.

[135] Wang, F., et al., *An adaptive control strategy for virtual synchronous generator.* IEEE Transactions on Industry Applications, 2018. **54**(5): p. 5124-5133.

[136] Van Wesenbeeck, M., et al. *Grid tied converter with virtual kinetic storage*. in *2009 IEEE Bucharest PowerTech*. 2009. IEEE.

[137] Guan, M., et al., *Synchronous generator emulation control strategy for voltage source converter (VSC) stations.* IEEE Transactions on Power Systems, 2015. **30**(6): p. 3093-3101.

[138] Paolone, M., et al., *Fundamentals of power systems modelling in the presence of converter-interfaced generation.* Electric Power Systems Research, 2020. **189**: p. 106811.

[139] Alipoor, J., Y. Miura, and T. Ise, *Power system stabilization using virtual synchronous generator with alternating moment of inertia.* IEEE journal of Emerging and selected topics in power electronics, 2014. **3**(2): p. 451-458.

[140] Lopes, L.A., *Self-tuning virtual synchronous machine: A control strategy for energy storage systems to support dynamic frequency control.* IEEE Transactions on Energy Conversion, 2014. **29**(4): p. 833-840.

[141] D’Arco, S., G. Guidi, and J.A. Suul. *Operation of a modular multilevel converter controlled as a virtual synchronous machine*. in *2018 International Power Electronics Conference (IPEC-Niigata 2018-ECCE Asia)*. 2018. IEEE.

[142] Magdy, G., et al., *Renewable power systems dynamic security using a new coordination of frequency control strategy based on virtual synchronous generator and digital frequency protection.* International Journal of Electrical Power & Energy Systems, 2019. **109**: p. 351-368.

[143] D'Arco, S., J.A. Suul, and O.B. Fosso, *Automatic tuning of cascaded controllers for power converters using eigenvalue parametric sensitivities.* IEEE Transactions on Industry Applications, 2014. **51**(2): p. 1743-1753.

[144] Liang, X. and C.A.B. Karim. *Virtual synchronous machine method in renewable energy integration*. in *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*. 2016. IEEE.

[145] Kezunovic, M., et al., *The Big Picture: Smart Research for Large-Scale Integrated Smart Grid Solutions.* IEEE Power and Energy Magazine, 2012. **10**(4): p. 22-34.

[146] Cvetkovic, I., et al. *Modeling of a virtual synchronous machine-based grid-interface converter for renewable energy systems integration*. in *2014 IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL)*. 2014. IEEE.

[147] Alsiraji, H.A. and J.M. Guerrero, *A new hybrid virtual synchronous machine control structure combined with voltage source converters in islanded ac microgrids.* Electric Power Systems Research, 2021. **193**: p. 106976.

[148] Alaboudy, A.K., H.H. Zeineldin, and J. Kirtley, *Microgrid stability characterization subsequent to fault-triggered islanding incidents.* IEEE transactions on power delivery, 2012. **27**(2): p. 658-669.

[149] Qoria, T., et al., *A PLL-free grid-forming control with decoupled functionalities for high-power transmission system applications.* IEEE Access, 2020. **8**: p. 197363-197378.

[150] Karimi, A., et al., *Inertia response improvement in AC microgrids: A fuzzy-based virtual synchronous generator control.* IEEE Transactions on Power Electronics, 2019. **35**(4): p. 4321-4331.

[151] Perez, F., et al., *Adaptive Variable Synthetic Inertia from a Virtual Synchronous Machine Providing Ancillary Services for an AC MicroGrid.* IFAC-PapersOnLine, 2020. **53**(2): p. 12968-12973.

[152] Zhang, W., et al., *Frequency support properties of the synchronous power control for grid-connected converters.* IEEE Transactions on Industry Applications, 2019. **55**(5): p. 5178-5189.

[153] Li, W., et al. *Frequency Control Strategy of Grid-connected PV System Using Virtual Synchronous Generator*. in *2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*. 2019.

[154] Alsiraji, H.A. and R. El-Shatshat, *Comprehensive assessment of virtual synchronous machine based voltage source converter controllers.* IET Generation, Transmission & Distribution, 2017. **11**(7): p. 1762-1769.

[155] Ise, T. and H. Bevrani, *Virtual synchronous generators and their applications in microgrids*, in *Integration of Distributed Energy Resources in Power Systems*. 2016, Elsevier. p. 282-294.

[156] Tamrakar, U., et al., *Virtual inertia: Current trends and future directions.* Applied Sciences, 2017. **7**(7): p. 654.

[157] Wang, S., et al., *On inertial dynamics of virtual-synchronous-controlled DFIG-based wind turbines.* IEEE Transactions on Energy Conversion, 2015. **30**(4): p. 1691-1702.

[158] Wu, W., et al., *A virtual inertia control strategy for DC microgrids analogized with virtual synchronous machines.* IEEE Transactions on Industrial Electronics, 2016. **64**(7): p. 6005-6016.

[159] Gonzalez-Longatt, F., E. Chikuni, and E. Rashayi. *Effects of the Synthetic Inertia from wind power on the total system inertia after a frequency*

disturbance. in *2013 IEEE International Conference on Industrial Technology (ICIT)*. 2013.

[160] Zhong, Q.-C., et al., *Improved synchronverters with bounded frequency and voltage for smart grid integration.* IEEE Transactions on Smart Grid, 2016. **9**(2): p. 786-796.

[161] Natarajan, V. and G. Weiss, *Synchronverters with better stability due to virtual inductors, virtual capacitors, and anti-windup.* IEEE Transactions on Industrial Electronics, 2017. **64**(7): p. 5994-6004.

[162] Brown, E. and G. Weiss. *Using synchronverters for power grid stabilization*. in *2014 IEEE 28th Convention of Electrical & Electronics Engineers in Israel (IEEEI)*. 2014. IEEE.

[163] Sakimoto, K., Y. Miura, and T. Ise, *Stabilization of a Power System Including Inverter-Type Distributed Generators by a Virtual Synchronous Generator.* Electrical Engineering in Japan, 2014. **187**(3): p. 7-17.

[164] Sakimoto, K., Y. Miura, and T. Ise, *Stabilization of a power system including inverter type distributed generators by the virtual synchronous generator.* IEEJ Transactions on Power and Energy, 2012. **132**(4): p. 341-349.

[165] Zhang, W., et al., *Synchronous Power Controller With Flexible Droop Characteristics for Renewable Power Generation Systems.* IEEE Transactions on Sustainable Energy, 2016. **7**(4): p. 1572-1582.

[166] Chen, Y., et al. *Improving the grid power quality using virtual synchronous machines*. in *2011 international conference on power engineering, energy and electrical drives*. 2011. IEEE.

[167] Hesse, R., D. Turschner, and H.-P. Beck. *Micro grid stabilization using the virtual synchronous machine (VISMA)*. in *Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ'09), Valencia, Spain*. 2009.

[168] Muftau, B., M. Fazeli, and A. Egwebe, *Stability analysis of a PMSG based Virtual Synchronous Machine.* Electric Power Systems Research, 2020. **180**: p. 106170.

[169] Lu, L. and N.A. Cutululis. *Virtual synchronous machine control for wind turbines: a review*. in *Journal of Physics: Conference Series*. 2019. IOP Publishing.

[170] Ma, Y., et al., *Virtual synchronous generator control of full converter wind turbines with short-term energy storage.* IEEE Transactions on Industrial Electronics, 2017. **64**(11): p. 8821-8831.

[171] Xiaolin, Z., et al. *Hardware in loop simulation test of photovoltaic virtual synchronous generator*. in *2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2)*. 2018. IEEE.

[172] Niino, S., et al. *Virtual Synchronous Generator Control of Power System Including LargeWind Farm by using HVDC Interconnection Line*. in *2019 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*. 2019. IEEE.

[173] Nakamura, A., et al. *Stability Enhancement of Power System including Wind Farm by Voltage Control and Virtual Synchronous Generator Control*. in *2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST)*. 2021. IEEE.

[174] Linn, Z., Y. Miura, and T. Ise, *Power system stabilization control by HVDC with SMES using virtual synchronous generator.* IEEJ Journal of Industry Applications, 2012. **1**(2): p. 102-110.

[175] Yan, X., et al., *Research on distributed PV storage virtual synchronous generator system and its static frequency characteristic analysis.* Applied Sciences, 2018. **8**(4): p. 532.

[176] Shi, R., et al., *Self-tuning virtual synchronous generator control for improving frequency stability in autonomous photovoltaic-diesel microgrids.* Journal of Modern Power Systems and Clean Energy, 2018. **6**(3): p. 482-494.

[177] Chen, J., et al., *100% Converter-Interfaced generation using virtual synchronous generator control: A case study based on the irish system.* Electric Power Systems Research, 2020. **187**: p. 106475.

[178] Rehman, H.U., et al., *An advanced virtual synchronous generator control technique for frequency regulation of grid-connected PV system.* International Journal of Electrical Power & Energy Systems, 2021. **125**: p. 106440.

[179] Khatibi, M., S. Ahmed, and N. Kang, *Multi-Mode Operation and Control of a Z-Source Virtual Synchronous Generator in PV Systems.* IEEE Access, 2021. **9**: p. 53003-53012.

[180] Alawasa, K.M. and Y.A.-R.I. Mohamed, *Impedance and damping characteristics of grid-connected VSCs with power synchronization control strategy.* IEEE Transactions on Power Systems, 2014. **30**(2): p. 952-961.

[181] Harnefors, L., et al., *Robust Analytic Design of Power-Synchronization Control.* IEEE Transactions on Industrial Electronics, 2019. **66**(8): p. 5810-5819.

[182] Zhang, L., L. Harnefors, and H.-P. Nee, *Interconnection of two very weak AC systems by VSC-HVDC links using power-synchronization control.* IEEE transactions on power systems, 2010. **26**(1): p. 344-355.

[183] Yazdani, S., et al., *Internal Model Power Synchronization Control of a PV-Based Voltage-Source Converter in Weak-Grid and Islanded Conditions.* IEEE Transactions on Sustainable Energy, 2020. **12**(2): p. 1360-1371.

[184] Remon, D., et al. *An active power synchronization control loop for grid-connected converters*. in *2014 IEEE PES General Meeting| Conference & Exposition*. 2014. IEEE.

[185] Zhang, L., L. Harnefors, and H.-P. Nee, *Power-synchronization control of grid-connected voltage-source converters.* IEEE Transactions on Power systems, 2010. **25**(2): p. 809-820.

[186] Khazaei, J., Z. Miao, and L. Piyasinghe, *Impedance-model-based MIMO analysis of power*

synchronization control. Electric Power Systems Research, 2018. **154**: p. 341-351.

[187] Zhang, L., H.-P. Nee, and L. Harnefors, *Analysis of stability limitations of a VSC-HVDC link using power-synchronization control.* IEEE Transactions on Power Systems, 2010. **26**(3): p. 1326-1337.

[188] Wu, H. and X. Wang, *Design-oriented transient stability analysis of grid-connected converters with power synchronization control.* IEEE Transactions on Industrial Electronics, 2018. **66**(8): p. 6473-6482.

[189] 189. Sun, R., et al., *Transient Synchronization Stability Control for LVRT with Power Angle Estimation.* IEEE Transactions on Power Electronics, 2021.

[190] Zhang, L., L. Harnefors, and H.-P. Nee, *Modeling and control of VSC-HVDC links connected to island systems.* IEEE Transactions on Power Systems, 2010. **26**(2): p. 783-793.

[191] Mitra, P., L. Zhang, and L. Harnefors, *Offshore wind integration to a weak grid by VSC-HVDC links using power-synchronization control: A case study.* IEEE Transactions on Power Delivery, 2013. **29**(1): p. 453-461.

[192] Nanou, S.I. and S.A. Papathanassiou, *Grid code compatibility of VSC-HVDC connected offshore wind turbines employing power synchronization control.* IEEE Transactions on Power Systems, 2016. **31**(6): p. 5042-5050.

[193] Radwan, A.A.A. and Y.A.-R.I. Mohamed, *Power synchronization control for grid-connected current-source inverter-based photovoltaic systems.* IEEE Transactions on Energy Conversion, 2016. **31**(3): p. 1023-1036.

[194] Morris, J.F., K.H. Ahmed, and A. Egea-Àlvarez, *Power-synchronization control for ultra-weak AC networks: comprehensive stability and dynamic performance assessment.* IEEE Open Journal of the Industrial Electronics Society, 2021. **2**: p. 441-450.

[195] Yap, K.Y., J.M.-Y. Lim, and C.R. Sarimuthu, *A novel adaptive virtual inertia control strategy under varying irradiance and temperature in grid-connected solar power system.* International Journal of Electrical Power & Energy Systems, 2021. **132**: p. 107180.

[196] Noguchi, T., et al., *Direct power control of PWM converter without power-source voltage sensors.* IEEE transactions on industry applications, 1998. **34**(3): p. 473-479.

[197] Escobar, G., et al., *Analysis and design of direct power control (DPC) for a three phase synchronous rectifier via output regulation subspaces.* IEEE Transactions on Power Electronics, 2003. **18**(3): p. 823-830.

[198] Zhang, Y., et al., *Performance improvement of direct power control of PWM rectifier with simple calculation.* IEEE Transactions on Power Electronics, 2012. **28**(7): p. 3428-3437.

[199] Hadji, K., et al. *Predictive Direct Power Control of a Three-Phase Three-Level NPC PWM Rectifier based on Space Vector Modulation*. in *2021 12th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*. 2021. IEEE.

[200] Bharath, C. and S. Mohapatro. *Modified Direct Torque Control Scheme for Induction Machine Using Space Vector Modulation*. in *Proceedings of Symposium on Power Electronic and Renewable Energy Systems Control*. 2021. Springer.

[201] Habetler, T.G., et al., *Direct torque control of induction machines using space vector modulation.* IEEE Transactions on industry applications, 1992. **28**(5): p. 1045-1053.

[202] Kang, J.-W. and S.-K. Sul, *Analysis and prediction of inverter switching frequency in direct torque control of induction machine based on hysteresis bands and machine parameters.* IEEE Transactions on Industrial Electronics, 2001. **48**(3): p. 545-553.

[203] Djagarov, N., et al. *Adaptive controller for induction machine direct torque control*. in *2021 17th Conference on Electrical Machines, Drives and Power Systems (ELMA)*. 2021. IEEE.

[204] Yan, S., et al., *A Review on Direct Power Control of Pulse-Width Modulation Converters.* IEEE Transactions on Power Electronics, 2021.

[205] 205. Eskandari-Torbati, H. and D.A. Khaburi. *Direct power control of three phase pwm rectifier using model predictive control and svm switching*. in *4th Annual International Power Electronics, Drive Systems and Technologies Conference*. 2013. IEEE.

[206] Malinowsk, M. and M.P. Kazmierkowski. *Direct power control of three-phase PWM rectifier using space vector modulation-simulation study*. in *Industrial Electronics, 2002. ISIE 2002. Proceedings of the 2002 IEEE International Symposium on*. 2002. IEEE.

[207] Restrepo, J.A., et al., *Optimum space vector computation technique for direct power control.* IEEE Transactions on Power Electronics, 2009. **24**(6): p. 1637-1645.

[208] Mazouz, F., et al. *Direct power control of DFIG by sliding mode control and space vector modulation.* in *2018 7th International Conference on Systems and Control (ICSC)*. 2018. IEEE.

[209] Benbouhenni, H., Z. Boudjema, and A. Belaidi, *Direct power control with NSTSM algorithm for DFIG using SVPWM technique.* Iranian Journal of Electrical and Electronic Engineering, 2021. **17**(1): p. 1518-1518.

[210] Bouafia, A., J.-P. Gaubert, and F. Krim, *Predictive direct power control of three-phase pulsewidth modulation (PWM) rectifier using space-vector modulation (SVM).* IEEE transactions on power electronics, 2009. **25**(1): p. 228-236.

[211] Zhang, Y., Y. Peng, and C. Qu, *Model predictive control and direct power control for PWM rectifiers with active power ripple minimization.* IEEE Transactions on Industry Applications, 2016. **52**(6): p. 4909-4918.

[212] Kwak, S., U.-C. Moon, and J.-C. Park, *Predictive-control-based direct power control with an adaptive parameter identification technique for*

improved AFE performance. IEEE Transactions on Power Electronics, 2014. **29**(11): p. 6178-6187.

[213] Hu, J., et al., *Model predictive control of microgrids–An overview.* Renewable and Sustainable Energy Reviews, 2021. **136**: p. 110422.

[214] Yang, G., et al., *Model predictive direct power control based on improved T-type grid-connected inverter.* IEEE Journal of Emerging and Selected Topics in Power Electronics, 2018. **7**(1): p. 252-260.

[215] Bouafia, A., F. Krim, and J.-P. Gaubert. *Direct power control of three-phase PWM rectifier based on fuzzy logic controller*. in *2008 IEEE International Symposium on Industrial Electronics*. 2008. IEEE.

[216] Kadem, M., et al., *Fuzzy logic-based instantaneous power ripple minimization for direct power control applied in a shunt active power filter.* Electrical Engineering, 2020. **102**(3): p. 1327-1338.

[217] Bouafia, A., F. Krim, and J.-P. Gaubert, *Fuzzy-logic-based switching state selection for direct power control of three-phase PWM rectifier.* IEEE transactions on industrial electronics, 2009. **56**(6): p. 1984-1992.

[218] Roy, T.K., et al. *Direct power controller design for improving FRT capabilities of dfig-based wind farms using a nonlinear backstepping approach*. in *2018 8th International Conference on Power and Energy Systems (ICPES)*. 2018. IEEE.

[219] Sun, D., X. Wang, and Y. Fang, *Backstepping direct power control without phase‐locked loop of AC/DC converter under both balanced and unbalanced grid conditions.* IET Power Electronics, 2016. **9**(8): p. 1614-1624.

[220] Wai, R.-J. and Y. Yang, *Design of backstepping direct power control for three-phase PWM rectifier.* IEEE Transactions on Industry Applications, 2019. **55**(3): p. 3160-3173.

[221] Choi, H.-W., et al., *Deadbeat predictive direct power control of interleaved buck converter-based fast battery chargers for electric vehicles.* Journal of Power Electronics, 2020. **20**(5): p. 1162-1171.

[222] Ramaiah, S., N. Lakshminarasamma, and M.K. Mishra. *An Improved Deadbeat Direct Power Control for Grid Connected Inverter System*. in *2021 IEEE 12th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*. 2021. IEEE.

[223] Jin, S., et al., *Deadbeat direct power control for dual three‐phase PMSG used in wind turbines.* IET Renewable Power Generation, 2021.

[224] Cheng, C., et al., *Dead-beat predictive direct power control of voltage source inverters with optimised switching patterns.* IET Power Electronics, 2017. **10**(12): p. 1438-1451.

[225] Lin, H., et al., *Integral sliding-mode control-based direct power control for three-level NPC converters.* Energies, 2020. **13**(1): p. 227.

[226] Tiwary, N., et al., *Sliding mode and current observer‐based direct power control of dual active bridge converter with constant power load.* International Transactions on Electrical Energy Systems, 2021. **31**(5): p. e12879.

[227] Gui, Y., et al., *Improved direct power control for grid-connected voltage source converters.* IEEE Transactions on Industrial Electronics, 2018. **65**(10): p. 8041-8051.

[228] Verveckken, J., et al., *Direct power control of series converter of unified power-flow controller with three-level neutral point clamped converter.* IEEE Transactions on Power Delivery, 2012. **27**(4): p. 1772-1782.

[229] Serpa, L., et al. *Five-level virtual-flux direct power control for the active neutral-point clamped multilevel inverter*. in *2008 IEEE Power Electronics Specialists Conference*. 2008. IEEE.

[230] Portillo, R., et al., *Model based adaptive direct power control for three-level NPC converters.* IEEE Transactions on Industrial Informatics, 2012. **9**(2): p. 1148-1157.

[231] Datta, R. and V. Ranganathan, *Direct power control of grid-connected wound rotor induction machine without rotor position sensors.* IEEE Transactions on Power Electronics, 2001. **16**(3): p. 390-399.

[232] Amrane, F., B. Francois, and A. Chaiba, *Experimental investigation of efficient and simple wind-turbine based on DFIG-direct power control using LCL-filter for stand-alone mode.* ISA transactions, 2021.

[233] Beniss, M.A., et al., *Performance analysis and enhancement of direct power control of DFIG based wind system.* International Journal of Power Electronics and Drive Systems, 2021. **12**(2): p. 1034.

[234] Mazouz, F., et al., *Adaptive direct power control for double fed induction generator used in wind turbine.* International Journal of Electrical Power & Energy Systems, 2020. **114**: p. 105395.

[235] Li, S., et al., *Direct power control of DFIG wind turbine systems based on an intelligent proportional-integral sliding mode control.* ISA transactions, 2016. **64**: p. 431-439.

[236] Barra, K. and D. Rahem, *Predictive direct power control for photovoltaic grid connected system: An approach based on multilevel converters.* Energy Conversion and Management, 2014. **78**: p. 825-834.

[237] Ouchen, S., et al., *Experimental validation of sliding mode-predictive direct power control of a grid connected photovoltaic system, feeding a nonlinear load.* Solar Energy, 2016. **137**: p. 328-336.

[238] Sarra, M., O. Aissa, and J.-P. Gaubert, *An investigation of solar active power filter based on direct power control for voltage quality and energy transfer in grid-tied photovoltaic system under unbalanced and distorted conditions.* Journal of Engineering Research, 2021. **9**(3B).

[239] Eloy-Garcia, J., S. Arnaltes, and J. Rodriguez-Amenedo, *Direct power control of voltage source*

inverters with unbalanced grid voltages. IET Power Electronics, 2008. **1**(3): p. 395-407.

[240] Chandorkar, M.C., D.M. Divan, and R. Adapa, *Control of parallel connected inverters in standalone AC supply systems.* IEEE transactions on industry applications, 1993. **29**(1): p. 136-143.

[241] Majumder, R., et al., *Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop.* IEEE transactions on power systems, 2009. **25**(2): p. 796-808.

[242] De Brabandere, K., et al., *A voltage and frequency droop control method for parallel inverters.* IEEE Transactions on power electronics, 2007. **22**(4): p. 1107-1115.

[243] Bhatt, N., R. Sondhi, and S. Arora, *Droop Control Strategies for Microgrid: A Review.* Advances in Renewable Energy and Electric Vehicles, 2022: p. 149-162.

[244] Kulkarni, S.V. and D.N. Gaonkar, *Improved droop control strategy for parallel connected power electronic converter based distributed generation sources in an Islanded Microgrid.* Electric Power Systems Research, 2021. **201**: p. 107531.

[245] Dawoud, N.M., T.F. Megahed, and S.S. Kaddah, *Enhancing the performance of multi-microgrid with high penetration of renewable energy using modified droop control.* Electric Power Systems Research, 2021. **201**: p. 107538.

[246] Chen, J., et al., *A Virtual Complex Impedance Based $ P-\dot {V} $ Droop Method for Parallel-Connected Inverters in Low-Voltage AC Microgrids.* IEEE Transactions on Industrial Informatics, 2020. **17**(3): p. 1763-1773.

[247] Vandoorn, T., et al., *Review of primary control strategies for islanded microgrids with power-electronic interfaces.* Renewable and Sustainable Energy Reviews, 2013. **19**: p. 613-628.

[248] Awal, M. and I. Husain, *Unified Virtual Oscillator Control for Grid-Forming and Grid-Following Converters.* IEEE Journal of Emerging and Selected Topics in Power Electronics, 2020.

[249] Seo, G.-S., et al. *Dispatchable virtual oscillator control for decentralized inverter-dominated power systems: Analysis and experiments*. in *2019 IEEE Applied Power Electronics Conference and Exposition (APEC)*. 2019. IEEE.

[250] Awal, M., et al. *A Grid-Forming Multi-Port Converter using Unified Virtual Oscillator Control*. in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*. 2020. IEEE.

[251] Lu, M., et al. *A pre-synchronization strategy for grid-forming virtual oscillator controlled inverters*. in *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*. 2020. IEEE.

[252] Quedan, A., D. Ramasubramanian, and E. Farantatos. *Virtual Oscillator Controlled Grid Forming Inverters Modelling and Testing in Phasor Domain*. in *2021 IEEE 12th Energy Conversion Congress & Exposition-Asia (ECCE-Asia)*. 2021. IEEE.

[253] Ajala, O., et al., *Model Reduction for Inverters with Current Limiting and Dispatchable Virtual Oscillator Control.* IEEE Transactions on Energy Conversion, 2021.

[254] Groß, D., et al., *The effect of transmission-line dynamics on grid-forming dispatchable virtual oscillator control.* IEEE Transactions on Control of Network Systems, 2019. **6**(3): p. 1148-1160.

[255] Kammer, C. and A. Karimi, *Decentralized and distributed transient control for microgrids.* IEEE Transactions on Control Systems Technology, 2017. **27**(1): p. 311-322.

[256] Madani, S.S., C. Kammer, and A. Karimi, *Data-driven distributed combined primary and secondary control in microgrids.* IEEE Transactions on Control Systems Technology, 2020. **29**(3): p. 1340-1347.

[257] Yu, L., R. Li, and L. Xu, *Distributed PLL-based control of offshore wind turbines connected with diode-rectifier-based HVDC systems.* IEEE Transactions on Power Delivery, 2017. **33**(3): p. 1328-1336.

[258] Arasteh, A., L. Zeni, and N.A. Cutululis, *Fault ride through capability of grid forming wind turbines: A comparison of three control schemes.* IET Renewable Power Generation, 2022.

[259] Luo, S., et al., *A New Virtual Oscillator Control Without Third-Harmonics Injection For DC/AC Inverter.* IEEE Transactions on Power Electronics, 2021. **36**(9): p. 10879-10888.

[260] Dadinaboina, A.K.R., et al., *Improved power quality with an adaptive grid‐forming inverter control scheme in solar PV system.* International Transactions on Electrical Energy Systems, 2021: p. e13009.

[261] Abid, A., et al., *Dynamic economic dispatch incorporating photovoltaic and wind generation using hybrid FPA with SQP.* IETE Journal of Research, 2020. **66**(2): p. 204-213.

[262] Li, Y., et al., *Impedance Circuit Model of Grid-Forming Inverter: Visualizing Control Algorithms as Circuit Elements.* IEEE Transactions on Power Electronics, 2020. **36**(3): p. 3377-3395.

[263] Markovic, U., et al., *LQR-based adaptive virtual synchronous machine for power systems with high inverter penetration.* IEEE Transactions on Sustainable Energy, 2018. **10**(3): p. 1501-1512.

[264] Hernández, J.C., P.G. Bueno, and F. Sanchez-Sutil, *Enhanced utility-scale photovoltaic units with frequency support functions and dynamic grid support for transmission systems.* IET Renewable Power Generation, 2017. **11**(3): p. 361-372.

[265] Zhong, Q.-C., et al., *Grid-friendly wind power systems based on the synchronverter technology.* Energy Conversion and Management, 2015. **89**: p. 719-726.

[266] Nazir, M.S., et al., *Impacts of renewable energy atlas: Reaping the benefits of renewables and biodiversity threats.* International Journal of Hydrogen Energy, 2020.

[267] Alnatheer, O., *The potential contribution of renewable energy to electricity supply in Saudi*

Arabia. Energy policy, 2005. **33**(18): p. 2298-2312.

[268] Dincer I., *Renewable energy and sustainable development: a crucial review.* Renewable and sustainable energy reviews, 2000. **4**(2): p. 157-175.

[269] Nazir, M.S., et al., *Potential environmental impacts of wind energy development: A global perspective.* Current Opinion in Environmental Science & Health, 2020. **13**: p. 85-90.

[270] Ciulla, G., et al., *Modelling and analysis of real-world wind turbine power curves: Assessing deviations from nominal curve by neural networks.* Renewable energy, 2019. **140**: p. 477-492.

[271] Mongrain, R.S. and R. Ayyanar, *Control of nonideal grid-forming inverter in islanded microgrid with hierarchical control structure under unbalanced conditions.* International Journal of Electrical Power & Energy Systems, 2020. **119**: p. 105890.

[272] Cousse, J., *Still in love with solar energy? Installation size, affect, and the social acceptance of renewable energy technologies.* Renewable and Sustainable Energy Reviews, 2021. **145**: p. 111107.

[273] Batel, S. and D. Rudolph, *A Critical Approach to the Social Acceptance of Renewable Energy Infrastructures*, in *A critical approach to the social acceptance of renewable energy infrastructures*. 2021, Springer. p. 3-19.

[274] Hearn, R.N., *Comparative analysis of environmental assessment regulatory frameworks for wind energy development in Canada.* 2018.

[275] Menegaki, A., *Valuation for renewable energy: A comparative review.* Renewable and Sustainable Energy Reviews, 2008. **12**(9): p. 2422-2437.

[276] Sorknæs, P., et al., *The benefits of 4th generation district heating in a 100% renewable energy system.* Energy, 2020. **213**: p. 119030.

[277] Zhao, H.-r., S. Guo, and L.-w. Fu, *Review on the costs and benefits of renewable energy power subsidy in China.* Renewable and Sustainable Energy Reviews, 2014. **37**: p. 538-549.

[278] Olanipekun, B.A. and N.O. Adelakun, *Assessment of renewable energy in Nigeria: Challenges and benefits.* International Journal of Engineering Trends and Technology (IJETT)–Volume, 2020. **68**.

[279] Tan, S.T., et al., *Energy and emissions benefits of renewable energy derived from municipal solid waste: Analysis of a low carbon scenario in Malaysia.* Applied Energy, 2014. **136**: p. 797-804.

[280] Stigka, E.K., J.A. Paravantis, and G.K. Mihalakakou, *Social acceptance of renewable energy sources: A review of contingent valuation applications.* Renewable and sustainable energy Reviews, 2014. **32**: p. 100-106.

[281] Wüstenhagen, R., M. Wolsink, and M.J. Bürer, *Social acceptance of renewable energy innovation: An introduction to the concept.* Energy policy, 2007. **35**(5): p. 2683-2691