JPE 15-4-19

http://dx.doi.org/10.6113/JPE.2015.15.4.1054
ISSN(Print): 1598-2092 / ISSN(Online): 2093-4718

Power Quality Improvement in Autonomous Microgrids Using Multi-functional Voltage Source Inverters: A Comprehensive Review

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Abstract

Multi-functional voltage source inverters (VSIs) have attracted increasing attention in recent years for their advantageous auxiliary services for power quality enhancement in autonomous microgrids. These types of VSIs can not only achieve a proper control scheme in autonomous mode but also cope with the prescribed power quality and stability requirements. These functionalities are integrated within the same device, thereby significantly improving the cost-effectiveness of microgrids while decreasing the investment and bulk compared with those of multiple devices with independent functionalities. Control strategies for power quality enhancement in autonomous microgrids using multi-functional VSIs are comprehensively reviewed in this paper. In addition, such VSIs are discussed in detail, and comparisons of which are also provided. Lastly, a number of future research directions for multi-functional VSIs are recommended.

Key words: Autonomous microgrids, Microgrid control, Multi-functional voltage source inverter, Power quality

I. Introduction

Small autonomic grids have been utilized in remote communities for many decades. However, the interconnection of these remote grids with the public grid is not feasible because of economic and technical reasons. The trend of using fossil fuel in remote areas has become more apparent in the last few decades because of the availability and high capacity of such types of energies to generate huge amounts of electricity. Nonetheless, with the emergence of renewable and sustainable energies, integrating green technologies has become a priority in these stand-alone distribution networks.

Numerous technical issues should be addressed before green energies can be efficiently shared into distribution networks. In other words, not only should the potential advantages of renewable energy be harnessed, but the present levels of reliability and controllability should also be maintained. The emergence of microgrid is a reasonably attractive alternative for overcoming the challenges of integrating distributed energy resources (DERs) into active distribution networks [1].

A microgrid can be defined as a group of distributed generations (DGs), loads, power electronic devices, and energy storage systems that behaves as a controllable entity [2]-[4]. A microgrid can operate in both grid-connected and islanded modes [5], [6]. Typically, it operates in conjunction with the public grid. In this mode, power can be exchanged between the microgrid and the utility grid. However, whenever a power quality event or an external attack occurs within the utility grid, it can operate autonomously by being disconnected from the rest of the distribution system at the point of common coupling (PCC). In such mode, the generated power within the autonomous microgrid must be in balance with the demand of loads [7].

The growing interest to integrate intermittent green energy into microgrids presents major challenges with respect to reliable operation and control. Therefore, the operational challenges brought about by the integration of renewable energy resources (RERs) into microgrids should be addressed

Manuscript received Oct. 25, 2014; accepted Mar. 6, 2015
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by designing a control system that is appropriate for both grid-connected and autonomous modes.

In grid-connected mode, the frequency of the microgrid and the voltage at the PCC are determined by the utility grid [8]. In this mode, the main responsibility of the microgrid control is to regulate the active and reactive power generated by the DER units. Moreover, the utility grid may not allow voltage regulation by the DER units to avoid any interaction with the same functionality provided by the utility grid [9].

Meanwhile, in autonomous mode, the voltage and frequency of the microgrid should be controlled using DERs, because these variables are no longer supported by the utility grid. Given that islanding operation requires that appropriate load sharing mechanisms be implemented to balance sudden active power mismatches, the islanding mode is considerably more challenging than the grid-connected mode [5]. Furthermore, the physical inertia of islanding operation is quite smaller than that of the grid-connected mode. More importantly, developing a schematic compensation method to realize accurate reactive, imbalance, and harmonic power sharing is crucial to an autonomous microgrid with a large number of nonlinear or imbalanced loads. Therefore, the islanding mode of operation requires adequate control and management systems that satisfies the prescribed power quality requirements for sensitive load. In islanding mode, the key principles of microgrid control structure include voltage and frequency control, active and reactive power-sharing control, power quality control, and optimized microgrid operating costs [10], [11].

In view of the presence of sensitive loads in autonomous microgrids, power quality is highly important for different types of electric consumers. Multi-functional inverters play an important role in improving the power quality and stability of these networks when the DGs are voltage source inverters (VSIs). They can be used either with additional compensation equipment or by being integrated into DG local controllers. In recent years, the use of multi-functional VSIs for power quality enhancement in autonomous distribution networks has gained considerable because of advantages such as reduced investment as well as improved cost-effectiveness of DGs, operation costs, and bulk [5].

Control strategies for power quality enhancement in autonomous microgrids using multi-functional VSIs are comprehensively reviewed in this paper. These VSIs are discussed in detail, and comparisons of which are also presented. This paper is organized as follows. The hierarchical control of islanded microgrids is reviewed in Section II. Two different approaches for power quality improvement in stand-alone distribution networks are presented in Section III. Different control methods for power quality enhancement using multi-functional VSIs in islanded distribution networks are reviewed in Section IV. Various control strategies for stability improvement by multi-functional VSIs in autonomous mode are explained in Section V. The discussion, as well as a number of interesting research points, is provided in Section VI. The drawn conclusions are presented in Section VII.

II. Hierarchical Control of Inverter-based Islanded Microgrids

In consideration of the control structure of traditional power systems, two different approaches, namely, centralized and decentralized techniques, can be introduced to control power electronic based microgrids [12], [13]. In a fully centralized technique, a central controller (CC) uses extensive communication links to perform the control actions for all units. By contrast, in a fully decentralized approach, the controller of each DG unit operates based on the local measurement. For microgrid applications, neither a fully centralized nor a fully decentralized control can be implemented because of the large number of controller units and stringent performance requirements.

A possible solution to these limitations is to introduce a hierarchical control scheme [14], which was initiated by the Union for the Coordination of Transmission of Electricity (UCTE) in continental Europe [15]. This scheme is a compromise between fully decentralized and centralized approaches that comprises three different levels. On the basis of the infrastructure requirements and the speed of response, these levels can be classified into primary, secondary and tertiary controllers, as shown in Fig. 1 [16]. The fastest level is the primary control, which is responsible for the output control and power-sharing control, subsequent to the islanding process [17]. The secondary control restores the voltage and frequency deviations of the islanding mode caused by the primary control. Indeed, it is responsible for mitigating the steady-state errors produced by the power-sharing unit [18]. Given that the main target of the tertiary control is to manage the power flow between the public grid and the microgrid in grid-connected mode, it can be considered part of the public grid [19] and is therefore not discussed further in the present paper.

At the primary level, the main task of the inverter output controller is to regulate the electrical signals of the autonomous microgrid. In an inverter-based DG unit, the inverter output control typically includes an external loop for voltage control and an internal loop for current regulation. The power-sharing controller is mainly used for active and reactive power sharing. Preferably, power sharing is performed with the use of droop controllers without the need for communication links. The conventional droop controller can be operated effectively in medium voltage networks, where the lines have a predominant inductive behaviour. Thus, this controller cannot be directly applied to low voltage microgrids. To cope with this challenge, a virtual impedance can be employed to link the power converter to the AC bus [18]. Therefore, the line impedance can be predominately inductive, and the droop control can be operated properly. Fig. 2 shows the primary level, including the

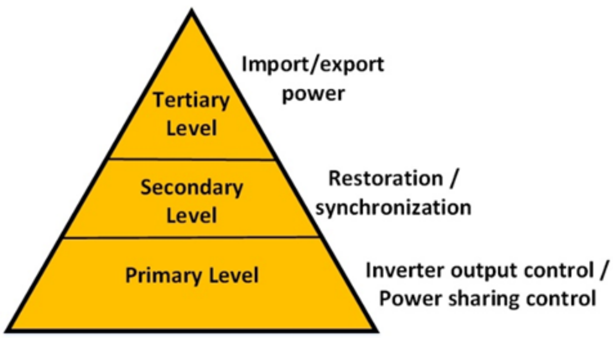

Fig. 1. Hierarchical control levels of a microgrid.

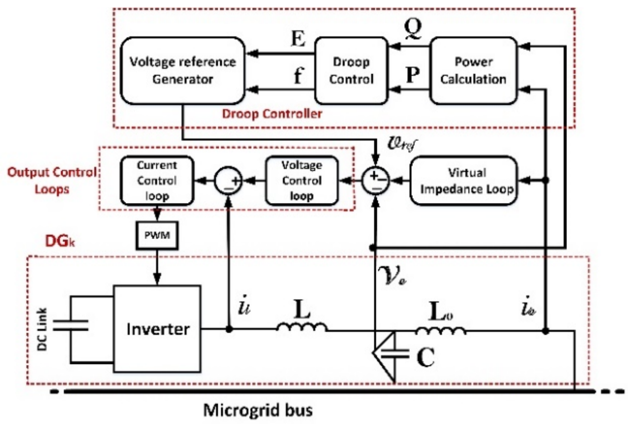

Fig. 2. Primary control: droop control with virtual impedance, and inner control loops applied to an inverter.

output control loops, the virtual impedance loop and the droop controller.

The secondary level is also used to compensate the frequency and voltage deviations caused by the primary level [18]. In some cases, the frequency or voltage of microgrids decreases because of an unexpected increase in demand. As shown in Fig. 3, to match the demand with generation, the frequency or voltage of an islanded microgrid must be changed at the primary level. As shown in the figure, the voltage or frequency of an autonomous microgrid, even after the operation of the power-sharing unit, is below the rated value. In such a situation, the main objective of the secondary control is to restore the operating point. The reactive/active power-sharing control can be also improved at the secondary level by using an external loop [17]. As the voltage is not constant along the microgrid power line, an accurate reactive power sharing is difficult to achieve in the Q-V droop control, nor is an appropriate active power sharing in the P-V droop control [20], [21]. Therefore, these challenges should also be addressed using the secondary level.

III. Power Quality Improvement in Autonomous Distribution Networks

Compared with that in the grid-connected mode, the electronic loads are more vulnerable to power quality problems

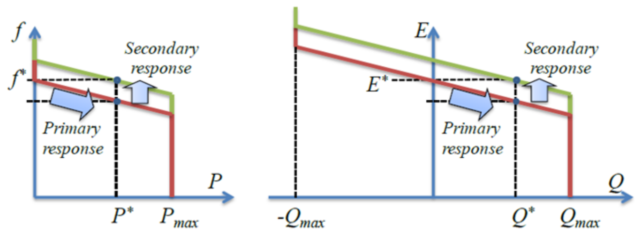

Fig. 3. P-f and Q-E primary and secondary control actions.

in the autonomous mode [22]. Moreover, the emergence of single-phase loads and DGs in microgrids may lead to an imbalance of the three-phase voltages. In addition, the presence of capacitive household and rectifier loads can cause harmonic distortion in these islanded systems [23]. The supply of a combination of unbalanced and non-linear loads may affect the proper function of autonomous microgrids. The main challenges caused by unbalanced and nonlinear loads in microgrids include the malfunctioning of protection devices and adjustable speed drives, losses in rotating machines, and saturation of transformers [24]-[26].

For autonomous microgrids, the power quality should be maintained in much the same way as with hybrid power systems (HPSs) and uninterruptible power supplies (UPSs) [27]–[30]. According to the IEEE standards [27], [28], the voltage unbalanced factor (VUF) and the voltage total harmonic distortion (THD) should be maintained below 2% and 5% for sensitive loads, respectively.

As shown in Fig. 4, power quality enhancement in microgrids and distribution networks can be performed with two different approaches: dedicated active power filters (APFs) and existing multi-functional power converters [31]. APFs can be designed in shunt or series configurations. Multi-functional power converters can be classified into grid-feeding, grid-forming, and grid-supporting power converters, depending on their operation in microgrids [32]. Grid-feeding power converters operate as a current source in grid-connected mode, whereas grid-forming power converters operate in stand-alone mode as ideal AC voltage sources. Grid-supporting power converters operate in both grid-connected and islanded modes [33]. They operate as current sources in grid-connected mode, whereas they operate as voltage sources in autonomous mode. In the following subsections, the power quality enhancement using APFs and multi-functional VSIs in stand-alone distribution networks are presented.

A. Power Quality Improvement Using APFs

Conventionally, APFs are used to improve the power quality of distribution networks in both grid-connected and stand-alone mode. They can be explored in shunt or series configurations to eliminate voltage harmonics, regulate terminal voltage, suppress voltage flicker, and improve voltage balance in distribution networks [34].

A large volume of published studies have described the role

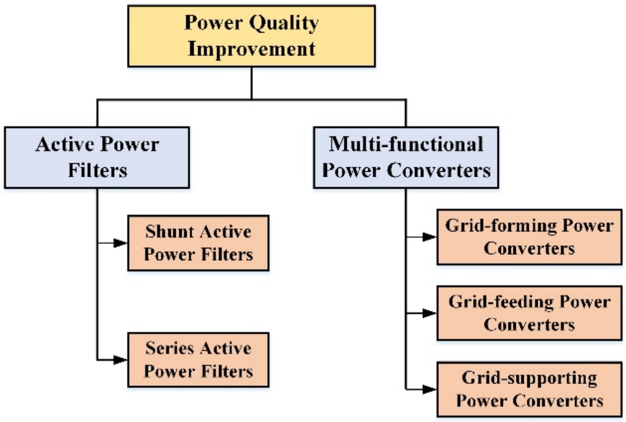

Fig. 4. Power quality improvement techniques in distribution networks.

of shunt APFs in improving the power quality of distribution networks [35]-[39]. They can mitigate the imbalance of phases by balancing the line currents. Shunt APFs have been also used to reduce harmonics. They can be regarded as a kind of current source compensating for the harmonic current resulting from nonlinear loads [40]. Nevertheless, the cost of shunt APFs is relatively high, and they are not preferable for large-scale systems, because the power capacity of the filter should be directly proportional to the load current to be compensated. Moreover, their compensating performance is better in the current-type harmonic source than in the voltage-type harmonic source [41].

Series APFs are also widely used for compensating the voltage imbalances and harmonics by injecting zero and negative sequence voltages as well as harmonic voltage to distribution networks [42]-[44]. In the case of harmonic compensation, they operate as a harmonic isolator rather than a harmonic voltage generator. In fact, series APFs provide a high impedance for harmonics while providing zero impedance for the fundamental frequency. Furthermore, they can regulate the PCC voltage at a desired value by controlling the inverter output to compensate for any abnormal utility voltage. Although the use of series APF is an effective solution for protecting consumers from an inadequate power quality, they are difficult to implement because of the time-delay effect in controlling the active filter system, which is caused by additional low or high-pass filters that are used in generating the reference voltage for unbalance utility and harmonic current compensation [44], [45].

As series APFs typically connect before the load in a series structure by a matching transformer, they can reduce the reliability of the power system [41], [45]. Moreover, they can only mitigate the harmonic distortion and compensate the short circuit in the load end. This short circuit current passes through the series transformer winding, which may overload the series transformer [45].

The use of a series/parallel active power filter is another approach to improve the power quality of distribution networks. The work by Yun et al. [46] proposed a grid-interfacing power quality compensator for a microgrid. In this approach, one inverter is connected to the microgrid in shunt structure, while the second is in series with the microgrid. For the microgrid situation, installing additional APFs for each of the DGs is uneconomical. Moreover, in the case of severe load imbalance and harmonic distortion, the amplitude of the current injected by active filter can be very high and exceed the filter rating. It can be considered a negative point, especially in terms of the cost and volume of the DG interface converter. Thus, instead of installing APFs in autonomous networks, a preferable solution is to provide power quality service by multi-functional VSIs.

B. Power Quality Improvement Using Multi-functional VSIs

In autonomous microgrid, VSIs are mainly responsible for transferring power and controlling the system. However, power quality enhancement can be accomplished by presenting a proper control scheme for both grid-connected and autonomous mode, when the DGs are of inverter-based type [47]. However, the control scheme and power quality issues in grid-connected microgrids significantly differ from that in autonomous operation.

Control strategies of multi-functional grid-connected inverters for power quality enhancement are comprehensively reviewed in [8]. In this mode, the frequency of microgrid and the voltage at the PCC must be determined by the utility grid. The main responsibility of the microgrid control is to regulate the active and reactive power generated by DER units. According to Zeng et al. [8], the power quality at the PCC is a very important issue for the stable and economical operation of grid-connected microgrids, because the price of the electricity sold to the utility grid will be determined by its quality at the point of connection. In this mode, power converters should be operated in grid-feeding or grid-supporting mode as current sources. Despite the implementation of an autonomous mode, the control structure for grid-connected power converters contains a power controller and a current control loop [8]. The power control loop is used to deliver pre-set active and reactive power to an energized grid, whereas the current loop is employed for current regulation. In this mode, the power converters cannot operate independently, and their operation normally is adjusted using a high-level controller such as a maximum power point tracking (MPPT) controller.

Meanwhile, the power converter must be operated either in grid-forming or grid-supporting mode as voltage sources for autonomous operation. In this mode, the voltage and frequency of the microgrid should be determined using such VSIs, because these control variables are no longer supported by the utility grid. Moreover, given that islanding operation requires the implementation of appropriate load sharing mechanisms to balance sudden active power mismatches, the islanding mode is significantly more challenging than the grid-connected mode. Despite the fact that only the power quality at the PCC is

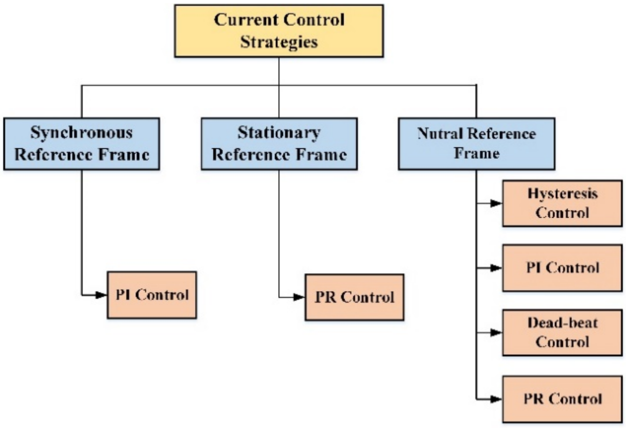

Fig. 5. Existing control strategies for the inner current loop.

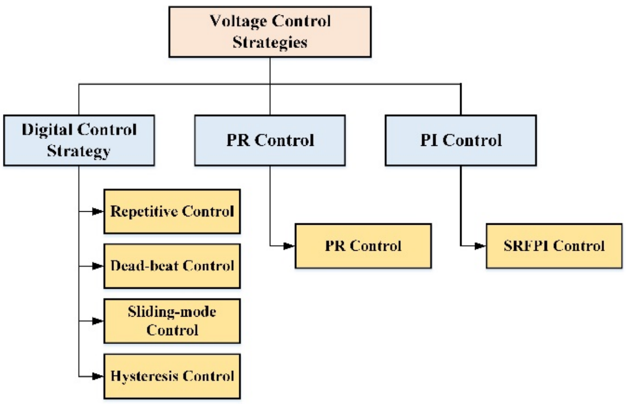

Fig. 6. Existing voltage control strategies for the outer voltage loop.

important, the power quality requirements for different areas and buses can differ in the autonomous mode because of the presence of sensitive loads. In other words, the power quality requirements are commonly distinguished in various areas depending on the type of electric appliances [19]. Here, the power quality improvement in islanding operation is considered.

Researchers have recently shown an increasing interest in using multi-feedback control loops in conjunction with the droop method to operate two or more VSIs in stand-alone microgrids. This technique consists of an outer voltage loop that regulates voltages and an inner current loop that generates the gate signals of the PWM. Fig. 5 shows the existing control strategies for the inner current loop. As shown, these strategies are classified into three different methods based on their reference frame structures, namely, proportional-integral (PI) controllers in the dq frame, proportional-resonant (PR) controllers in the stationary reference frame, and hysteresis controller as well as the PR and PI controllers in the abc frame.

Fig. 6 shows the existing voltage control strategies for the outer voltage loop used for the control of VSIs in autonomous microgrids. Based on the reference frame and the type of controllers, these strategies can be classified into three different control structures, namely, digital control strategies, PR controllers in the stationary reference frame, and the synchronous reference frame PI (SRFPI) regulators. For microgrid applications, power quality should be maintained in much the same way as with HPSs and UPS. However, power sharing and secondary controllers are not considered in single-bus autonomic grids. To address the power quality problems, various voltage control techniques combined with different current loop strategies for stand-alone distribution networks such as HPSs, UPSs and autonomous microgrids have been presented in the literature. In the next section, these strategies are presented.

IV. Control Techniques of Multi-functional VSIs for Power Quality Enhancement in Autonomous Microgrids

Several control techniques for multi-functional VSIs in autonomous mode have been presented in the literature. Based on the reference frame and the type of controllers, these strategies can be classified into three different structures, namely, digital control strategies, PR controllers in the stationary reference frame, and PI regulators in the synchronous reference frame. In the following subsections, these strategies are presented, and their advantages and disadvantages are compared.

A. Digital Control Strategies

In view of the low cost and the availability of innovative digital signal processors, digital control schemes based on repetitive control, dead-beat (DB) control, hysteresis, and discrete-time sliding-mode control have been suggested in recent years for the voltage control of islanded distribution networks.

To eliminate harmonic distortions of the output voltage caused by nonlinear loads in three-phase islanded distribution networks, several approaches based on digital repetitive control has been suggested in [48]-[50]. The work by Cárdenas et al. [50] presented a repetitive control technique to achieve low load-voltage THD in four-leg matrix converters feeding non-linear loads, as depicted in Fig. 7. The main task of this controller is to mitigate the harmonic distortion of non-linear loads. Given that the nature of distortions is periodic, the repetitive control strategy can easily manage the distortions caused by nonlinear loads. The reason is that such a simple learning control technique provides a high gain at the fundamental frequency. Nonetheless, this technique is limited by slow dynamics, poor tracking accuracy, large memory requirements, and poor performance against non-periodic disturbances.

Deadbeat and sliding-mode controllers exhibit excellent dynamic performance in the direct control of the instantaneous inverter output voltage. They can prevent overshoot and ringing, even with their fast response. However, these

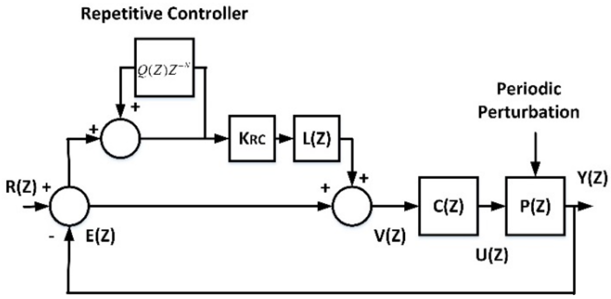

Fig. 7. Control diagram of repetitive control presented in [50].

techniques suffer from disadvantages such as complexity, sensitivity to parameter variations and loading conditions, and steady-state errors.

In [51], by combining DB with repetitive technique, an improved controller is designed to regulate the voltage and frequency of an islanded microgrid. The control strategy can effectively cope with unbalanced and nonlinear loads. To eliminate the impact of load dynamics, this technique employs a feed-forward compensation. Furthermore, a current control scheme is used to regulate the dq components of the voltage source converter. Although popular for current-error compensation, the DB predictive controller is quite complex and sensitive to system parameters. Moreover, the effectiveness of the suggested technique in multi-bus microgrids has not been evaluated.

A new control strategy based on the dynamic reference voltage hysteresis for controlling three-phase four-leg inverter is proposed in [52]. In this approach, the stability of the system is improved by designing the differential negative feedback. The proposed method is designed to suppress the harmonic current. Although this scheme brings a fast response, it suffers from variable switching frequency.

B. PR controllers in the Stationary Reference Frame

The PR controller has attracted growing interest in instantaneous voltage control of three-phase VSIs [53]-[59]. In [53], a droop-based control strategy is offered to share unbalanced and nonlinear loads between DG units in an autonomous microgrid. The proposed method is composed of an internal current loop and an external voltage loop in the abc coordinate system. The voltage loop is realized by the PR regulators in the abc reference frame. The suggested method can independently control the phase voltage of four-leg VSIs. However, a major drawback of this approach is its complex matrix controllers. Moreover, this approach is sensitive to frequency variation and to the phase shift of current sensors.

The work by Rokrok and Hamedani [54] presented an improved control strategy for the inverter-based DG unit in islanded mode, as shown in Fig. 8. The authors utilized two cascaded feedback loops and a feed-forward path to meet the power quality requirements under an unbalanced load condition. The cascaded loop comprises an internal current controller and an external voltage loop, so that the voltage and

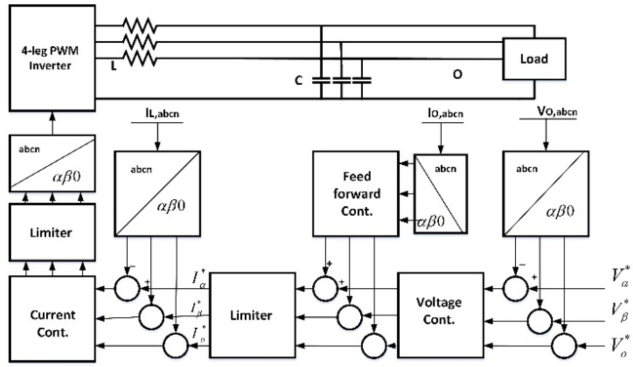

Fig. 8. Control strategy for the autonomous VSI suggested in [54].

current can be adjusted within the standard values. The current control loop is designed by the state feedback method, whereas the outer voltage loop is implemented by the PR regulator. The PR controller can effectively compensate for the low-order harmonics. However, the method suffers from serious limitations, such as the sensitivity of the controller to frequency variation and to the phase shift of current sensors.

Savaghebi et al. suggested a secondary control strategy for voltage unbalance compensation in a stand-alone microgrid in [55]. The local controllers are responsible for generating accurate gate signals for VSIs. It comprises an inner current loop, an outer voltage loop, a virtual impedance controller, and a droop controller. The outer voltage loop and the inner current controller are implemented using the PR compensators in the stationary reference frame. The active and reactive power sharing unit is also designed based on the positive sequence active and reactive powers. Moreover, a derivative coefficient term is added to the positive sequence active power sharing loop to enhance the dynamic behavior of the power control. The virtual resistant loop is also added to the local control unit to damp the oscillations of the system. To control the unbalanced voltage, a secondary level compensates for the voltages by sending appropriate signals to the local controller.

Hamzeh et al. [56] suggested a novel methodology for the autonomous operation of a multi-bus microgrid under an unbalanced load condition. The suggested method consists of a droop control, an external voltage loop, an internal current loop, and a negative sequence impedance controller (NSIC). The droop controller effectively shares the active and reactive power among DG units, and the external voltage loop adjusts the load voltage. This approach suggests an effective solution to compensate the negative sequence current of the unbalanced loads on the basis of sharing the negative sequence current among local and non-local loads.

A novel methodology based on the stationary reference frame in two levels has been proposed in [58]. The primary control structure contains a droop control, a virtual impedance loop, an external voltage loop, and an internal current loop. This level is designed to effectively share the active and reactive powers. In addition, the frequency deviations are restored by the secondary control. The internal current loop is implemented based the PR regulator in the stationary reference frame.

The proposed approach presented in [59] is fundamentally the same as that mentioned in [56]. This approach presents a new multi-functional control strategy that compensates the harmonic currents of nonlinear and unbalanced loads in an islanded microgrid. The proposed controller is composed of a droop controller, a voltage controller based on the multi PR controller, a virtual negative sequence controller, and a harmonic impedance controller. Moreover, an internal current loop with a proportional regulator is applied to the stationary reference frame to generate the switching signals. This method can control the bus voltages and effectively share the negative sequence currents and the harmonics among DG units.

C. SRFPI Controllers

Synchronous coordinate systems with PI controllers are widely used for VSIs in islanded distribution networks, because this approach provides zero steady-state error. Nonetheless, unbalanced condition leads to non-zero steady-state errors in synchronous coordinate systems. To cope with this challenge, low pass filters (LPFs) are used in [60], [61].

A combination of synchronous and stationary frames is used to compensate for the distorting effects of nonlinear and unbalanced loads in [62]. In fact, in this method, the synchronous reference frame based on the integral regulator is applied to manage the positive and negative sequence distortions. Moreover, to compensate for the zero sequence distortion, a zero-damping band-pass filter is employed in the stationary reference frame. However, a zero steady-state error for the zero sequence component is not truly achieved because of the use of a PI compensator in the stationary reference frame.

Several approaches based on the symmetrical component calculations (SCC) have been proposed in [63]-[67] to cope with the limitations of the SRFPI method. Based on the synchronous reference frame, Vechio et al. [63] described two control strategies for three-phase four-leg inverter in a transformerless HPS. In this study, the authors compared the main characteristics of these two methods. The first method utilizes the conventional PI regulators in the dqo reference frame to effectively control the voltage and current in desired values. Meanwhile, the second strategy is proposed on the basis of decomposition of three-phase voltages and currents. In other words, the unbalanced voltage and current are decomposed into positive, negative, and zero sequence components so that the control variables can be adjusted independently in three different sequence components. In this scheme, similar to the first method, the conventional PI regulators are applied to regulate the voltage and current variables.

The second method shows better performance than the former. The reason is that the independent control in three different sequence components provides superior performance to compensate for the unbalanced loads. However, the main limitation of the decomposition method in the dqo coordinate system is the complexity of reference frame transformation. Moreover, the method presents delays because of the use of all-pass filters for the symmetrical component calculators,. Furthermore, given that the proposed method are designed with relatively low cross-over frequency, a slow dynamic response is realized.

A new control methodology using an isochronous control function for four-wire inverter-based DG is presented in [67]. The main objectives of the suggested method are to provide flexible control scheme and appropriate load sharing for parallel grid forming inverters. The controller is implemented by using the concept of symmetrical components. The control scheme is designed for each component independently. In this study, an internal current loop and an external voltage loop in the dq frame are employed to provide the desired electrical signals for grid-forming inverter. To generate the reference signals for the current loop, the total active and reactive loads are measured. Afterward, the measured load is divided by the total rated power and is compared to the active and reactive power supplied by the inverter. Then, this difference is used as the reference current for current control loop. The proposed controller shows good performance in controlling voltage and frequency. However, this method is disadvantaged by complexity, delay, and slow dynamic response.

V. STABILITY IMPROVEMENT USING MULTI-FUNCTIONAL VSIS IN AUTONOMOUS MICROGRIDS

As previously mentioned, the control and management of autonomous microgrids without the support from the utility grid are more challenging than the grid-connected mode. Moreover, the physical inertia of islanding operation is quite smaller than the grid-connected mode. Therefore, the cut in or cut off local loads, disturbances, and small interruptions such as the output power fluctuations in DERs can cause power quality and stability issues. Specifically, the frequency and voltage quality would decline, and the system stability would deteriorate. However, with the development of power electronics, multi-functional VSIs can improve the dynamic stability and power quality [68].

Small signal stability in a microgrid is related to the feedback controller, the continuous load switching, and the power limit of micro sources [69]. Moreover, reactive power limits, load dynamics, and tap changers create the majority of the voltage and frequency stability problems in a microgrid [69].

The microgrid stability in autonomous mode is discussed in [70] and [71]. The effects of constant power load and different load conditions on the microgrid stability during autonomous mode are investigated in [72]. In [73], an active damping

TABLE I
PERFORMANCE COMPARISON OF DIFFERENT VOLTAGE CONTROL STRATEGIES IN AUTONOMOUS MODE

Voltage control structure	Type of controller	Advantages	Disadvantage
Digital control strategies	Repetitive controller	Excellent ability in eliminating periodic disturbances and ensure a zero steady-state error at all the harmonic frequencies.	Slow dynamics, poor tracking accuracy, a large memory requirement, and poor performance to non-periodic disturbances.
	Dead-beat controller	Control of the harmonics, excellent dynamic performance in direct control of the instantaneous inverter output voltage, prevent overshoot and ringing.	Complexity, sensitivity to parameter variations, loading conditions, and steady-state errors.
	Sliding-mode controller	Excellent dynamic performance in direct control of the instantaneous inverter output voltage, prevent overshoot and ringing, an acceptable THD, if it is designed well.	The problem in discrete implementation, complexity, sensitivity to parameter variations and loading conditions, and steady-state errors.
	Hysteresis controller	Robust and simple, their implementation does not require complex circuits or processors, and fast transient response.	The major drawback of this controller is the frequency of switching variable with changes in parameter loads and operating conditions.
PI control	SRFPI controller	The zero steady-state error, independent control of active and reactive components.	For unbalanced systems, it does not ensure good performance. They are not the best solutions to compensate higher harmonic disturbances and it has a complex structure.
PR control	PR controller in the stationary reference frame	Simple to implement, ability in eliminating the steady-state error associated to the tracking problem and ability in control of the harmonics.	The mains being exponentially decaying response to step changes, and great sensitivity and possibility of instability to the phase shift of sensed signals.

control with a virtual resistance is used to regulate the voltage and frequency of the islanding mode. The efficacy of voltage feedback signal to adjust the autonomous voltage and frequency control with an internal oscillator in islanding mode are investigated in [71]. Power sharing among VSIs with various voltage and current controllers with associated stability is presented in [74].

Multivariable control methods have been proposed in [75], [76] to improve the dynamic response of microgrids and ensure robust stability against uncertainties in load parameters because of the presence of nonlinear loads. Studies on multivariable control of microgrids have primarily focused on the voltage regulation of a single-DG-unit microgrid with its dedicated RLC load, where load parameters are perturbed around their nominal rated values [75] or within a pre-specified range [76].

An adaptive droop function is employed in [77] to preserve the stability of the system for different loading conditions. An adaptive feed-forward compensation mechanism is proposed in [78] to improve the stability of the microgrid at different operating points. A hierarchical control scheme is proposed in [25] to improve the flexibility and expansibility of droop-based microgrids. This control scheme includes a primary droop controller, a secondary control loop to restore voltage and frequency to the original values after system changes, and a tertiary control to regulate the power flow between the microgrid and the external grid.

VI. DISCUSSION AND FUTURE TRENDS

Although a wide variety of control techniques have been introduced and developed to control the power quality of autonomous microgrids, meeting all of the abovementioned power quality demands at the same time is difficult. The reason is that each control strategy can cope with a specific requirement. In this sense, a critical comparison among recently used voltage control techniques for power quality improvement in islanding operation is presented in Table I.

In view of the availability and low cost of advanced digital signal processors, digital control strategies based on repetitive control, dead-beat control, hysteresis control, and discrete-time sliding-mode control have been suggested in recent years. Digital repetitive control has been offered to decrease harmonic distortions of the output voltage created by nonlinear loads, with its excellent ability in eliminating periodic disturbances. However, in practical applications, this technique is limited by slow dynamics, poor tracking accuracy, a large memory requirement, and poor performance against non-periodic disturbances.

Deadbeat and sliding-mode controllers exhibit excellent dynamic performance in the direct control of the instantaneous inverter output voltage. A unique feature is that, even with their fast response, if wisely designed, they prevent to overshoot and ringing. Despite the advantages that they offer, these techniques suffer from drawbacks such as complexity, sensitivity to parameter variations and loading conditions, and steady-state errors. The hysteresis controller is easy to implement. However, the major drawback of this controller is the frequency of switching variable with changes in parameter loads and operating conditions.

In the SRFPI controller, the zero steady-state error is ensured by using a conventional PI regulator. However, complexity, delay and the slow dynamic response are the main disadvantages of this method. Moreover, it cannot cope with harmonic distortions and unbalanced conditions effectively.

The PR controller has shown superiority in eliminating the steady-state error associated to the tracking problem of AC signals. This technique has also attracted increasing interest in instantaneous voltage control of three-phase VSIs. Moreover, it can eliminate harmonic disturbances.

Further research should be conducted to cover all the power quality demands at the same time. Based on the analysis of previous publications, further research is recommended to be conducted in the following areas; (1) in spite of the numerous investigations that have been done in the field of microgrid, none of the control techniques have been considered an effective solution to compensate reactive current, harmonic, and unbalanced current at the same time. Future research should therefore concentrate on the novel power electronic configuration such as multi-level inverters to fulfill all of the abovementioned requirements at the same time; (2) all of the previously mentioned publications used VSIs by small capacity in their research, whereas in industrial applications, the capacity of VSIs is much more than the experimental prototype; (3) considerably more work should be conducted to exploit new control strategies; that is, innovative control approaches such as LQR and robust control should be applied to achieve better performance; and (4) many multi-functional VSIs in autonomous microgrids might weaken the stability performance of islanding operation to prevent disturbance. Further research should be exerted to analyze the stability of these microgrids.

VII. CONCLUSION

In recent years, multi-functional VSIs have attracted increasing attention for their advantages on auxiliary services for power quality enhancement in stand-alone distribution networks. Control strategies for power quality and stability enhancement in autonomous microgrids using multi-functional VSIs are comprehensively reviewed in this study. Furthermore, these control schemes are discussed and compared in detail. Lastly, several suggestions for future work are proposed. This paper is expected to be a useful reference for researchers and engineers involved in multi-functional VSIs.

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