INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
V. Lavanya and N. S. Kumar , *Vol.8, No.1, March, 2018*

A Review: Control Strategies for Power Quality Improvement in Microgrid

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Received: 03.06.2017 Accepted:29.07.2017

Abstract- Power generation through the renewable energy sources has become more viable and economical than the fossil fuel based power plants. By integrating small scale distributed energy resources, microgrids are being introduced as an alternative approach in generating electrical power at distribution voltage level. The power electronic interface provides the necessary flexibility, security and reliability of operation between micro-sources and the distribution system. The presence of non-linear and the unbalanced loads in the distribution system causes power quality issues in the Microgrid system. This paper explores and reviews different control strategies developed in the literature for the power quality enhancement in microgrids. Also comparisons of different control methods are presented with suggestions for future research.

Keywords Renewable energy sources, Distributed Energy Resources, Distributed generation, microgrid, controllers, power quality.

1. Introduction to Distributed Generation and Microgrids

Conventional power systems are facing problems like depletion of fossil fuels, poor energy efficiency and environmental pollution etc. Also the ever increasing demand for reliable and quality power delivery put lot of pressure on conventional power system. All these have paved the way for the generation of power locally at distribution voltage level with the help of non-conventional / Renewable energy resources like wind, solar photovoltaic cells, hydro, natural gas, biogas, fuel cells etc., [1]. The power system reliability can also be improved by way of integration of large number of small distributed energy resources (DER) [2]. DERs are usually of smaller capacity having low energy density, as they are dependent on geographical nature of a region. The transmission and distribution losses are minimized as the power generation at distribution voltage level is very closer to the load centers. A DER can be directly connected to the distribution network or can be interconnected to form microgrid (MG). DERs can be used to perceive the benefits like increased energy efficiency, reduced carbon emission and improved power quality and reliability (PQR) [3]. In [4], integration of DERs, operation of microgrid, its control aspects, power quality issues in microgrid system is elaborated.

In addition to these advantages, the performance and efficiency of Distributed generation (DG) has been significantly improved due to the advancements in the power electronics technology. Deployment of inverter interfaced

DG in power systems mitigates the peak load and improves the power quality [5 - 7].

A microgrid (MG) is a group of loads, DG units and energy storage systems (ESS) that operate in coordination to the power system at the distribution voltage level. The point at which the microgrid is connected to the main grid is called point of common coupling (PCC) [8, 9]. Generally, microgrids are operated in grid connected mode; but it is usually designed in such a way that they have sufficient amount of power to feed in atleast a part of the load even after the disconnection from the utility grid. The control and operational strategy needs to be taken care for the operation of microgrid which remains in isolated (islanded) mode of operation. Based on the type of distributed energy resource (DER) units, their level of dissemination, characteristics of load connected and power quality constraint, the control and operation of microgrid is different from that of traditional power generation systems [8, 10, 11, 12].Different micro sources, storage devices and concept of microgrid along with operation of microgrid and the role of microgrid in the environment have been discussed in [13-15].

In grid connected MG system, the system dynamics are taken care by the utility itself whereas in islanded mode, the dynamics are dictated by the micro sources themselves [16]. MG acts as a single controlled entity i.e., as an aggregated load within the power system and it supplies uninterruptible power to meet the local electrical/ heat requirements, increases reliability, minimizes the losses and offers good voltage support. In utility connected mode of operation, the micro sources are being controlled to supply the stipulated power in to the system and the microgrid should be designed in such a way that smooth transition takes place from grid connected to isolated mode or vice versa depending upon the grid conditions. While working in stand-alone mode, sources are controlled so that all the local loads are fed by micro-sources themselves, retaining the voltage and frequency as per the required values [16, 17].

Voltage Source Inverter (VSI) based microgrid are being designed and developed with the help of different control strategies focusing to supply harmonic free sinusoidal voltage and current to the power system even when the loads connected are of non- linear in nature or under grid voltage disturbances [18,19]. Different control structures for the Distributed Power Generation systems (DPGS) based on micro-sources is discussed focusing on harmonic compensation in [20]. Also the authors have addressed different control strategies that can be implemented during the unbalanced grid fault conditions. The behavior of the inverter in a microgrid system under different operating scenario like failure of utility power, variation of frequency, harmonic currents on the inverter side and fault currents in the grid connected and islanded mode have been analyzed and demonstrated in [21]. With the help of the study, the authors have concluded that intelligent controllers are needed for inverters in a microgrid system to have reactive power control, voltage support and to eliminate the harmonics.

In this paper, different control strategies that are developed in the literature for the improvement of power quality in microgrid systems have been reviewed and discussed. Further, the review is extended to discuss different filters, power quality compensators and optimization techniques that are dealt in the literature for the improvement of power quality in microgrids.

This paper is organized as follows: In Section 2, the Power quality issues in microgrids are presented. Section 3, discusses power control strategies in microgrids. Section 4, analyzes the features and implementation of different controllers for the Power Quality improvement in microgrids. Section 5 discusses about the Filters for power quality improvement. Power Quality compensators are presented in Section 6. Section 7 discusses the possibility of Optimization techniques for the PQ Improvement. Comparison of different control strategies and suggestions for future research are given in section 8. Finally, section 9 proposes the conclusion.

2. Power Quality in Microgrids

Power quality is defined as maintaining a pure sinusoidal voltage waveform with the defined magnitude and frequency within the prescribed limit without having any deviations in the shape and the magnitude [1]. Power quality disturbances take place in a system when there is any deviation in magnitude and frequency of the power waveform beyond the specified range; hence creates problems to a customer. The different types of power quality disturbances are: (1) Voltage unbalance, (2) Transients, (3) Voltage sags and swells (4) Over-voltages and under-voltages, (5) Outage, (6) Harmonic distortion, (7) Voltage notching, (8) Flicker and (9) Electrical noise.

Due to the presence and widespread use of several sensitive electrical and electronic gadgets in industrial and commercial sectors, Power Quality and Reliability issues have gained importance in the recent years [1]. Distributed generation (DG) and integration of resources (DERs) in the form of microgrids helps to improve the power quality and hence the reliability of the power delivered in meeting the needs of the customers. The capability of microgrids operating in two different modes helps to supply the high priority / critical loads during the periods of power failure from the utility grid. The transition from grid-connected to stand-alone modes can be done by the seamless operation of Static Transfer Switch with the help of intelligent controllers to avoid any disturbance to the sensitive / critical loads [1, 22]. Power quality is a major concern in small scale islanded systems because of the presence of non-linear and unbalanced loads, which forms a larger proportion of the total load. This creates the voltage distortion problems like voltage sags / swells in a relatively weak system [6, 23,24]. In islanding mode, the disturbances like voltage distortion and unbalance are most likely case as the line impedance is very high and the load distribution is of uneven when compared with the grid connected mode. In order to filter out the harmonics and to suppress the unbalance, the power electronic interface converter (inverter) can be controlled effectively [25]. In grid connected mode, the disturbances like unbalanced utility voltages and voltage sag are the most frequent problems [26, 27].

As the voltage generated from the sources like wind, solar, fuel cells etc., are highly intermittent in nature, they cannot be connected directly to the grid. An interface converter is needed to connect the power output from these sources to ac power distribution system. In [28, 29], the power electronic interfaces that are used for the integration of Renewable energy sources (RES) and Energy storage systems (ESS) are discussed along with the technique with which these can be connected, as the need of power electronic interface is subject to the requirements related to RES and its effect on power system operation. A DG inverter is used to convert direct current to alternating current and which adjusts the phase angle and amplitude of the output voltage by having proper control technique so as to deliver the required real and reactive power. Hence power quality problems get compensated with the help of control strategies of the interfacing inverter [30 - 32].

3. Control Methods for Voltage and Power Flow Control in Microgrid

The structure of inverter based microgrid is shown in Fig.1. The controller of an interfacing inverter includes power control loop, voltage control loop and current control loop. The external power control loop includes droop characteristics for real and reactive power in order to maintain the magnitude and frequency of the inverter output voltage. The voltage and current controllers are used to eliminate the high frequency disturbances and hence damping out the oscillations with the help of filter. [16, 33, 34,35].

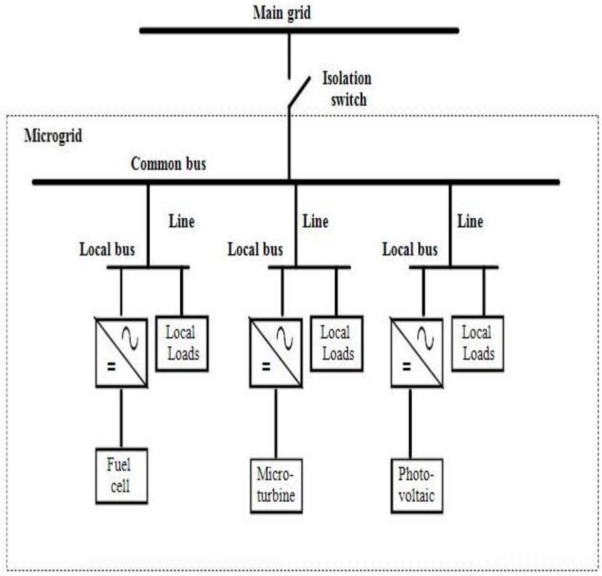

Fig. 1. Structure of Inverter based Microgrid

3.1. *Droop control method*

Droop control is an efficient method which is mainly used to improve the real and reactive power control. Droop controllers are applicable for both modes of operation of a microgrid [11]. The active power-frequency (P-ω) droop controller and reactive power-voltage (Q-V) droop controller are used in microgrid systems to achieve power sharing [34-51]. The block diagram of droop controllers [34] used for real and reactive power sharing are shown in Fig.2 and Fig.3.

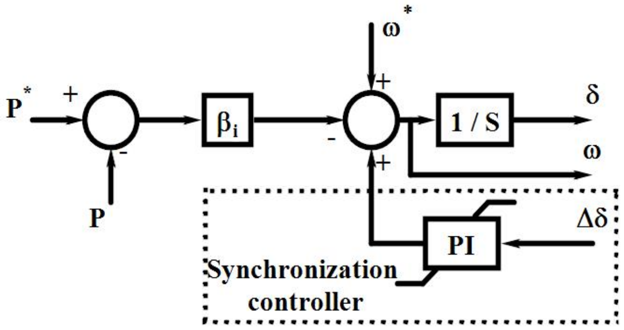

Fig.2. Real power compensation

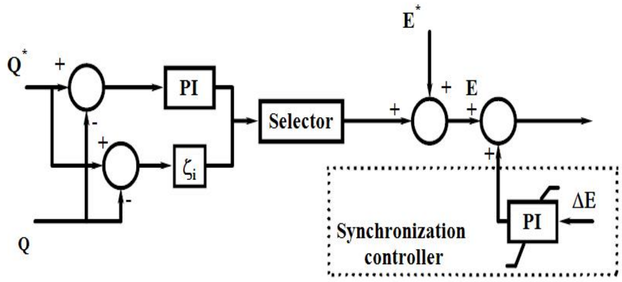

Fig.3. Reactive power compensation

The mathematical expressions governing the droop controllers P – ω are given by the equations (1) and (2)

$$\omega_j(t) = \omega^* - \beta_j\left(P_j^* - P_j(t)\right) \tag{1}$$

$$\beta_j = \frac{\omega^* - \omega_{min}}{P_j^* - P_{j,max}} \tag{2}$$

where $P_j(t)$ is the actual active power output of the Distributed generation system and β_j is the slope of the P- ω droop characteristics [34].

The mathematical expressions governing the droop controllers Q – E are given by the equations (3) and (4)

$$E_j(t) = E^* + \zeta_j\left(Q_j^* - Q_j(t)\right) \tag{3}$$

$$\zeta_j = \frac{E^* - E_{min}}{Q_{j,max} - Q_j^*} \tag{4}$$

where $Q_j(t)$ the actual reactive power is output of the distributed generation system and ζ_j is the slope of the $Q - E$ droop characteristics [34].

For a stand-alone system, to minimize the voltage Total Harmonic Distortion (THD) at the PCC, algorithms are proposed based on droop control, addressing the issues related to reactive power sharing [44]. A capacitive virtual impedance loop is applied to suppress voltage harmonics present at the PCC.

In grid connected mode [52], an inner current control loop is used to modify the injected active and reactive power as a function of grid voltage and frequency, whereas in autonomous mode, the power converter is operated in three sub-modes like conventional droop mode, PQ mode and Synchronization mode. In order to balance the microgrid power, (V_g/V_{dc}) droop control [53] is used, which varies the dc link voltage so as to get the required voltage at the inverter output. P-V_g droop control avoids the voltage limit violation when the voltage exceeds the constant power band. A hierarchical control, which includes droop control and virtual impedance loop based on stationary reference frame is proposed [54] for VSI based MG system, where the phase angle and voltage reference are adjusted according to real and reactive powers.

A virtual inductor is introduced [55] at the inverter output in a power electronics interfaced DG system to avoid the coupling between real and reactive powers. Online impedance voltage drop effect estimation has been implemented in order to achieve the required power sharing along with local load demand compensation.

An enhanced droop control method with online virtual impedance adjustment, uses frequency droop control [56, 57], to compensate reactive power load, imbalance power load and harmonic power load sharing errors. The Voltage Controlled harmonic compensation method [58, 59] provides voltage and frequency support in a microgrid. Voltage controlled mode is flexible compared to current controlled mode as it is capable of operating in compensation, rejection and uncontrolled mode. Further, power sharing is improved by changing the voltage bias of the conventional droop characteristics activated by a sequence of synchronization events through a low bandwidth communication network [60].

Transient response of the droop controller is improved by measuring the average power using the integration method rather than traditional low pass filter [61]. Virtual inductance is used in the controller which rejects the grid voltage harmonic disturbance and hence improves the output current quality. A voltage based droop control strategy mitigates the unbalance in islanded and grid connected microgrids [62, 63]. Also virtual output impedance loop proposed in [64] enhances the load sharing stability, the quality of P-ω and Q-V droop control and suppresses Negative Sequence Circulating Currents (NSCC) in parallel inverters. A wireless load sharing controller based on Virtual impedance loop [65] improves the system damping, provides automatic harmonic current sharing and reduces the effect of phase errors on active power sharing.

The reactive power sharing with $Q - \dot{V}$ droop control [66] is made independent of the output line impedances by regulating the voltage magnitude with $\dot{V}$. A generalized droop control (GDC) [17, 67] decouples the active and reactive power impacts on the voltage and frequency. It provides a simultaneous voltage and frequency control but is highly dependent on the line parameters between inverter interfaced distributed generation and load.

4. Power Quality Improvement with Controllers

The VSI in a microgrid system can be controlled in different methods based on the Distributed Power Generation Systems (DPGS). The system dynamics (stability) and quality of power delivered is improved by way of utilizing the controllers and hence the satisfactory performance of the system can be obtained. Voltage regulation design in inverter-based DG is of two forms: 1) voltage control loop design and 2) current control loop design. The different voltage and current controllers that are developed in the literature are presented and discussed in this section.

4.1. Proportional-Integral (PI) controller

PI controllers are in use for quite a long time especially in the stationary reference frame; but, it has its own drawbacks like steady-state errors, sensitive to parameter variations etc., Proportional–integral (PI) controllers are used to generate the reactive current component especially in direct-quadrature axis reference (d-q) frame as they have good performance when regulating DC quantities [20]. The basic transfer function of a PI controller is given by the equation (5).

$$G_{PI}(s) = K_p + \frac{K_i}{s} \tag{5}$$

where K_p is the proportional gain and $K_i$is the integral gain of the PI controller.

PI controllers are simple and can regulate the fundamental component, but there exists bandwidth limitation and poor harmonic compensation which leads to steady state error [5, 33].

A control strategy for three-phase VSI integrating the three-phase load, utility grid and the dc microgrid (DCMG), under various operating situations is discussed in [68] which use dual PI controllers for ac voltage regulation and inner current control [69]. Proportional-Integral (PI) controller along with Proportional-Resonant (PR) and Dead Beat (DB) controllers have been implemented [70] to generate the reference parameters and the performances of the controllers are discussed under faulty grid conditions. The PI control scheme gives better performance in balanced systems, when synchronously rotating (d, q) reference frame is being used. The PI controller is not applicable to unbalanced case, which is the most common occurrence in microgrids.

A frequency adaptive hybrid voltage and current controlled method (HCM) is proposed [38, 39] to accomplish superior harmonic compensation performance using distributed generation unit with power electronics interfaces. The conventional droop control method is replaced by a Proportional –Integral regulator when DG is operating in grid connected mode. The frequency in a microgrid system is determined by adopting frequency reference obtained from power control loop as a time varying parameter rather than using phase locked loop (PLL) or frequency locked loop (FLL). Local harmonic compensation is taken care by HCM [39] with smooth transition between the modes of operation. A proportional-integral (PI) controller also helps to achieve accurate active and reactive power control and sharing in a grid connected system [55]. The steady state reactive power regulation and compensation of impedance voltage drop is achieved with the controller.

Two separate synchronization PI regulators [40, 41], are used for external real and reactive power loops in order to achieve synchronization of microgrid with utility by aligning the voltage phasors at both ends, which ensures smooth transition from islanded mode to utility connected mode when the fault is cleared.

4.2. Proportional –Resonant (PR) controller

Proportional resonant (PR) controllers [20, 30, 70, 71] are widely used when the control variables are sinusoidal as these controllers enhance the reference tracking performance when used in stationary reference frame. PR controllers also alleviate the shortcomings associated with PI controllers. PR controllers are used to minimize the steady state error associated with the system and reduction of individual harmonics. The block diagram of PR controller is shown in Fig.4.

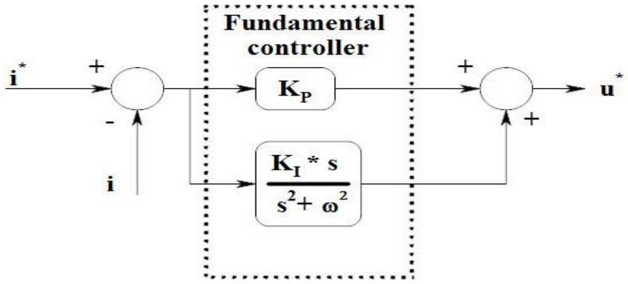

Fig.4. Block diagram of Proportional –Resonant controller

In general the PR voltage and current controller equations will be of

$$G_V\,(s) = k_p\,V + \frac{k_r\;V\,s}{s^2+\omega^{*2}} \tag{6}$$

$$G_I(s) = k_p\,I + \frac{k_r\;I\,s}{s^2+\omega^{*2}} \tag{7}$$

PR controller [37] is designed to ensure excellent reference tracking and hence regulates the load voltage. Conventional droop controller is used for sharing the average power components of the loads and a negative-sequence output impedance control (NSIC) strategy is proposed to effectively share the oscillatory portions of the load power when the unbalanced loads are present. For the compensation of voltage unbalance in an islanded mode, a stationary reference frame based control scheme is proposed [30,54], where authors have used droop controllers, a virtual impedance loop [72 - 74], voltage and current controllers of resonant type and a compensator for unbalance compensation.

A hierarchical control scheme developed in [75, 76], enhances the voltage quality of sensitive load buses (SLB) in microgrids. To damp out the oscillations and to have an independent control of P and Q, virtual impedance loop has been designed to set the phase angle and magnitude of output impedance and thus enhances the performance and stability of the controllers.

Proportional resonant controllers are used mainly used to have a control on voltage and current, in a stationary reference frame [77]. For minimizing current harmonic distortions in grid-connected VSIs with an LCL filter, a new current feedback control strategy is proposed [78] which use the weighted average value of the currents flowing through LCL filter as the feedback to the PR regulator. The voltage unbalance compensation has been achieved by reducing the negative sequence voltage using PR current controller [79]. A Dual Second Order Generalized Integrator – Frequency Locked Loop (DSOGI-FLL) is used to extract the positive and negative sequence component [80, 81] under unbalanced and distorted conditions in order to achieve grid synchronization.

A proportional controller (P) and a harmonic resonant regulator (R) tuned at the fundamental and harmonic frequency has been designed [82] without any co-ordinate transformation to filter out the negative sequence components and to decompose the harmonic components. Harmonic output voltage components can be controlled by resonant controller tuned at the harmonic frequency [82, 83].

Another control scheme proposed in [84] focuses mainly on reduction of current harmonic distortion in adverse conditions when grid experiences abnormal conditions like harmonics and imbalances in the voltage waveform. The authors have analyzed, whether standard resonant current controller can be used under abnormal operating conditions. The standard resonant controller has two compensators Proportional Resonant (PRES) compensator and Resonant harmonic compensator (RESH) connected in parallel. The PRES compensator is employed to track the fundamental component of the current reference signal whereas the RESH compensator is used to attenuate the selected grid current harmonics.

Proportional-resonant controllers (PR) are employed in both single-phase and three-phase grid converters and their suitability for current control is demonstrated in [85]. Tuning of PR controllers can be done at grid frequency for fundamental current regulation and at the harmonic frequency to compensate harmonics. A hybrid system is implemented in [86] which include a proportional integral (PI) controller and a generic harmonic resonant controller in a frame rotating at the harmonic frequency.

An enhanced virtual impedance control scheme addresses the issues related to load sharing at fundamental and selected harmonic frequencies, where implementation of modified resonant voltage controller is done to provide accurate power sharing and to mitigate voltage harmonics at PCC, without extracting the harmonic component and fundamental component [42, 87].

4.3. Hysteresis controller

Hysteresis current control is a controller having non-linear control loops with hysteresis comparators. The block diagram of hysteresis controller is shown in Fig.5. A VSI can be controlled with a hysteresis controller in such a manner so that the current fed in to the grid has to follow a reference value [88]. Hysteresis controller is simple in structure, robust in nature, is independent of load parameter variations. It also provides good transient response. Only disadvantage is the switching frequency of the controller is not fixed. To obtain fixed switching frequency, a controller has to be designed with adaptive band [20, 89].

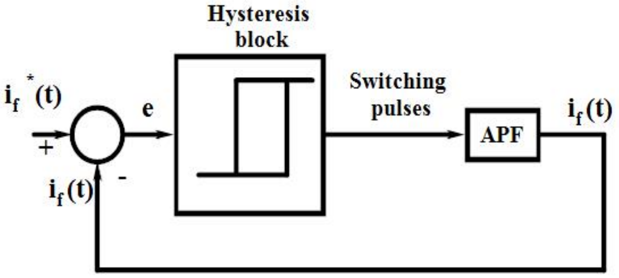

Fig.5. Block diagram of hysteresis controller

Unified Power Quality Conditioner based power distribution network addresses voltage sags and swells, current and voltage harmonics compensation mainly based on adaptive hysteresis band control [90]. A novel current tracking control strategy combining the hysteresis control and the one cycle control are designed in [91], to force the inverters to track the reference currents generated. In [92] ,a novel intelligent controller has been developed which acts as an active power filter (APF) to the main grid and autonomously detects any power quality problems, filters out load-created harmonics and compensates unbalances and/or DC offsets resulting from the local AC load connected at the point of common coupling (PCC). A modified hysteresis current controller is used to generate the drive signals for VSI which overcomes the problem associated with switching frequency in a common hysteresis current controller.

An adaptive hysteresis band control algorithm presented in [93] modulates the width of the hysteresis band dynamically to control the switching frequency of the inverter. A reference current generator based on mathematical model has been employed to control the current injected in to the grid which improves the power quality.

4.4. Repetitive controller

Repetitive control is derived from the internal model principle with which periodic error occurring in dynamic systems can be eliminated. The block diagram of the repetitive controller is shown in Fig.6. Repetitive feedback controllers (RC) are basically based on the concept of iterative learning control (ILC). Repetitive controllers are suitable for utility converters having reference signals and / or the disturbances are of periodic in nature. The periodic error associated in the systems can be eliminated with a repetitive controller as it acts as a periodic waveform generator [94] which is in addition to the closed loop control action that it performs.

A repetitive controller (RC) [95] is used to follow the reference current and eliminate the errors due to the grid voltage and the load current variations. The load reactive power and the current harmonics are very well compensated in a grid-connected single-phase H-bridge inverter based on RC [96].

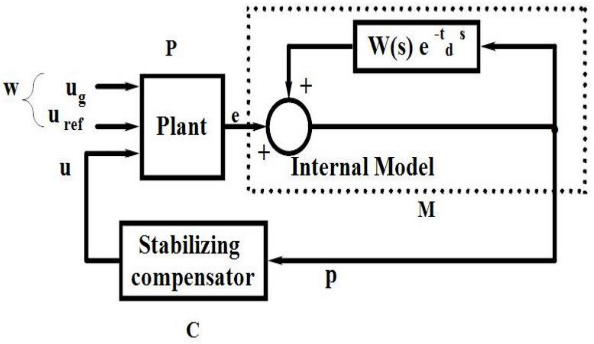

Fig.6. Block diagram of the repetitive controller

A mixed-frame and a stationary-frame repetitive control scheme proposed in [97] deals with the harmonic problem that takes place in the utility grids. A PR regulator in the stationary frame for fundamental positive- and negative-sequence current control and a number of simple repetitive delay lines in either the synchronous or stationary frame for harmonic compensation has been employed to reject the grid and load disturbances.

An improved repetitive control scheme adopting a new Finite Impulse Response (FIR) filter design method with adjustable linear-phase low-pass characteristics improves the tracking performance and reduces the harmonic distortion for the grid-connected VSI systems [98].

4.5. Dead Beat controller

Deadbeat control has the advantages like high tracking speed and control accuracy, but is sensitive to the accuracy of system model. A deadbeat current controller [5] is used to track the reference current generated by the other controllers in the system. To attain proper voltage regulation and to mitigate the voltage disturbances, the authors have used a hybrid voltage controller for generating the reference current [5]. In [99], the authors have analyzed the performance limitations of digital dead beat current controller applicable to three phase voltage source converters considering stability as a parameter and developed a modified line voltage estimation technique to improve the robustness of the controller when there exists parameter variations.

A dual sequence voltage controller developed in [100] effectively mitigates the unbalanced voltage disturbances. A high performance dead beat type current controller has been proposed in [101] for inverter-interfaced distributed generation (DG) for improving the transient response. A novel deadbeat current controller is developed [102] for single phase PV grid connected inverters. Discrete-time model of the system is used to produce the inverter voltage for achieving the current reference. A novel adaptive self-tuning load model [103] with deadbeat current control for a voltage-source inverter proves to be inherently self-commissioning/self-tuning and guarantees optimum performance, without the constraint conditions.

4.6. H_∞ controller

Current controller consisting of an internal model and a stabilizing compensator has been proposed in which the controllers have been designed based on H_∞ control [104 - 106]. H_∞ repetitive current controller injects balanced current to the grid even under grid disturbances. The performance of the H_∞ - repetitive controller seems to be very good compared to the conventional PI, PR, and DB controllers [106]. The output current THD level is within the prescribed limit, even though the loads are of nonlinear /unbalanced in nature and this holds good during grid-voltage distortions as well [107].

The cascaded current–voltage control based on H_∞ repetitive control strategy [108] improves the power quality considering the inverter voltage and the grid current. Voltage loop and current loop for a micro source inverter based on H_∞ loop shaping controller stabilizes the nominal and perturbed system [109].

The H_∞ control theory [110] improves the performance of the system when there is a changeover in the modes of operation of a microgrid, with real-time accuracy leading to improvement of power quality. In [111,112], H_∞ -Repetitive controller minimizes the harmonics in a grid connected microgrid system.

4.7. Fuzzy and neural based controllers

A control strategy based on Fuzzy logic controller and neural networks improves the functionality of the non-linear DG interface to control real and reactive power and mitigate harmonics, unbalance, and voltage fluctuations. In [113], a Fuzzy Logic Controller (FLC) is used for voltage regulation and Adaptive Linear Neuron (ADALINE) is used for the elimination of harmonics and unbalance compensation. A robust interfacing scheme for grid connected DG inverters has been presented in [114] which consist of Dead-beat natural frame current controller; adaptive neural network (NN) based disturbance estimator and robust sensorless synchronization loop. NN's self-learning feature allows a feasible and adaptive controller design which gives good performance even though disturbances are there in the grid side.

A new intelligent droop control using adaptive neuro-fuzzy inference system (ANFIS) [67] provides a solution for intelligent model-free based generalized droop control (GDC) for attaining voltage regulation and frequency regulation in an isolated system.

FLC is implemented along with the conventional PI controller for voltage regulation and frequency regulation in AC microgrid [115, 116]. The superiority of FLC is the result of its ability to manage the non-linear behavior of many practical systems of complex control structures by taking advantage of heuristics and expert knowledge of the process being controlled [117-118].

5. Filters for Power Quality Improvement

A novel control strategy is proposed in [119] for the grid connected inverter which can be utilized as a (a) power converter (b) shunt Active power filter (APF). When it operates as a converter, it injects power generated from RES to the grid. Also as a filter, it compensates the current unbalance; also it eliminates the load current harmonics.

The power quality compensator proposed in [95] can perform the following two functions, power control and active power filter; Elimination of harmonics, compensation of reactive power and mitigation the load unbalance are the main objective of the power quality compensator. Unified Power Quality Conditioner system proposed in [90] consists of two voltage source inverters acting as series active and shunt active power filters [120- 122]. To compensate current and voltage-quality problems of sensitive loads, controllers are developed [123] for Unified Power Quality Conditioner with a novel reference current generation method.

Frequency/sequence selective filters [124] are also used for improving power conditioning capability in voltage-source inverter (VSI) based microgrid. The nonlinear load current harmonic compensation and the control of active power flowing from the renewable energy source to the grid can be done with the help of DG units which can function as shunt active power filter [96,125]. Here the grid current is not getting disturbed and hence it remains almost sinusoidal in shape.

6. Power Quality Compensators

A decentralized power sharing algorithm [126] controls the power management. The DG is used for compensating the power quality issues like the compensation of unbalance and harmonics in load in which case the reference current used for improving the power quality takes care of the active and reactive power to be supplied by the micro-sources. A three phase Active Power Conditioner (APC) presented in [127] acts as an interface between RES and the microgrid which is used to improve the power quality in a microgrid system. An improved control strategy is used to compensate the harmonics and to allow the line current to be balanced and sinusoidal even under unbalanced load conditions.

A power quality compensator proposed in [95] mainly focuses on achieving a high power factor and low distortion thus making the system more flexible. In this, the grid current is shaped to be balanced sinusoidal rather than the inverter output current and is made in phase with the grid voltage. Power Quality Compensator proposed in [40,41] consists of series inverter and shunt inverter where the series inverter is implemented to maintain a set of balanced line currents by introducing negative and zero sequence components to compensate for voltage unbalance and to limit the flow of large fault currents when the voltage level goes below the limit (sag) and the shunt inverter is controlled to maintain a set of balanced sensitive load voltages and to dispatch power and share the demand with the other parallel connected DGs, when MG islands. Control algorithm includes Power control algorithm (P-f and Q-V droop characteristics) and Voltage (outer controller) and Current (inner controller) control (PI) algorithm. Flux-charge control algorithm is also analyzed by the authors to control the series inverter during utility voltage sags [40].

In [83], current control for regulating harmonic, fundamental positive- and negative-sequence currents has been performed by the series converter; voltage control for maintaining sinusoidal and balanced voltage under nonlinear/unbalanced load conditions has been performed by the parallel converter. Control of the series converter decides the power transfer between the grid and the microgrid. The capacity of the local system and the power demand from the distribution grid decides the reference / demanding power.

Compensation of active, reactive and harmonic components can be done using a control strategy [128] which improves the grid power factor and reduces THD of grid current. Also, independent real and reactive power control has been achieved with fast dynamic response in tracking power variations.

An adaptive Lyapunov function based control scheme [129] and a sliding mode based control scheme [130] are used to compensate the negative-sequence current components caused by unbalanced loads and to directly regulate the positive-sequence power components injected by DG units into the microgrid. A multi-objective control strategy for the integration of Microgrid in to utility grid has been investigated [131] to eliminate harmonic distortion, to supply active power and to compensate reactive power along with grid frequency regulation under fluctuating and non-linear load conditions. A Dual Voltage Source Inverter (DVSI) Scheme proposed in [132] consists of Main Voltage Source Inverter (MVSI) which is used to inject the real power generated by the microgrid and an Auxiliary Voltage Source Inverter (AVSI) which is used to perform reactive, harmonic and unbalanced load compensation and thus enhances the power quality. To mitigate the unbalanced voltages in low-voltage three-phase microgrids, negative sequence voltage compensation is done [133] where a DSOGI is used to extract positive and negative sequence components.

7. PQ Improvement using Optimization Techniques

The controllers of a microgrid system can be designed based on optimization technique. The controllers, filters and other power sharing methodology can be formulated as an optimization problem [134]. Optimization is applicable for linear as well as non-linear models of both grid-connected and islanded type microgrids. Particle Swarm Optimization (PSO) technique is employed to search for the optimal settings of the optimized parameters. In [135], the reduction of voltage harmonics in a micro-grid system of multiple DG sources with the combination of PSO-based PWM and SPWM inverters has been proposed. In [136], an optimal power control strategy based on a real-time self-tuning method is presented. The parameters considered for the performance evaluation are voltage and frequency regulation and power sharing. The performance of the system is evaluated especially when there is change in mode of operation of microgrid and during sudden change in load. PSO is an intelligent computational algorithm [43, 136] which is used for real-time self-tuning of the power control parameters. For Optimal THD control in distribution systems under non-linear loads, a hybrid Genetic- Fuzzy algorithm has been used in [137]. Application of genetic algorithm [46] achieves optimal performance in Islanded microgrids by optimizing the unbalance present in the system, thus improving the power quality.

8. Comparison of Control Strategies and Suggestions for Future Research

The controllers that are developed and designed in the literature addressing power quality issues have been discussed in this paper. The different features of some of the existing controllers are discussed here focusing the advantages and disadvantages. PI controller is simple in structure and provides good performance in a balanced system, but it is not at its best when applied to unbalanced system and to compensate harmonics in the system. PI regulators are not fast enough to achieve voltage regulation and mitigate voltage variations.PR controllers can ensure a zero steady state error with excellent reference tracking but only near the resonant frequency of the controller and can eliminate harmonics well.

Hysteresis current controller is simple in structure and provides fast transient response but it doesn’t have fixed switching frequency. Dead beat controllers are also simple but are sensitive to variations of system parameters.On the other hand, Repetitive controllers are good in eliminating the periodical disturbances and reduces the harmonic distortions due to non-linear loads but with certain disadvantages like slow dynamics, poor accuracy etc., Fuzzy based controllers are insensitive to system parameter variations. H_∞ controller offers low THD and provides good performance under plant uncertainties and disturbances but is relatively slow in nature compared to other controllers.

Table 1 shows the performance comparison of differnt controllers designed for a grid connected VSI under different operating conditions like: without local loads, unbalanced resistive local loads and non-linear local loads considering the THD of the currents sent to the grid [106].

Table 1. Performance comparison of controllers

Controller Type	Total Harmonic Distortion - Current THD		
	Without any local loads	Unbalanced resistive local loads	Non-linear local loads
PI controller	4.38%	5.03%	16.02%
PR controller	3.84%	5.39%	16.71%
DB controller	3.65%	5.54%	16.54%
$H\infty$ controller	1.03%	1.55%	5.27%

Table 2. Advantages and disadvantages of different control methods

Method	Advantages	Disadvantages
PI Controller (Natural Reference Fame)	• Control structures are simple. • Can regulate the fundamental component.	• Controller matrix is complex due to the presence of off-diagonal elements which represents the cross coupling between the phases. • Does not ensure good performance for unbalanced systems.
PI Controller (Synchronous Reference frame)	• Exhibits satisfactory performance for regulating DC variables. • Ensures zero steady state error.	• Poor lower order harmonic compensation.
Proportional Resonant Controller (PR)	• Robust current controller • Ensures zero steady state error • Attains high gains.	• Error free performance can be achieved near the controller’s resonant frequencies.
Hysteresis current control	• Simple in structure. • Robust in nature. • Independent of load parameter variations. • Provides extremely good dynamics.	• Leads to resonance problem due to the load parameter variations and change in operating conditions. • No concern about the low-order harmonics. • Doesn’t have fixed switching frequency. • The current waveform contains harmonics at switching and sampling frequencies order and the current error is not within the hysteresis band. • Applicable only to lower power levels as the switching losses are more.
Repetitive Control	• Periodic disturbances are eliminated. • Robust • Ensures a zero steady-state error at all the harmonic frequencies.	• Stability is a problem when the load disturbances are non-periodic. • Slow response when the load fluctuates.
Deadbeat control	• Simple. • High tracking speed and control accuracy can be achieved. • Performance depends on the sampling frequency.	• Sensitive to system parameter variations.
H∞ Control methods	• Applicable to Multi-Input Multi-Output (MIMO) systems. • Offers low THD and improved performance. • Complexities of the plant, uncertainties, disturbances or poor dynamics are taken care. • Ensures good performance under all types of loads.	• Slow dynamics. • Understanding of high level mathematics is required as the modeling is complex.
Fuzzy Control Methods	• Ability to manage the non-linear behavior of complex control structures by taking advantage of heuristics and expert knowledge of the process being controlled. • Insensitive to system variations.	• Slow control method.
Neural Networks	• Used in current controllers as they are robust in nature.	• Lack of performance in off-line training method.

Comparison of the different control methods are presented in Table 2 which shows the advantages and disadvantages of each controller. Comparison of each controller is in terms of rapidity, stability, harmonic elimination, robustness against parameter variation and unbalanced compensation. It is highly difficult to specify a particular control method is superior to others, as each method has its own merits and demerits.

Though there are many discussions in the literature about the control strategies for the power quality improvement in a microgrid system, no control technique provides solution to address all the power quality issues like voltage unbalance, voltage sags and swells, harmonic distortion and power sharing issues at the same time. Hence further research can be focused on the development of control technique to satisfy the requirements at the same time.

9. Conclusion

This paper has explored the developments in microgrid and its control for the improvement of power quality. The different control strategies implemented in literature for the enhancement of power quality in both isolated and grid connected microgrid systems under unbalanced and non-linear load conditions have been discussed. In the field of renewable energy, as the research and development all over the world is mainly focusing in the real time implementation of smart grid, the study of microgrid, its control strategies and the challenges in integrating with the utility aiming to generate and feed quality and reliable power to the grid / customers is very well needed.

The major concern in the near future will be the integration of microgrid in to the existing power system, due to the variable nature of renewable energy sources and its rapid growth. Hence it is necessary to take measures to improve the control aspects so as to integrate the microgrid with the main grid effectively with improved power quality.

Although different types of controllers have been developed to improve the power quality in a microgrid system, new controllers addressing multiple power quality issues simultaneously needs to be developed. Hence, further research can be done in developing new robust control techniques for the microgrid systems to eliminate the problems associated with all power quality issues at the same time.

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