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A review of reactive power compensation techniques in microgrids

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ABSTRACT

Renewable energy based Distributed Generation (DG) has been the solution to researchers to combat the problem of increasing load. In DG based microgrids, the loads and generators are in the close vicinity to aid continuous power supply. However, the power electronic interfacing towards DG systems gives rise to some of the serious power quality problems, such as, the reactive power compensation and the generation of harmonics that pollutes the power distribution system. Reactive power compensation is becoming a challenging task to sustain an acceptable degree of power quality in microgrids due to tightly coupled generation and distribution. Therefore, current research is to cope up with the expanding microgrid system and mitigation of these concerned issues. Recent trends are geared towards the realization of multitasking devices to tackle several power quality problems simultaneously. Hence, the objective of this paper is to present an overview of a microgrid and its modeling utilizing the actual environmental data. Subsequently, the challenges and power quality issues faced in the microgrid are observed and succeeded by a review of compensation methods against these concerns using various control techniques, algorithms, and devices.

1. Introduction

Electrical practices for the entire power system industry are tremendously changing and these progressions will mark an evolution of new concepts and strategies in the future, particularly concerning the planning and operation of the power systems. The detrimental effects such as aging, hazardous atmospheric changes associated with conventional energy sources make renewable energy based distributed generation to take a lead in future power generation. Distributed generators like solar, the wind, biomass, fuel cells and microturbines will give significant momentum for power generation in the coming future. A microgrid (MG) is a small scale power network designed for a low voltage distribution system to provide a power supply for a small community/island [1,2]. The microgrid operates in two operating modes; grid connected (connected to the conventional grid to allow power exchange) and individual/islanded mode (independent of the conventional grid). The major elements of MG have DG units like PV and wind generators, storage devices, different loads, and power controllers. The interconnection of these DGs to the conventional grid is normally achieved by employing power converters. The use of power converters offers vast benefits like optimal operation and flexible control [3]. However, this power electronic interfacing creates a plethora of power quality problems [4–7]. Power quality problems in a microgrid are of a large variety such as voltage harmonics, voltage sags, voltage swells, voltage unbalance, current harmonics, reactive power compensation (RPC), current unbalance and circulation of neutral currents, impulse transients, and interruptions [8]. Among these, reactive power compensation is considered as a major concern in this paper.

The power system operates on AC system and most of the loads used in our daily life demand reactive power. Thus reactive power or VAR compensation is characterized as the administration of reactive energy to enhance the performance of the AC system. The issue of reactive power compensation is seen from two ways: load and voltage support. The aim is to achieve an improved power factor and real power balance from the load point of view, while the voltage support is primarily necessary to reduce voltage fluctuations at a given terminal of a transmission or distribution line. In both the cases, the reactive power that flows through the microgrid has to be effectively controlled and compensated.

In islanded operating condition, the microgrid has to maintain the reactive power balance independently due to the absence of an infinite bus. The firmly coupled generation and utilization along with the presence of non-dispatchable intermittent renewable power sources require reactive power support. Similarly, in a grid interconnected mode, the reactive power compensation is also found to be challenging due to linear and non-linear loads. This paper envisages reactive power issues of a microgrid in different conditions. In this regard, a microgrid is modeled and developed consisting of renewable energy sources such as PV and wind energy conversion system (WECS), and connected to a

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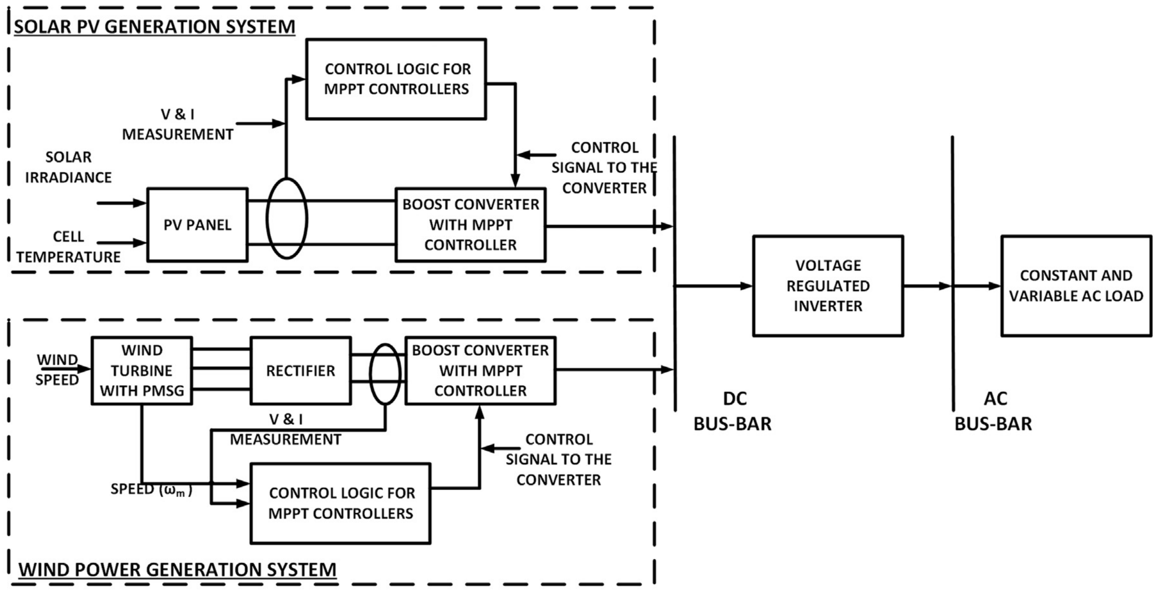

Fig. 1. Block diagram of microgrid.

load. Maximum power point tracking (MPPT) controllers are employed for both PV and WECS. The power quality problems of the microgrid, when subjected to supply and load variations, is observed and presented in the next section. Further, a review of compensation methods against these issues using various control techniques, algorithms and devices are discussed.

2. Microgrid and its power quality issues

A system containing a microgrid with two DG sources connected to a common AC bus is shown in the Fig. 1. The two DG sources include a wind generation source and a PV generation source respectively. In this DG network, linear and nonlinear loads are connected to the AC bus [9]. The modeling of the each DG source is described below:

2.1. Modeling of PV modules in microgrid

A PV cell based on the two-diode model is considered in the construction of MG. The two-diode solar PV model yields more accurate results as compared to other existing models, especially at lower illumination levels [9]. Hence the two diode model is considered as an appropriate model for PV cell where its voltage and current are related by:

$$I=I_{ph} - I_{S1}\left[e\left[\frac{V + R_s{*}I}{N_1{*}V_t}\right] - 1\right] - I_{S2}\left[e\left[\frac{V + R_s{*}I}{N_2{*}V_t}\right] - 1\right] - \frac{V + R_s{*}I}{R_P} \quad (1)$$

where, I_{s1}, I_{s2} are the reverse saturation currents of the two diodes, V_t is the module thermal voltage, photo-generated current is I_{ph}, N_1, N_2 are the quality factors of the two diodes D_1, D_2 used in the two-diode model. R_s, R_p are the series and shunt resistances. Based on Eq. (1), a two-diode model is developed with equation based implementation in MATLAB. The simulations are carried out and the results are validated using the extracted circuit parameters from the data sheet [9]. The behavior of I-V and P-V curves of the two-diode model of a PV cell, when simulated in MATLAB, are shown in Fig. 2 (a). The electrical parameters obtained at standard test condition (STC) from simulation of the two diode model of PV panel are compared with the electrical parameters of the manufacturer datasheet given in Table 1. It can be seen from this table that the simulated parameters and the actual parameters of the solar cell (as given by the manufacturer) fairly coincide with each other.

The model consists of 14 panels connected in series with each other. The MPPT voltage and currents are 30.5 V & 8.05 A respectively and generate the output power of 245 W. As the output voltage is quite low it is required to step up PV system output voltage to the desired value of 415 V using a boost converter. An MPPT algorithm is used to track the MPP to control the boost converter with a duty cycle to achieve continuous desired output voltage. Perturb & Observe (P & O) algorithm is used to control the duty cycle of the boost converter so that MPPT is achieved. The resultant power rating of the modeled PV generator is 3 kW with 14 panels, each having a power rating of 245 W maximum as described in Table 1. Similarly, a 3 kW, 415 V wind-based generator is developed and connected to the MG.

2.2. Modeling of wind generator in microgrid

A wind generator with Permanent Magnet Synchronous Generator (PMSG) is considered as the second DER in the construction of MG. The wind turbine output power [10] is given by (2)

$$P_0 = \frac{1}{2}\rho A V_{wind}^3 C_p(\lambda,\ \theta) \quad (2)$$

where P_o represents the turbine output mechanical power, C_p is turbine power coefficient λ represents the rotor blade's tip speed ratio, θ represents the pitch angle of the blade, ρ represents the density of air, A represents the area swept by the blades of the turbine, V_{wind} represents the wind speed. The considered wind turbine parameters are R=1.25 m, length of blade L = 2.5 m, $A = 19.63\ m^2$, ρ=1.225 kg/m^2. The wind energy conversion system (WECS) is modeled and developed by using these parameters. To keep the output voltage constant at a desired value of 415 V, an MPPT controlled boost converter is employed. The duty cycle of the boost converter is controlled by Hill Climb Search (HCS) MPPT algorithm for the WECS.

An MG containing PV-wind MG generating system is implemented in a Simulink / MATLAB environment by appropriately modeling the DG sources, MPPT controllers, Boost converters and the DC bus. The developed system along with its controllers has been investigated for the real-time data. The actual environmental data like solar irradiation and wind profile have been collected with the help of a weather monitoring system of Birla Institute of Technology and Science, Hyderabad Campus, India. The record of solar insolation and wind speed in a day is observed as shown in Fig. 2 (b) & (c). The variations in the output voltage, active and reactive power flow in each DG is

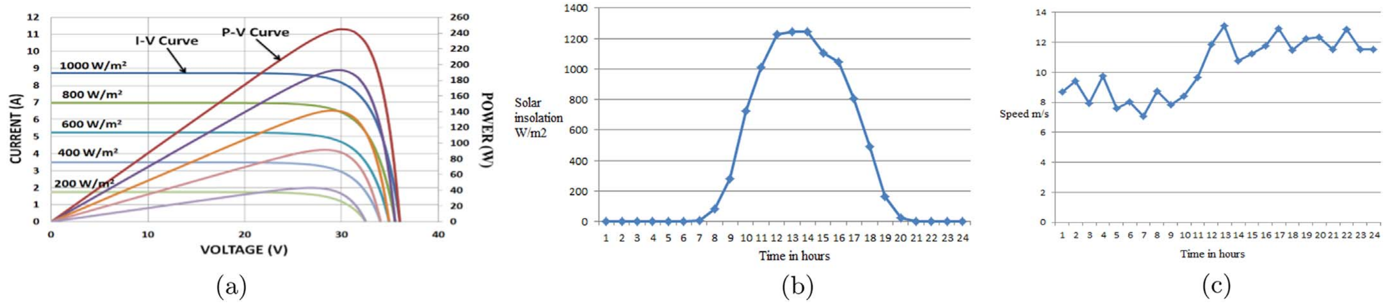

Fig. 2. Performance of PV-Wind Microgrid. (a) I-V and P-V characteristics of a PV panel. (b) Variation of solar insolation in a day. (c) Variation of wind speed in a day.

Table 1
Comparison of two diode model of PV panel at standard test condition with manufacturers data sheet.

Electrical Parameters	Manufacturer Data-sheet	PV panel with two diode model at STC
V open cir (V)	37.5	37.5
I short cir (A)	8.73	8.729
P(max) (W)	245	245.06
V(MPP)(V)	30.5	30.75
I(MPP)(A)	8.04	7.97

observed with respect to changes in environmental conditions as described in Fig. 2 (b). The output voltage and P responses in case of PV generating system due to the variation in solar irradiation within a range of 600–1000 W/m^2 for a duration of 1 s are shown in the Fig. 3 (a). Similarly, the output voltage, P, and Q responses in case of WECS due to the change in wind speed within a range of 8–12 m/s for the duration of 1 s is shown in the Fig. 3 (b).

Due to the frequent variations of the nature of the loads (harmonic and reactive) connected, power quality issues are also observed. It is thus concluded that the requirement of reactive power compensation in the MG is necessary to compensate the supply and load side disturbances. A suitable technique with the appropriate device is necessary for RPC in the microgrid. In this regard, a review has been made and presented on the required compensation against the aforementioned issues using various control techniques, algorithms, and devices in the next section.

3. Review of reactive power compensation in microgrids

3.1. Control techniques

Many innovative control techniques have been used for enhancing the power quality by providing compensation for the microgrid. The converters used in the microgrid are controlled to deliver desired real and reactive power. Reactive power/voltage and active power/frequency droop concept were mainly used for the power control in the microgrid. The droop control (P/f-Q/V) strategy was downscaled from

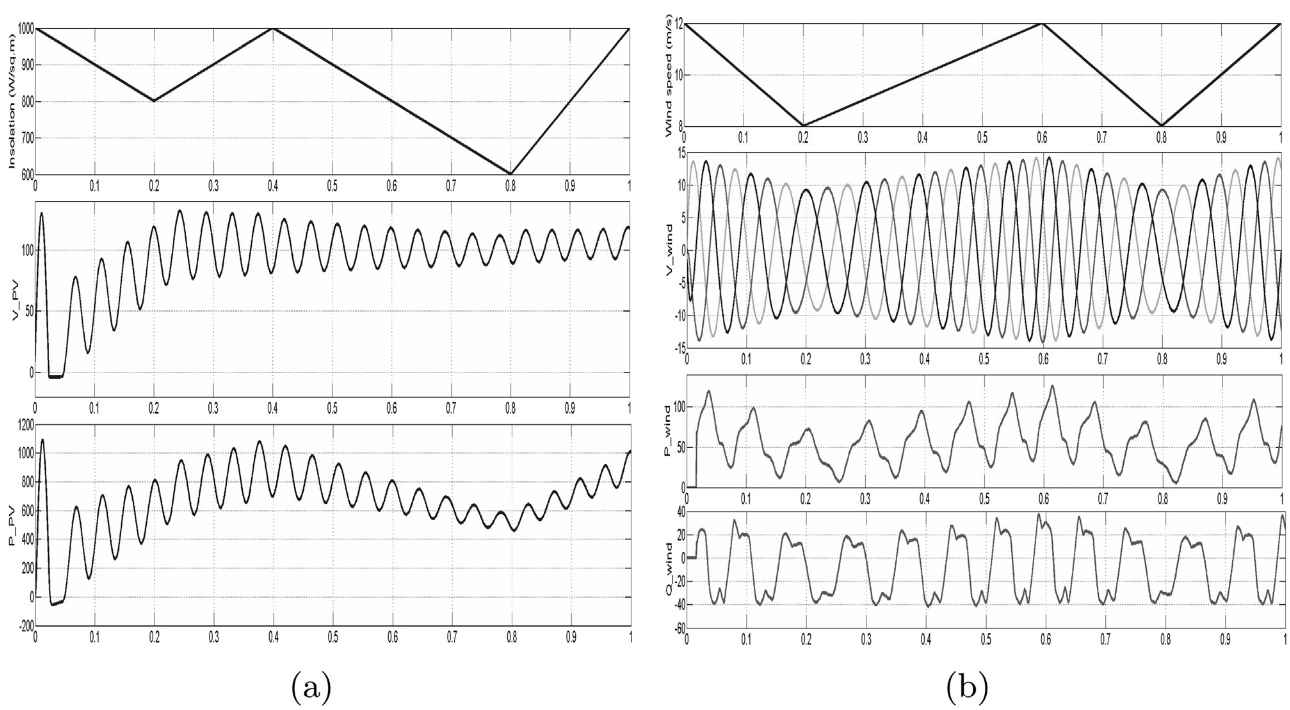

Fig. 3. Voltage, P & Q variation in PV-Wind Microgrid. (a) Voltage & P variation due to change in solar insolation. (b) Voltage, P & Q variation due to change in wind speed.

a conventional grid to low voltage grids in [11]. An improved (P/f-Q/V) control was used to compensate for the imbalance load condition in [12]. A new Adaptive Notch Filtering (ANF) approach was applied without PLL to provide voltage regulation and reactive power control [13].

Co-ordinated P-Q control from DG units to the utility grid by changing voltage amplitude and phase of PWM converter was presented in [14]. Furthermore, the current balance control, in addition to P-Q control, was discussed in [15]. In [16], the effect of load & nature of DG source along with V/f-P/Q control was considered.

It has been established that in grid-connected mode, the microgrid can be used for reactive power control, thus transforming its operation into static VAR compensation besides acting as an energy source [17]. Even in autonomous mode, real and reactive power balance can be achieved using node voltage regulation [18].

Power converter building block for sliding mode control of active and reactive power [19], a neural controller in parallel with the PI controller for improved droop control [20] were designed to provide RPC. Reactive power regulation by cooperative control of electronic power processors was suggested in [21].

P/f-Q/V droop control was modified to comply with inertial and non-inertial nature of DG sources [22]. The droop controller design based on three features, current (power) decoupling, the first-order inertia, and droop control was presented in [23].

Instantaneous P-Q theory for reactive power compensation was introduced in [24]. Reactive power allocation (RPA) strategy based on phasor analysis for P-Q management was given in [25]. Reactive power based control against wind flow swings in WECS based microgrids was presented in [26]. Direct P-Q control for micro-hydro ECS [27], direct/inverse droop control of active and reactive power control in both interconnected and islanded microgrids [28] were the other suggested control methods.

Harmonic compensation in addition to reactive power compensation using droop control was presented in [29]. P-Q control using Finite Hybrid Automata (FHA) including droop control for switch-mode microgrids was discussed in [30].

Lyapunov current control of P-Q was used to give superior performance over conventional PI or resonant control for microgrids [31]. Dubbed Generator Emulation Controls (GEC) were incorporated to allow DG inverters to provide voltage regulation support, reactive power compensation, and fault ride-through effectively in microgrids [32].

Instantaneous reference current generation avoiding the usage of PLL and PARK's transformation blocks [33] was provided to enhance P-Q control. However, PARK's transformation with decoupled active and reactive currents was applied to obtain independent P-Q control in [34].

Voltage regulation with sliding mode control to provide reactive power compensation was discussed in [35]. The dynamic reactive power compensation of a microgrid with different photovoltaic permeability was proposed in [36].

Droop control of Island microgrids in [37], bidirectional current control of DC microgrid connected to AC microgrid in [38] were presented.

Back to-back voltage source converter (BTB-VSC) was used to regulate bi-directional power flow through a DC link [39]. Flexible ABC theory - Lagrange optimization was applied for reactive power compensation of a distribution microgrid [40]. Q $\dot{V}$ droop control method with $\dot{V}$ restoration mechanism was proposed to improve reactive power sharing [41]. Reactive power sharing errors using the conventional droop control was reduced by injecting a small real power disturbance in [42].

A new consensus based P-f and Q-$\dot{V}$ droop control was suggested in [43]. A model predictive control based dynamic voltage and VAR control were presented in [44]. Besides, inspired by the conventional P-f droop control, a $\int Q$ dt - V droop control was proposed in [45] by reducing the voltage proportional to the integration of the reactive power. This control mainly reduces the errors in reactive power sharing. Microgrid acting as APF to provide harmonic reactive power compensation using model predictive control was given in [46]. A review of optimal active and reactive power flow in microgrids was presented in [47]. Power flow analysis and different control modes of DGs, such as droop, PV, and PQ, in an islanded MG, were described in detail in [48]. Reactive power compensation issues in interlinking converters of microgrid were caused by a phenomenon known as a limit cycle. The appearance of the limit cycle was eliminated by using non-linear hysteresis control given in [49]. A tariff based fuzzy logic controller was designed for microgrids with reactive power and harmonic compensation as main functions in [50].

The above control techniques starting from droop control, inverse droop control, control with and without PI controller, with and without PLL, various novel proposed control schemes were applied in a microgrid to provide reactive power compensation.

3.2. Algorithms

The following algorithms were implemented by various researchers in providing reactive power compensation in microgrids. The algorithms were micro genetic algorithm [5], flux charge current-limiting algorithm [6], applied micro genetic algorithm with minimal real power loss [51], strategic frame based energy management [52].

Sensorless algorithm for the decoupled control of torque and reactive power in WECS based microgrid [53], and conservative power theory for voltage unbalance and reactive power compensation [54] were discussed. Furthermore, the smart control algorithm for P-Q management [55], the power control loop and voltage-current close loop control algorithm for combined PQ and droop control [56] were proposed. The ranking algorithm to withstand maximum P-Q load abilities [57], the phasor pulse width modulation algorithm [58], the multi-objective optimal power flow algorithm for multi microgrids [59], and the randomized gossip-like algorithm [60] were suggested to enhance the power quality in microgrids. A distributed control algorithm was proposed to solve reactive power compensation problem in microgrids in [61]. Thus, various proposed algorithms for providing reactive power compensation in PV and wind-based microgrids are listed above.

3.3. Devices

The power quality problems in microgrids are to be mitigated by providing harmonic, reactive power and unbalanced compensation. Otherwise, power quality of microgrids is adversely affected. In addition, they cause disturbance to other consumers and interference in nearby communication networks. Existing survey suggests the application of different compensation devices as a solution to reactive power compensation. Usage of capacitor banks, application of TSC and TCR devices of classic technology mitigates some of the aforementioned power quality problems. Conventional passive LC filters were used to mitigate harmonics and reduce the number of capacitor banks while improving power factor. However, the main drawbacks like bulkiness, resonance, fixed compensation are the deterrents of the classical methods. Power electronics based Flexible AC transmission systems, also known as FACTS devices, have been developed and seemingly provide a powerful solution to compensation. Initially, FACTS based reactive power compensation in WECS was discussed in [62]. The power electronic interfacing to ensure power quality in microgrids was introduced in [4,64]. The conventional grid reactive power compensation FACTS devices were suggested to be implemented in microgrids in [5]. A three-phase four-wire grid-interfacing power quality compensator was proposed in [6].

Few devices proposed for compensation were, D-UPFC for voltage sag/swell control [65], shunt active power filter [66] for VAR compen-

Table 2
Various reactive power compensation methods.

Method	Compensation technique
Control techniques	[31–36,38–41,43–45,49,50]
Algorithms	[5,6,51–61],
Devices	[62,63,4,64,6,65–106]

sation, static synchronous compensator (STATCOM), battery energy storage system (BESS) [67], and voltage and frequency controller (VFC) with a DC chopper to control the reactive and active power [68].

Combination of DSTATCOM and DG in grid connected mode [22], Dynamic voltage regulator [69], UPFC [70] were proposed to provide power quality compensation.

Reactive power management in a hybrid electrical station (photovoltaic and hydro turbine) and diesel generators constituting a microgrid can be achieved when DFIG was connected to the microgrid [107]. Similarly, a combination of synchronous generator and induction generator was suggested in parallel operated micro hydro plants [108] for providing compensation. DFIG-WECS with PQ based PWM converters was suggested in [71].

Distributed switching power processors and static reactive compensators [72], Dynamic power limiter with matrix converter at PCC [73], DSTATCOM for VAR regulation [74] were the other suggested power electronic interfacing devices in microgrids.

A microgrid voltage stabilizer (MGVS) [75], microgrid with wireless technology (ZigBee, 2.4 GHz) [76] were designed and recommended for active-reactive power control and coordination. Multi-function devices like constant frequency UPQC with matrix converter [77], universal power line manager consisting UPQC, UPFC and matrix converter [78] were suggested for mitigation of different power quality problems. VAR compensator was applied in parallel operated the wind or hydro microgrid along with self-excited induction generator [109]. UPFC for combined conventional and DG grid compensation [82], UPQC for power quality improvement [93–95], Kalman filter in WECS [79] for VAR control, Battery storage along with micro-wind energy generation system (μWEGS) [80] for voltage support were presented for various compensation methods in microgrids. The combination of SVC and APF in [81], UPFC in microgrids incorporated with Hamilton Jacobi Bellman Formulation [83] has given reactive power support in microgrids. A comparison has been made on reactive power - voltage regulation between SVC and static capacitors in [84]. Smart microgrid with power line communication modem (PLC modem) for reactive power compensation coordination was discussed in [85].

Nine IGBT's based UPFC topology [86], STATCOM as a custom power device (CPD) [87–89], SVC in LV grids with TCR and TSC [90] were suggested for reactive power compensation and voltage fluctuation mitigation in microgrids.

Distribution level power electronic devices like STATCOM, SSSC, UPFC, multi-terminal and back-to-back converters for DG connected network compensation were additionally discussed in [91].

UPQC for interconnecting PV modules to grid with power angle control, thereby enhancing power quality was discussed in [92]. Similarly, enhanced UPQC with different modeling aspects and energy systems [96], and a multi-converter UPQC (MC-UPQC) using fuzzy logic controller [97] provide RPC. Implementation of three phase four wire distribution UPQC [98], comparison between STATCOM and UPQC for asymmetrical faults of WECS [99], UPQC for intelligent islanding and seamless reconnection of microgrids [100], advanced UPQC for grid integration and VAR control [101], H ∞ controller for series unit voltage and shunt unit current track compensation in microgrids [102], improved iUPQC controller as STATCOM for grid voltage regulation and reactive power support [103] provide a review of UPQC in providing power quality in microgrids.

Power quality problems in conventional grid-connected with renewable energy sources can be solved with the application of FACTS devices [63]. UPQC can be used in microgrids for voltage sag/swell mitigation [104], supply/load disturbance compensation [105]. In grid-connected mode, RPC is provided by UPQC while its DC link energy is restored by PV array as proposed in [106].

Table 2 gives the summary of the various methods in terms of control techniques, algorithms, devices for providing RPC. Recent trends are geared towards the realization of multitasking devices which can tackle several power quality problems simultaneously. Furthermore, the performance of the system can be very effective if the source supplies only the active power whereas reactive power should be locally supported. From the above discussion, it is clear that the switched reactive power compensators, traditional rotating synchronous condensers, static VAR compensators employing thyristor switched capacitors and thyristor controlled reactors were used to provide power quality compensation. However, they may not be suitable to be operated in the microgrid due to the drawbacks like bulkiness, resonance, fixed compensation. Active filters can operate in this direction, by functioning at the point of installation without considering the power quality status of the entire system. Active power filters, on the other hand, are flexible and smaller in size. In addition, they optimize the performance of the system by providing multitasking (Voltage regulation, Reactive power compensation, Harmonic compensation etc.). Hence, the active power conditioning device UPQC, which is a combination of series and shunt active power filters is recommended as a single solution for mitigating these multiple power quality problems of voltages and currents in microgrids.

4. Conclusion

Power distribution system is turning out to be very defenceless against various power quality issues as the microscope renewable energy penetration is emerging vitally towards consumer end. This reconciliation of DERs in power system has further forced new difficulties like power quality compensation to the industry. To keep up the controlled power quality regulations, providing compensation at all the power levels is turning into a typical practice. In this regard, a distributed generation based microgrid consisting of a WECS, solar PV, and stand-alone AC loads has been considered in this paper to analyze its performance under various operating conditions. It is found that when the wind velocities are changing or partial shadowing occurs, it would cause huge disturbances in the source, apart from load variations imparting their own perturbances in the form of power quality disturbances. Due to this unpredictable nature, it is almost impossible to maintain an accurate AC power balance between the source and load. Subsequently, maintaining nominal voltage is essential in microgrid which requires reactive power balance. Various control techniques, algorithms, and devices are categorized and presented in this paper. Hence, a detailed study has been made to find an appropriate solution to mitigate the power quality issues by providing required reactive power compensation.

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